50 BREAKTHROUGHS

Critical scientific and technological advances needed for sustainable global development

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This is the beginning of a conversation.

When the Millennium Development Goals were launched in 2000, the rallying cry was around the need for more development aid. As international institutions coalesce around the post-2015 Sustainable Development Goals, it is likely there will be a heavy emphasis on the role of science and technology in achieving them.

Through the post-WWII history of efforts to alleviate global poverty, a small number of breakthrough technologies have had transformative impact: the polio vaccine has all but eradicated a disease that was leading to life-long paralysis in millions of people around the world; new seed varieties developed by Norman Borlaug launched the Asian Green Revolution, which led to agricultural self-sufficiency through much of Asia; insecticide-treated bed-nets have led to remarkable successes in malaria control; and antiretroviral drugs appear to have rendered HIV/AIDS a chronic and manageable disease. More recently, the mobile phone revolution has led to innovations like the M-PESA mobile money platform, which has become the primary means of payment for low-income populations in Kenya.

Such major breakthroughs, however, are rare. One reason, we found, is that there is limited broad understanding of the underlying issues, and the role that technology can play. While deep knowledge rests among a small number of topic-specific experts, the nature of the international development sector is that a large number of the decision makers—donors, social impact investors, program officers, employees in government agencies, practitioners working in NGOs or international institutions—often make their decisions based on limited information and analysis. As a result, far too much of the effort in the technology-for-development space is focused on incremental technologies, which—despite compelling narratives, significant funding, and considerable media hype—fail to reach any reasonable scale or impact.

To be sure, technology is not essential to solving many of the problems surrounding global poverty. Tremendous progress can be made through institutional reform, infrastructure development, education, access to user finance, behavior change, and other policy and social interventions. Indeed, even when technology is necessary, it cannot achieve meaningful impact on its own. This study focuses on problems for which new technologies are critical. By definition, these breakthroughs do not currently exist, at least not in the right configuration of cost and usability. Typically, there is no need for them in industrialized countries, and the private sector likely does not see enough profits to invest in creating them for developing world markets. They represent breakthroughs because they have to be dramatically different from existing technologies in industrialized settings: available at a fraction of the cost, requiring only a fraction of the energy, significantly less reliant on technical skills to operate, not needing elaborate infrastructure, and being generally robust and maintenance-free.

These breakthroughs are decidedly not ‘low-tech’, in that they cannot be achieved by backyard hobbyists or part-time volunteers inspired by humanitarian objectives. They require serious science, robust engineering, and inventive business models for distribution, scale and sustainability. These breakthroughs have to be part of a new paradigm of technologies for a new set of users. Unlike in past decades, the proliferation of new off-grid energy and communication platforms offers unprecedented opportunities to create leapfrog technologies, some of which may even be valuable in industrialized countries.
Motivation and objectives

In this context, the main purpose of our study is to identify where such paradigm-shaping breakthroughs are most required. The intended reader of this study is the ‘informed generalist’ in international development rather than topic-specific experts. The study aims to:

- Launch a thought-provoking conversation among practitioners in the technology-for-development ecosystem in order to focus collective effort on the breakthroughs that really matter.

- Provide contextual background for technologists who may not yet have realized the relevance of their work to global poverty.

- Provide funders a guide to asking the right, and likely hard, questions as they evaluate their investment options.

As a part of this study, we consulted with a large number of topic-specific experts. It is important to note that not all of them agree with our conclusions. Undoubtedly, new evidence will disprove some of our conclusions and analyses. In many cases, the evidence that exists—and informs our analysis—does not rise to the level of academic precision. Notwithstanding these risks, we are sharing our findings with the belief that the problems we seek to address require urgent decisions with the best data available, and that our ecosystem needs a common starting point for debate.

Which brings us back to our first point. This is the beginning of a conversation.
ABOUT LIGTT, AND THE GENESIS OF THIS STUDY

LIGTT (pronounced ‘light’), is the Institute for Globally Transformative Technologies at the Lawrence Berkeley National Lab (LBNL). Founded in 1931 by the Nobel Prize winning physicist Ernest Orlando Lawrence, LBNL is one of the world’s oldest and most storied institutions for scientific research.

Over the years, its scientists have discovered or synthesized many of the elements in the last row of the periodic table, invented a range of major technologies such as synthetic antimalarial drugs, electronic ballasts for more efficient lighting, Home Energy Saver (the web’s first do-it-yourself home energy audit tool), a pocket-sized DNA sampler called the PhyloChip, windows with embedded electrodes that enable window glass to respond to changes in sunlight, and synthetic genes for anti-AIDS superdrugs. One of Berkeley Lab’s most notable breakthroughs is the discovery of dark energy, a critical construct in astrophysics, which permeates all of space and accelerates the expansion of the universe. A number of LBNL’s scientists have also served on the Intergovernmental Panel on Climate Change. Over the years, LBNL scientists have won 13 Nobel Prizes.

LIGTT was created in 2012, with the aim of leveraging LBNL’s capabilities—3,500 scientists and engineers, $800 million in annual R&D, hundreds of patents, and dozens of facilities for experimentation, simulation, testing and fabrication—to develop and deploy breakthrough technologies for sustainable global development. LIGTT continues in LBNL’s tradition of fostering transformative technologies, with the difference that we also focus on innovative business models for deployment. One of the first questions the LIGTT team set about trying to answer was, “what technologies should we focus on?” This led to an internal study to identify what eventually became the 50 Breakthroughs. LIGTT aims to develop many of these breakthroughs, working with scientists from LBNL and other research institutions around the world.
GEOGRAPHIC FOCUS

The geographic focus of this study is sub-Saharan Africa and South Asia, primarily because poverty is concentrated in these regions. The map below shows the various parts of the world, ranked in terms of the United Nations’ Human Development Index (or HDI, a composite metric which combines wealth, health and education), and grouped into population deciles. According to the HDI, the worst-off countries are in sub-Saharan Africa and South Asia (UNDP, 2013). While our focus throughout this study is on the two poorest regions, poverty persists in other parts of the world as well. In principle, the solutions identified in this study are just as applicable elsewhere as they are in both South Asia and sub-Saharan Africa.

* Map not to scale
Traditionally, studies focused on future-facing topics have relied on surveys of experts, using approaches like the Delphi Method\(^1\), a structured iterative process of interviews and reviews. Early in our study, we discovered two challenges with such a process. First, the absence of a broad, credible evidence base about what works has led to entrenched opinions. Second, such an approach would likely have led to a laundry list of 50 technologies or devices, rather than to a robust problem analysis which logically leads to the breakthroughs required—agnostic to specific technologies.

Hence, this study employs a six-part approach to reach its conclusions:

1. Describe and analyze the 5-10 most important contextual facts about the specific problem.
2. Identify the key challenges, which have kept effective solutions from becoming a reality.
3. Identify, based on input from recognized topic-specific experts, the most promising interventions to overcome those hurdles.
4. Determine the dependence of each of these interventions on: policy reforms, infrastructure development, education and human capital development, behavior change, access to user finance, an innovative business model, and finally, a new breakthrough technology.
5. We focus on interventions with a significant dependence on a breakthrough technology, and identify the important parameters the technology needs to fulfill. Based on the underlying technical challenges, we then estimate the time-to-market by when these breakthroughs may become deployable products.
6. Finally, we identify the most important hurdles to sustainable, large-scale deployment, based on many of the factors listed above (e.g., policy reforms, etc.), and score the difficulty of deployment on a 5-point scale: simple, feasible, complex, challenging, and extremely challenging. The purpose of this final analysis is to encourage technologists and funders to understand these challenges before making major investments in their work.

Each chapter is divided into three parts: Core Facts and Analysis, Key Challenges, and Scientific and Technological Breakthroughs. The 5-point scale and the complexity we ascribe to each of the factors and constraints relevant to the deployment of a particular technology are illustrated in Table A. The lowest score (feasible) is reserved for cases when the particular constraint is not relevant to deployment; the constraint is given the highest score (extremely challenging) if it can be a serious bottleneck to deployment. The aggregate score reflects the overall degree of difficulty, considering the collective weight of the individual constraints. The methodology is clearly subjective. Exhibit A is a sample of how we have illustrated the difficulty of deployment for each breakthrough across the study. This particular sample highlights a CHALLENGING breakthrough.

\(^1\) A structured communication technique, originally developed as a systematic, interactive forecasting method which relies on a panel of experts who anonymously reply to questionnaires and subsequently receive feedback in the form of a statistical representation of the ‘group response’, after which the process repeats itself. The Delphi method is based on the assumption that group judgments are more valid than individual judgments. It was originally developed by the RAND Corporation in the 1950’s to forecast the impact of technology on warfare.
<table>
<thead>
<tr>
<th>Policies</th>
<th>Simple</th>
<th>Feasible</th>
<th>Complex</th>
<th>Challenging</th>
<th>Extremely Challenging</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimal role of policy/regulation</td>
<td>Low role of policy/regulation</td>
<td>Regulated market with supportive policies</td>
<td>Highly regulated market with policy changes required</td>
<td>Highly regulated and controversial changes required</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>Minimal need for infrastructure</td>
<td>Dependent on existing infrastructure</td>
<td>Requires some improvements to existing infrastructure</td>
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</tr>
<tr>
<td>Human capital</td>
<td>Minimal need for human capital development</td>
<td>Low-moderate need for human capital development</td>
<td>Moderate need to train a limited number of people</td>
<td>Requires high level of training for large numbers of people</td>
<td>Requires national scale training programs</td>
</tr>
<tr>
<td>Access to user finance</td>
<td>Financing not required</td>
<td>Limited financing required</td>
<td>Moderate financing needed, viable mechanisms available</td>
<td>Significant financing required, limited mechanisms available</td>
<td>Significant financing required, no identified mechanism</td>
</tr>
<tr>
<td>Behavior change</td>
<td>No behavior change required</td>
<td>Minimal behavior change required</td>
<td>Moderate behavior change required with evidence of behavior change being viable</td>
<td>Major behavior change required, potentially on daily basis</td>
<td>Significant behavior change needed on daily basis, changes contrary to cultural norms</td>
</tr>
<tr>
<td>Existing demand</td>
<td>Strong existing demand</td>
<td>Existing demand</td>
<td>Moderate demand</td>
<td>Low demand, needs to be built</td>
<td>Extremely low demand or not a perceived need</td>
</tr>
<tr>
<td>Market fragmentation/ Distribution channels</td>
<td>Highly concentrated market or well defined channels</td>
<td>Fairly concentrated market and/or well defined channels</td>
<td>Moderate fragmentation of customers, under-developed channels</td>
<td>Fragmented market, weak distribution channels</td>
<td>Highly fragmented, challenging to reach customers</td>
</tr>
<tr>
<td>Business model innovation</td>
<td>Clear deployment models existing at scale</td>
<td>Deployment model in process of scaling</td>
<td>Deployment model(s) being tested</td>
<td>Deployment model(s) being tested, major hurdles outstanding</td>
<td>No identified deployment model, major hurdles identified</td>
</tr>
</tbody>
</table>
Breakthrough – Difficulty of deployment

- **Extremely Challenging**
  - Policies
  - Infrastructure
  - Human capital
  - Access to user finance
  - Behavior change
  - Existing demand
  - Market fragmentation/Distribution channels
  - Business model innovation

- **Challenging**
  - Low role of policy/regulation
  - Requires high level of training for large numbers of people
  - Moderate behavior change required with evidence of behavior change being viable
  - Moderate demand
  - Deployment model(s) being tested, major hurdles outstanding

- **Complex**
  - Requires some improvements to existing infrastructure
  - Moderate financing needed, viable mechanisms identified

- **Feasible**
  - Moderate demand

- **Simple**
  - Moderate demand
Across the 9 areas covered in this study, we have identified 50 breakthroughs which can make a substantial difference to the lives of the poor, especially those living in South Asia and sub-Saharan Africa. Not surprisingly, many of these breakthroughs address issues in multiple areas of this study (and are color-coded accordingly; color key below). In some cases, several individual—but related—breakthroughs have been consolidated into one which is more expansive. While it is difficult to rank these 50 in terms of their relative importance, we have identified a list of top 10. These ‘top 10’ are in no particular order of importance; neither are the rest. Over and above these 50, we also mention here a particular breakthrough that repeatedly emerged as a cross-cutting theme, taking our total tally in this list to 51.

### The 9 areas of this study

- Global health
- Food security and agricultural development
- Education
- Human rights
- Gender equity
- Water
- Access to electricity
- Digital inclusion
- Resilience against climate change and environmental damage

1. **A new method for desalination: scalable, low cost, and using renewable energy.**

   Water scarcity is one of the most critical problems the world is facing today, and this problem is likely to get significantly worse in the coming years. An increasing amount of the world’s freshwater is becoming brackish, and more is being dissipated into oceans and other bodies of unusable water. Reclaiming this seawater and inland brackish water through desalination will need to be a significant part of the larger solution to meet the needs of the growing global population. Current forms of desalination (e.g., reverse osmosis) are prohibitively expensive and energy-intensive.

2.  

   2 – 4. **Vaccines that can effectively control and eventually help eradicate the major infectious diseases of our time—HIV/AIDS, Malaria and TB.**

   Collectively, HIV/AIDS, Malaria and TB kill almost 4 million people a year, and represent a significant disease burden for low income populations in sub-Saharan Africa and South Asia. Effective vaccines for these diseases do not exist yet due to the intrinsic complexity of the pathogens causing them, and a lack of understanding of the specific mechanisms through which our immune systems protect against these diseases.

3. **‘Smart’ electronic textbooks which dynamically adapt content for different skill levels, languages and other user specific needs.**

   Education for low income students is fundamentally constrained by the absence of qualified teachers and adequate instructional tools. As smartphones and tablets become increasingly affordable and feature-rich, and as so much of the world gets connected to the Internet, there is a tremendous opportunity to leapfrog current education methods, and create new models of content development, content delivery and instruction. ‘Smart’ electronic textbooks will require curated and up-to-date...
content, ‘wiki’ interfaces for vernacular and other locally relevant and gender-inclusive material, visual and dynamic learning tools for students, interfaces and tools for teachers, student-teacher interaction and peer-to-peer collaboration.

6 Biometric ID systems, linking birth registry, land title registry, financial services, education history, medical history, and other information critical for ICT enabled services.

Individuals born in industrialized countries have formal IDs, which are linked to a range of services vital to their wellbeing and empowerment, and are an intrinsic part of their day-to-day lives. ID systems are inadequate in most developing countries, in part due to the absence of the institutional framework necessary for issuing and using IDs for individuals and businesses. This is one of the reasons why a majority of citizens in many low income countries operate in informal economies, cannot assert all the rights they are entitled to, and cannot hold their governments accountable for services. Biometric technologies can enable developing countries to bootstrap ID systems, empowering individuals to assert ownership of land and other assets, have accurate medical, educational and financial histories available to service providers, and truly become part of formal economic structures. Stringent safeguards are required to ensure privacy, and to protect individuals from being targeted by repressive regimes.

7 Affordable (under $50) smartphones that support full-fledged Internet services, and need limited electricity to charge.

The recent penetration of mobile phones across the broader developing world has been nothing short of dramatic. However, most low income consumers still use basic phones which do not offer advanced functionality beyond voice and SMS text. For true digital inclusion, we believe that smartphones—with their ability to exchange information via a range of modalities (e.g., touchpad, voice-driven control, various ports), and their ability to support a wide array of Internet-based services—are essential. Unfortunately, today’s smartphones are too expensive for low income users.

8 A new generation of homes with advanced construction material, especially for the urban poor: durable, lightweight, and affordable, with integrated solar-powered lighting, ventilation, and toilets.

The majority of the poor—particularly in urban areas—live in densely packed shacks made with found material, which have very limited light or ventilation, and no running water or sanitation. This contributes to a range of health problems such as TB, diarrheal disease, pneumonia, and other respiratory conditions. Improving living conditions by reinventing the home for the poor, with the characteristics listed above, can significantly improve quality of life and is critical for improving health outcomes in developing countries.

9 New methods to produce fertilizers to replace current processes, which are extremely capital intensive and have significant environmental footprints.

Production of synthetic fertilizers—a mainstay of agricultural yields for many decades—depends on processes that are very capital intensive (manufacturing plants and mines costing hundreds of millions to billions of dollars), and in the case of nitrogen, extremely dependent on natural gas (nitrogen fixation factories must be located close to natural gas sources). As a result there are no fertilizer manufacturing plants in sub-Saharan Africa, and this creates a cost burden for African farmers who must buy fertilizer from international sources. From a more global perspective, current production processes have a large
A ‘utility-in-a-box’ for making it simpler, cheaper and faster to set up and operate renewable energy mini-grids.

Currently, setting up mini-grids in rural areas is time consuming, complex and costly, due to weak and fragmented supply chains, poor roads, a lack of skilled workers, and the absence of standardized, modular components. A ‘utility-in-a-box’—a bundled package of mini-grid components that can be easily integrated and installed, and whose parts work seamlessly, making operations simpler—would make mini-grids much more attractive to both service providers and investors, and significantly reduce barriers to expansion. In short, it would make the business of running rural mini-grids more profitable and less risky.

Short course TB treatment drugs that will lead to significant improvements in treatment adherence, and curb the spread of drug resistance.

Currently, treating drug-sensitive TB with the typical cocktail of antibiotics takes more than 6 months. As a result, patients often stop treatment prematurely, leading to treatment failure and causing drug resistance. A short course drug can significantly increase treatment adherence, and therefore also reduce the spread of drug-resistant TB.

Microbicides to provide a method of protection against HIV/AIDS and Human Papillomavirus (HPV) for women who are otherwise vulnerable to infection through sexual contact with their partner.

Women often struggle to get their male sexual partners to use condoms. Vaginal or rectal microbicides, if effective, can be a viable and discreet alternative to condoms for controlling the spread of HIV/AIDS and other sexually transmitted diseases, especially HPV which causes cervical cancer.

Improved, longer-lasting antiretroviral therapy (ART) formulations to control HIV viral replication and increase patient adherence.

ART formulations currently on the market require continuous, long-term treatment, the cost of which is difficult for low income populations to bear. Reformulation of current ART drugs for higher effectiveness, simplified treatment regimens (e.g., single fixed-dose pill), and reduced toxicity can help significantly increase access and adherence.

PrEP (pre-exposure prophylaxis) to reduce the risk of HIV infection.

PrEP is the use of antiretroviral therapy (ART) by those at a high risk for HIV infection (e.g., among couples where one partner is infected), to reduce the risk of contracting the disease. Very recently, a promising combination ART, Truvada, has been approved by the USFDA. However, Truvada needs to be taken daily, for as long as the user wants protection. This is challenging for low income populations, who do not have access to adequate healthcare and counseling. A range of oral and long-acting injectable...
ART drugs are under development, which could help overcome these challenges. However, despite early encouraging signs, gaps remain in understanding the safety, effectiveness, and long-term implications of the emerging suite of PrEP drugs.

**A complete cure drug for Malaria that eliminates all malarial parasites, at every stage of the lifecycle, from the human body.**

Existing drugs for treating malaria do not completely destroy the malarial parasite from the patient’s body, and lead to an asymptomatic reservoir among patients who have been successfully treated. These individuals can then transmit the disease to others when bitten by mosquitoes capable of carrying the parasite. A complete cure—which eliminates all malaria parasites in the patient’s body—will be a pivotal tool in controlling malaria.

**New long-lasting chemical mosquito repellents delivered in novel ways.**

While a number of chemical mosquito repellents are already available, it is unlikely that they will provide sustained control, given the ability of mosquitoes to develop resistance. To tackle this, new classes of long-lasting chemical repellents are required. To achieve scale, they will have to be delivered through novel mechanisms that are easy to use and adopt. While research is progressing, and some chemicals and delivery devices (e.g., topical patches) are showing promise, their long-term spatial efficacy has not yet been sufficiently field-tested or demonstrated.

**New long-lasting non-chemical spatial mosquito repellents or attractants for vector control.**

The most effective repellents or protectants currently used in malaria-endemic countries are indoor insecticide sprays and insecticide-treated bed nets. As effective as these methods have been, they have their limitations. They offer protection only when people are under the nets or indoors. Mosquitoes develop resistance to chemical insecticides, and anecdotal evidence suggests that the effectiveness of commonly used indoor sprays has been declining. Spatial non-chemical repellents or attractants have the potential to overcome the challenge of vector resistance while providing coverage over a broad area (e.g., a room or a home). Some such repellents (e.g., based on sound) exist in the market, but have not proven effective. An ideal repellent or attractant must be designed to be energy efficient and long-lasting (possibly powered by ambient light), targeting the mosquito’s sensory receptors. Such a device would need to be able to run uninterrupted for several months without frequent replenishment.

**An integrated, easy to operate, affordable, and solar-powered suite of medical devices specifically for maternal, child and primary care in low resource settings.**

Currently, building a reasonably equipped clinic costs more than $100,000. In addition, essential devices are often difficult to install, complicated to use, and expensive to maintain. A suite of the key 10-15 devices that are designed for ease of installation and use (e.g., a ‘clinic-in-a-box’) and collectively cost $10,000 or less can serve as a building block for expanding healthcare in rural areas. Integration needs to occur with respect to power supply and management, patient data, diagnostics, and communication. Potential devices include: diagnostics for critical maternal conditions (malnutrition, anemia, malaria, HIV, syphilis, hypertensive disorders); sterilizers; ultrasound; devices to care for preterm or low birthweight infants (continuous positive airway pressure or CPAP, warmers if skin-to-skin warming is not possible, phototherapy); medical refrigeration; and ICT devices or interfaces for tracking patient data and coordinating care.
19 **Low cost, off-grid oxygen concentrators.**

Oxygen therapy is a valuable intervention for treating children with severe pneumonia, but is seldom used in developing countries, especially in rural areas. While various types of oxygen concentrators are available in industrialized countries, these are expensive (over $1,000), require reliable power, regular maintenance, and significant training for users. The oxygen concentrator needs to be redesigned to be less expensive, robust, easy to maintain, and not dependent on grid power. An ideal system should include oximetry as part of the system.

20 **Automated and multiplex immunoassays that can test for a wide range of diseases, and are compatible with easily collected sample types.**

Currently, a patient presenting a particular symptom, for example fever, needs to be tested for the range of conditions that could cause the symptom—each with its own diagnostic—until a positive result is achieved. Most rural clinics serving low income patients do not have the necessary diagnostics available to test the full range of conditions linked to specific symptoms. As a result, some conditions are misdiagnosed, often resulting in inappropriate treatment. One common problem is presumptive treatment, which happens often in the case of malaria where the disease is endemic. Instead of being tested for the actual febrile illnesses they have, patients are simply treated for malaria. Point-of-care immunoassays that can use different types of samples (e.g., saliva, whole blood, urine), and test for multiple biomarkers from a single patient sample, represent a major breakthrough in diagnosis and patient care.

21 **Point-of-care nucleic acid tests (NATs) that are simple, robust, and compatible with easily collected sample types.**

Nucleic acid tests (NATs) are a highly reliable method of detecting the presence of pathogens in a patient, by detecting the presence of the pathogen’s genetic material (DNA or RNA). This method can be used to accurately quantify the level of infection, identify pathogen strains, and determine drug resistance profiles, which is essential for diagnosing and treating diseases like TB and HIV. Currently, NATs are expensive and complex, and require trained laboratory technicians. They are mainly used in hospitals and centralized laboratories. Low cost point-of-care NATs represent a major breakthrough in disease detection. These tests should be compatible with simple sample types (such as whole blood), rapid, user-friendly for minimally trained technicians, robust (despite high heat and humidity), and not reliant on refrigeration, running water, or stable electricity.

22 **Fully integrated single diagnostic platforms that eliminate the need for individual platforms for separate disease conditions.**

Even as progress is made on individual diagnostic technologies and platforms—immunoassays, nucleic acid tests (NATs), etc.—the ultimate breakthrough is a bench-top diagnostic platform that can integrate a wide variety of individual platforms such as optical readers (e.g., for HIV screening), bench-top chemistry analyzers, and NATs (e.g., for TB and viral load testing). Such a platform needs to perform all diagnostic test menus required at the point-of-care in peripheral health clinics. As with other point-of-care diagnostics, the ideal technology would be portable, rapid, not reliant on refrigeration, running water or grid electricity, able to function effectively in high heat and humidity, and easy to use for minimally trained technicians. It should cost no more than a few thousand dollars.
Low cost off-grid refrigerators for preserving vaccines (and other temperature sensitive pharmaceuticals) in remote settings.

Vaccines and a number of other life saving pharmaceuticals are highly temperature sensitive, making it very difficult to administer them in remote, low resource settings. Currently, most rural clinics have neither electricity nor refrigerators, and cannot provide vaccinations. The equipment used for vaccination outreach campaigns in remote areas—insulated boxes with freezer packs—is highly ineffective; many vaccines freeze, others get too warm, and outreach trips are limited to 1 or 2 days. A solar-powered vaccine refrigerator in the $500-$1,000 range will significantly improve the ability of remote clinics to immunize rural populations. A reliable, portable ‘passive’ cooling mechanism that is considerably less expensive (under $100) and can keep the vaccines from either freezing or getting too warm for several days, will also be very helpful.

Thermo-stabilizing mechanisms for preserving vaccines and other temperature sensitive, lifesaving pharmaceuticals so that they do not require refrigeration.

While a new generation of low cost refrigeration (or passive cooling) technologies can address the problem of vaccine preservation, the long-term solution is to obviate the need for refrigeration altogether. This can be done by making the pharmaceuticals thermostable, through stabilizing additives, novel molecular formulations, or other means. While a number of promising technologies are in the early stages of development, none has been extensively field tested, or proven applicable to the full set of essential vaccines.

Nutrient-dense and culturally appropriate foods for infants to complement breast milk during the weaning period.

Malnutrition underlies nearly half of all childhood deaths in sub-Saharan Africa and South Asia. A key problem is that during the weaning period, many infants are fed thin, grain-based porridges as a complement to breast milk. This does not provide sufficient nutrition during this critical period of growth. Affordable, nutrient-dense and culturally appropriate complementary foods for infants can make marked improvements in childhood nutrition.

Affordable off-grid refrigeration for smallholder farmers and small agribusinesses.

The absence of affordable refrigeration and electricity severely limits the ability of smallholder farmers to produce, preserve and sell high-value perishable commodities like vegetables, fruits, meat and dairy. A new kind of refrigerator that costs less than $50 and can run on solar power will help smallholder farmers take such high-value commodities to market, thereby increasing their incomes.

Low cost refrigerated vehicles, sturdy enough for unpaved roads in rural areas.

The ability to transport food to markets while preserving its freshness will help farmers increase their incomes from higher-value produce like vegetables, fruit, meat, and dairy products. Currently, the absence of refrigerated transportation is one of the factors contributing to the lack of a market for such commodities. Refrigerated trucks available on the market today are unaffordable for small agribusiness entrepreneurs, and are generally built for paved roads. In order to be useful in sub-Saharan Africa, refrigerated transportation vehicles must be built for unpaved, rough terrain, and cost less than $5,000.
Low cost systems for precision application of fertilizers and water.

Overuse of fertilizers and water contributes to significant environmental damage. In South Asia, since the Green Revolution, groundwater has been severely depleted, and fertilizer runoffs are causing ‘dead zones’ in waterways around the world. Overuse can also be a tremendous economic waste for smallholder farmers. Precision application systems for irrigation and fertilizers, calibrated to crop type and soil conditions, can be a very cost effective way to increase agricultural yields, while also reducing negative impacts on the environment.

A low cost drilling system for shallow (rain-fed) groundwater wells, combined with portable sensors for measuring groundwater depth. Such systems should reduce the cost of drilling wells to under $100 per farmer in Africa.

Most smallholder farmers in sub-Saharan Africa do not have access to irrigation. Wells are expensive to dig, drilling equipment is expensive to hire (and typically needs to be transported by truck), and it is hard to precisely locate groundwater. A new type of lightweight drill for shallow groundwater (e.g., one that can be transported by motorcycle instead of truck) can decrease capital costs. In addition, equipment for detecting groundwater can change the hit-or-miss nature of digging for water. It will be important to ensure that non-renewable groundwater is not overused.

Low cost (under $50) solar-powered irrigation pumps.

Currently available manual irrigation pumps are expensive and strenuous to use, especially for women farmers. Motorized pumps available on the market are even more expensive, and the cost hurdle is compounded by the recurring cost of fuel. A solar powered pump that is under $50 can dramatically increase access to irrigation. As with other irrigation solutions, it will be important to ensure that non-renewable groundwater is not overused.

Affordable herbicides or other mechanisms to control weeds, ideally ones that are more environmentally friendly than herbicides currently on the market.

Weeds are among the biggest causes of on-field losses for smallholder farmers. General herbicides—not specifically targeting particular types of weeds—can damage the food crops they are intended to protect. An herbicide specifically targeting the biological vulnerabilities of the most destructive weeds can dramatically reduce crop waste. Ideally, such herbicides will be more environmentally friendly than herbicides currently available in most markets.

A low cost (under $50) tilling machine.

Weeds are responsible for significant on-field losses for smallholder farmers. A commonly used method of eliminating weeds is to till the soil before planting. Mechanized tillers currently on the market cost 4-5 times more than what a typical smallholder farmer can afford. Animal-drawn tilling has not proven entirely effective, and manual tilling is simply too cumbersome and too slow. A mechanized tiller that costs under $50 can greatly improve weed control and lead to major improvements in agricultural yields.
A low cost alternative to liquid nitrogen for preserving animal semen.

Artificial insemination (AI) is an effective mechanism for breeding cattle and other animals, leading to significant improvements in livestock health and productivity. Preservation and transport of animal semen requires extremely low (sub-100°C) temperatures, currently achieved with liquid nitrogen. Production of liquid nitrogen at a large scale is expensive (although it appears more feasible at a small scale). A mechanism to preserve and transport animal semen without the need for a substance as cold as liquid nitrogen, thereby avoiding the capital costs associated with producing liquid nitrogen, can lead to a greater adoption of AI in Africa. This, in turn, can lead to major improvements in livestock health and farmer incomes.

High-nutrient and low cost, sustainable animal fodder.

Currently, most livestock farmers in sub-Saharan Africa practice extensive forms of livestock production, which involves animals grazing over large tracts of land but with limited access to nutrient-dense food. This grazing also contributes to deforestation and desertification. Affordable, nutrient-rich animal fodder made with sustainable and locally available ingredients can make a significant contribution to productivity (i.e., more and better quality of milk and meat), while also reducing environmental damage.

A portable toolkit for agricultural extension workers and livestock veterinarians.

Extension agents can provide valuable training for farmers, helping them optimize yield and improve produce quality. However, most extension agents do not have the tools to perform many of the services farmers need. An ideal extension worker toolkit should help them test soil quality, install and repair irrigation and other on-farm equipment, test the quality of produce (e.g., through chemical probes), and show videos or other instructional material to farmers. A similar toolkit for veterinarians and livestock extension agents, including point-of-care diagnostics for major diseases, a vaccine cooler, and other tools to provide on-farm care for animals can significantly improve the health and productivity of livestock.

Spatial repellent for on-farm pests.

Insects and other pests reduce potential yield by up to 15% for smallholder farmers in Africa. While crop damage is caused by several pests, a small number—borers, mealybugs, mites—cause a disproportionate share of these losses. A low cost spatial repellent that irritates pests (e.g., based on particular sound frequencies) could be an effective and sustainable mechanism to protect crops. It can also reduce the need for chemical pesticides, which can be harmful to health and the environment.

New seed varieties that are tolerant to drought, heat, and other emerging environmental stresses.

Climate change and water shortages are putting heavy stresses on crops and agricultural output. These stresses will continue to increase in the coming years. Just as new seed varieties were critical to the Green Revolution in Asia and Latin America, new varieties of seeds for essential cereals (e.g., maize, rice) that are tolerant to drought, heat, and other emerging environmental stresses will be necessary for agricultural development and food security in the near future.
Low cost (under $50) wearable, or otherwise easily concealable, cameras with automatic geocoding and timestamps, capable of ‘SOS’ data preservation (e.g., via satellite).

The rapid proliferation and falling cost of digital cameras, especially those integrated into mobile phones, has dramatically increased the number of human rights violations that are documented. This unprecedented level of transparency has made perpetrators more likely to face justice, and would-be perpetrators more wary. Cameras that are more inconspicuous and affordable, and capable of recording exact time, date and place where the images and videos are captured, will likely lead to greater levels of documentation of human rights violations. Note that such technologies will cause legitimate privacy concerns.

Low cost aerial vehicles to capture high resolution imagery for use by civil society groups, to document large-scale human rights violations.

Many large-scale human rights violations occur in the open, partly because perpetrators have no fear of accountability. In recent years, satellites are being increasingly used to document large-scale destruction of habitats such as villages, forests. However, continuous coverage of at-risk locations requires satellite data that is currently not accessible to civil society groups; and neither is imagery of high enough resolution to be actionable. Low cost (under $100,000) satellites are now being developed, and may make focused monitoring and documenting of violations more feasible. In addition, very inexpensive drones—increasingly available today—can be a valuable tool for collecting detailed imagery. However, drones are typically deployable over a specific location only after an incidence has taken place, and therefore more likely to be useful in contexts where there are recurring violations.

A simple point-of-use, low cost DNA-based rape kit.

One key hurdle in holding perpetrators of sexual violence accountable is the lack of hard evidence. A simple device that captures biological evidence in the form of DNA, and rapidly analyzes and digitizes the data can be very valuable. Such a technology will be truly useful only when social and legal barriers to prosecution of sexual crimes are removed, making it possible for victims to seek immediate recourse in the first place.

A new generation of network technologies that radically cut the cost of expanding broadband coverage to rural areas.

Even as the penetration of mobile phones, tablets and other computing devices increases, their usefulness depends on the availability of broadband connections. Expanding access to rural areas is challenging—populations are less dense, further from main networks, and have lower purchasing power. Instead of the traditional network infrastructure used for broadband connectivity (i.e., blanket coverage with many adjacent cells each supported by a base station), a new set of network technologies is required. This could include low/medium altitude satellites, other aerial devices, and innovative use of unused portions of the radio frequency spectrum.

A new generation of ‘Internet of Things’ (IoT) devices which enable new services for low income populations.

The Internet of Things (IoT) is a paradigm in which distributed sensors, probes, actuators and other devices are used to collect environmental data and monitor objects and systems (including people)
Affordable homes that are resilient to extreme weather events, for the poor living in areas vulnerable to extreme weather. The increased frequency and intensity of extreme weather events is putting vulnerable communities at greater risk of losing their homes. It is unlikely that improved architecture with existing materials, by itself, will suffice. Improved materials are required for robust, affordable, environmentally and culturally compatible housing, and for designs that can scale-up to meet global demand.

A retrofitted filter to reduce particulate matter exhaust from old heavy-duty vehicles. Outdoor air pollution, primarily due to automobile exhaust from older vehicles, is a significant contributor to respiratory ailments and poor quality of life in urban centers of most developing countries. While the practice of extending the lives of automobiles to span generations is beneficial on the whole, poor maintenance of engines leads to high levels of particulate matter pollution. An inexpensive filtering device that can be retrofitted to the existing fleet of vehicles—especially the heavy-duty vehicles which cause most of the pollution—can significantly reduce particulate emissions from vehicular exhaust.

Low cost, distributed monitoring sensors to identify environmental toxins and their concentrations. Environmental regulations in many countries are either lax, or poorly enforced. As a result, toxins such as heavy metals and persistent organic pollutants (POPs) are increasingly affecting human health, especially among the poor. The absence of reliable data on the presence and the concentrations of various toxins is a major hurdle to addressing this challenge. Robust, reliable and affordable monitoring technologies are required to identify toxins, their concentrations, and the health threats those concentrations pose. Such devices, if connected to Internet-based aggregation systems, can be a powerful component of the Internet of Things (IoT) paradigm to improve the lives of the poor. The monitoring technologies should be able to analyze water, soil, food or other substances using simple preparation techniques, and detect a range of pollutants including inorganic materials (such as mercury,
lead, arsenic), synthetic organic chemicals (such as dioxin, PCBs and specific harmful pesticides), and volatile organic compounds (such as benzene and formaldehyde).

**Suite of solar photovoltaic mini-grid components, to significantly reduce upfront costs.**

Renewable energy mini-grids, particularly those using solar photovoltaics (PV), will be a critical part of the solution for electricity access in rural sub-Saharan Africa. Currently, the cost of electricity generated by solar PV mini-grids is too high for low income rural users. While affordable financing can close some gaps, steep reductions in upfront costs can make universal electrification a reality. This will require cheaper and more efficient PV technology through improvements in design, manufacturing and materials, and streamlining of ‘balance of system’ costs.

**Appliances for household use (e.g., TV, refrigerator) and income generation (e.g., irrigation pump), which are significantly more affordable and energy efficient than those on the market today.**

Electricity itself does not change people’s lives, it is what people do with electricity that does. In recent years, there has been a proliferation of devices such as portable solar powered lights and charging kits for mobile phones. However, to meet basic needs for development, a suite of appliances like TVs, refrigerators and irrigation pumps are required. Even if such appliances were affordable currently, the cost of powering them would far exceed the ‘energy budget’ of low income users. Hence, the energy efficiency of these appliances also needs to increase significantly.

**New bulk storage technologies for decentralized mini-grids, which provide improved performance at a significantly lower cost.**

Bulk storage for backup power and load balancing is crucial for reliable electricity in decentralized mini-grids, especially renewable energy ones, where supply (sun, wind) is intermittent. However, storage technologies that can be applied at mini-grid scale are not commercially available at the desired cost and performance. Lead acid batteries, the only commercially available option, are too expensive (often comprising 50% of total system cost) and have performance issues (low energy density, short life). Alternative and emerging battery technologies—e.g., flow batteries, lithium-ion (Li-ion) and sodium sulphur—are still pre-commercial and need significant cost and performance improvements. Li-ion will benefit from growth in the electric vehicle sector.

**Affordable and easy-to-use grid management solutions for decentralized renewable energy rural mini-grids.**

Currently, mini-grid installations in low income rural areas face several challenges: there can be overuse (or theft) by individual users; collection of user fees can be cumbersome; and it is difficult to pinpoint sources of breakdowns or system failures. Existing solutions for managing mini-grid systems are not affordable, and are too complicated for rural settings where there are few skilled workers with the technical expertise required for installation and maintenance. New, inexpensive and simpler solutions are required for forecasting demand, calibrating generation, ‘smart’ metering, and monitoring consumption and leakage.
Low cost (under $500) transport for families, ideally using renewable energy.

Through our analysis, a small number of potential breakthroughs kept emerging as important in individual sections, but never made it to the top of the list of any of the sections. Affordable transport, in particular, is one that is worthy of mention.

Personal and family transport has been a critical component of improving productivity and quality-of-life for large portions of the global population. Yet, for most of the rural poor, especially women, walking long distances and carrying heavy loads remains a daily reality. A number of promising low cost vehicles (e.g., three-wheeled solar and electric rickshaws) are becoming available in the $500-$1,000 range, although the full system (including power charging) is more expensive. An affordable automobile that runs on renewable energy will be transformative.
Beyond the list of breakthroughs, there are a number of important questions that warrant discussion: Are there any quick wins? Which breakthroughs have the most difficult path to impact? Which of these are commercially attractive for profit-seeking businesses, and which are important public goods without commercial prospects? What are the most appropriate funding mechanisms for these breakthroughs? How can various governments, funders and other institutions shape their agendas to enable the realization of these breakthroughs?

Some of these issues are discussed below, some in the concluding section of the study, and others will need to be part of the ongoing conversation this study hopes to spur. To that end, the following groupings—matrices—of the breakthroughs may be helpful.

**Matrix A** shows the technical complexity of each breakthrough (measured by the time-to-market, on the x axis), against the difficulty of deployment (y axis). Based on this analysis, there are 4 categories.

- The relative quick wins (bottom-left of the matrix), which appear to on the horizon from the technical point-of-view, with relatively achievable deployment models. It is important to note that categorizing a breakthrough as a quick win does not mean that it is guaranteed to happen. It simply suggests that anyone wishing to invest effort or funds into a problem with a likelihood of relatively quick results should consider this set of issues.

- Problems with seemingly imminent technical solutions (top-left of the matrix), but with significant barriers to deployment. The biggest risk facing current projects attempting to address these issues, is that there will be excessive focus on the technical solution without an appreciation of the deployment challenges.

- Problems which have significant technical hurdles (bottom-right of the matrix), but with seemingly surmountable deployment challenges. In such cases, once the technology problems are solved, there is a good chance that they will lead to impact.

- Issues which face major hurdles on both the technological and deployment fronts (top-right of the matrix). These represent the most difficult challenges in the technology-for-development space. For those investing in technologies to address these issues, it is important to be equally demanding of solutions to deployment hurdles.

**Matrix B** analyzes the funding models appropriate to each of the breakthroughs, based on their commercial attractiveness. The x axis shows the projected time to market, as a proxy for the amount of funds required. Along the y axis, it groups them into 4 categories.

- Technologies which have attractive commercial prospects in industrialized markets, as well as in developing country markets (bottom row). In all likelihood, there are ongoing investments to take advantage of these commercial opportunities. For funders seeking to invest in a true ‘double-bottom-line’ this space represents fertile territory.

- Some of the identified technologies will have an attractive market in developing countries (second row from the bottom). However, the profits will not be attractive enough for investors motivated
to maximize commercial returns. These represent very promising investments for funders focused on profitable ventures in emerging markets. Philanthropic grant capital may not be appropriate for these technologies, because such funding often does not require adequate rigor on sustainable deployment models.

- In many cases, technologies and products will (and should) be commercially sustainable in the long run, but the seed R&D capital may not be recouped. These are ideal for early-stage grants to lay the platform. These are identified in the second row (from the top).

- Some technologies (top row) can have significant social impact, but will not (and should not) earn profits. The only mechanism for these technologies to materialize, is through grant funding.
Breakthroughs appear imminent. Innovative business models need to be developed soon. The most difficult challenges: very complex technologies and daunting deployment hurdles.

<table>
<thead>
<tr>
<th>Likely time to market (years)</th>
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</thead>
<tbody>
<tr>
<td>Potential quick wins</td>
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<tr>
<td>Mostly a technology challenge.</td>
</tr>
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</table>

### Matrix A

<table>
<thead>
<tr>
<th>Difficulty of deployment</th>
<th>Feasible</th>
<th>Simple</th>
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<tbody>
<tr>
<td>7. Affordable smartphones</td>
<td>11. Short-course TB treatment</td>
<td>15. Complete cure for malaria</td>
</tr>
<tr>
<td>48. New generation of low-cost, energy efficient appliances</td>
<td>26. Off-grid refrigerator for households and farmers</td>
<td>44. Affordable homes resilient to extreme climate events</td>
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<td>39. Low cost aerial vehicles for imagery</td>
<td>41. Wireless broadband technologies</td>
<td>45. Retrofit filter for vehicle exhaust</td>
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<td>40. DNA-based rape kit</td>
<td>31. Herbicides for weeds</td>
<td>1. Energy efficient desalination</td>
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<td>37. New seed varieties tolerant to drought and heat</td>
<td>20. Automated multiplex immunoassays</td>
<td>33. Alternative to liquid nitrogen for preserving animal semen</td>
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<tr>
<td>12. Microbicides for HIV/HPV</td>
<td>27. Low cost refrigerated vehicle</td>
<td>36. Spatial on-farm pest repellent</td>
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<tr>
<td>38. Wearable cameras</td>
<td>45. Retrofit filter for vehicle exhaust</td>
<td>16. Long-lasting chemical mosquito repellent</td>
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<tr>
<td>25. Nutrient-dense infant weaning foods</td>
<td>42. IoT for low income populations</td>
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<td>47. Low cost PV mini-grid installation</td>
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<td>41. Wireless broadband technologies</td>
<td>46. Distributed sensors for environmental toxins</td>
<td>2-4. Vaccines for HIV, TB, Malaria</td>
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<td>42. IoT for low income populations</td>
<td>49. New bulk storage technologies</td>
<td>50. Mini-grid management solutions</td>
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<tr>
<td>51. Low cost family transport</td>
<td>5. Smart electronic textbooks</td>
<td>6. Biometric ID systems</td>
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<td><strong>Emerging markets potential, with initial grant support</strong></td>
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<td><strong>Attractive for emerging markets</strong></td>
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</table>
GLOBAL HEALTH

CHEMIST

NEW VACCINE FOR PNEUMONIA

Bring all children 1 year and below for the vaccination. £15.00.

[Image of a sign in a rural area with text about a new vaccine for pneumonia]
More than any other aspect of human development, global health has benefited from scientific and technological breakthroughs. Unfortunately, many of these breakthroughs have not reached those most in need, at the scale and in a shape that they require. People living in tropical countries—particularly in South Asia and sub-Saharan Africa—are exposed to a far greater array of health hazards than those living in other regions. By implication, these populations need access to the most powerful solutions. Yet, they have the least access to them.

While overall health outcomes in developing countries have improved over the past three decades, they lag the rest of the world in virtually every single metric. As summarized in Exhibit 1, indicators of the health of populations in developing countries are consistent with other indicators of development (World Bank, 2013) (WHO, 2013). Life expectancy in sub-Saharan Africa, while substantially higher now than it was even as late as the turn of the century (49.8 years), still lags behind the rest of the world. It stands at 54.2 years today, compared with 65.4 in South Asia, 80.1 in high income OECD countries, and a global average of 69.7 years. The maternal mortality ratio in sub-Saharan Africa is 500 (out of every 100,000 women giving birth), compared with 220 in South Asia, 13 in high income OECD countries, and a global average of 210. Mortality of children under 5 in sub-Saharan Africa is 106 (out of every 1,000 children born live), compared to 65 in South Asia, 6 in high income OECD countries, and 52 around the world. In sub-Saharan Africa and South Asia, 22% and 34% of children, respectively, suffer from malnutrition compared with 16% globally, and a negligibly small number in high income OECD countries.

The prevalence of—and mortality from—infectious diseases like TB, HIV/AIDS and Malaria, is also much higher in developing countries. In fact, these diseases already disproportionately affect people living in developing countries, compared with high income countries. According to the NCD Alliance, 80% of the global disease burden from non-communicable diseases today occurs in low and middle income countries. These countries are home to not only 80% of the world’s diabetes patients but also to 80% of all deaths from cardiovascular disease. NCDs are projected to cause an even higher disease burden in low and middle income countries within the next decade.

Even as the causes of mortality vary by population segment and geography, a handful of conditions account for the majority of fatalities. As Exhibit 2 (World Bank, 2013) (WHO, 2013) shows, the leading causes of childhood mortality in sub-Saharan Africa are a host of neonatal conditions, malaria, diarrheal disease, and lower respiratory infections like pneumonia. In South Asia, malaria is not as significant a driver of childhood mortality; in percentage terms, neonatal conditions alone account for nearly as many deaths in South Asia as neonatal conditions and malaria deaths put together in sub-Saharan Africa. For adult women in sub-Saharan Africa, the leading causes of mortality are HIV/AIDS, cardiovascular disease, lower respiratory infections and malaria, but in South Asia, HIV/AIDS and malaria are not as significant.
Health statistics in developing countries compared with global benchmarks

<table>
<thead>
<tr>
<th></th>
<th>sub-Saharan Africa</th>
<th>South Asia</th>
<th>High income OECD countries</th>
<th>World average</th>
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<tr>
<td><strong>Life expectancy</strong></td>
<td>54.2</td>
<td>65.4</td>
<td>80.1</td>
<td>69.7</td>
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<tr>
<td><strong>Maternal mortality</strong></td>
<td>500</td>
<td>220</td>
<td>13</td>
<td>210</td>
</tr>
<tr>
<td><strong>Mortality, children under 5</strong></td>
<td>106</td>
<td>65</td>
<td>6</td>
<td>52</td>
</tr>
<tr>
<td><strong>Malnutrition, children under 5</strong></td>
<td>22%</td>
<td>34%</td>
<td>16%</td>
<td></td>
</tr>
</tbody>
</table>

*Prevalence of malnutrition and malaria in high income OECD countries is negligible.

**Prevalence of major infectious diseases, each year**
(cases out of every 100,000 people in the population)

<table>
<thead>
<tr>
<th></th>
<th>TB</th>
<th>HIV</th>
<th>Malaria**</th>
</tr>
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<tbody>
<tr>
<td>reported cases</td>
<td>329</td>
<td>4,965</td>
<td>26,100</td>
</tr>
<tr>
<td>WHO estimates</td>
<td>309</td>
<td>292</td>
<td>1,100</td>
</tr>
<tr>
<td>WHO estimates</td>
<td>169</td>
<td>385</td>
<td>4,600</td>
</tr>
</tbody>
</table>

**This data shows the number of reported cases; WHO estimates can vary.**

*Exhibit 1: Countries in South Asia and sub-Saharan Africa have significantly worse health outcomes than their more industrialized counterparts, and also fare poorly when compared with global averages.*
Exhibit 2: The leading causes of mortality are different for each population segment (e.g., children vs. women), with some differences between sub-Saharan Africa and South Asia.

In addition to life expectancy and mortality, another valuable metric for understanding the state of health of national populations is morbidity, or the burden of disease on productivity and quality of life, measured in terms of disability-adjusted life-years (DALYs) lost. A look at the leading causes of DALYs lost in South Asia and sub-Saharan Africa reveals that the indicators for children are not significantly different between deaths and DALYs, but the statistics for adult women show some meaningful differences. This is primarily due to non-fatal conditions like mental/behavioral and musculoskeletal disorders, which cause a high disease burden (Exhibit 3).

1 Data on the health of adult men is not explicitly shown, because they are not as vulnerable to events such as pregnancy. Statistics for men are considered, as relevant, in other portions of this section.
Leading causes of DALYs lost in South Asia and sub-Saharan Africa

Exhibit 3: DALYs, which adjust mortality for disability, show that conditions like mental/behavioral and musculoskeletal disorders—while not leading to fatalities—cause a heavy disability burden among women. Among children, DALY statistics are similar to those for mortality.

With these outcomes in mind, it is no surprise that indicators that give a glimpse of the strength of health systems in sub-Saharan Africa and South Asia also lag behind substantially. Exhibit 4 shows some of these indicators in South Asia and sub-Saharan Africa compared with high income OECD countries and global averages.

Annual health expenditure per capita is $95 in sub-Saharan Africa and $53 in South Asia, compared with $5,457 in high income OECD countries, and $952 globally. As a combination of both public and private expenditure, this is a reflection how little public healthcare infrastructure there is in developing countries.
Exhibit 4: Healthcare systems in sub-Saharan Africa and South Asia, measured in terms of expenditure, human capital, and access to care, lag significantly behind high income OECD countries and global averages. The challenges are deep-rooted and structural, and discussed in detail in our chapter on Healthcare Delivery.
RECENT TRENDS IN GLOBAL HEALTH

As we analyze the role of technology in improving healthcare for low-income populations, the following three trends are important to consider.

Advances in technology and care practices are now redefining healthcare delivery systems in low resource settings
Traditionally, healthcare delivery systems have been highly dependent on infrastructure and human resources. The past few years have seen the emergence of a new generation of low cost medical devices which are more durable, less dependent on infrastructure, require less training to operate, and are much less energy intensive. As such, they are more appropriate for low resource settings. Combined with mobile technologies for improved referral systems, these new medical devices are laying the groundwork for health systems to become much more decentralized.

A number of gaps still exist in the understanding of the causes of major diseases
In recent years, important advances have been made in the scientific understanding of diseases, particularly pertaining to questions such as the etiology of diarrheal diseases and pneumonia, the complex drivers of malnutrition, and the long-term health impact of repeated exposure to diarrheal pathogens (beyond simply causing diarrheal disease). Despite these advances, major gaps still exist in the global health community’s understanding of individual diseases, as well as the interaction effects of these diseases in the context of poverty. The knowledge gaps exist at a higher, epidemiological level (e.g., the relative importance of various pathways to infection for diarrheal disease in rural vs. urban areas), as well as at more fundamentally scientific level (e.g., the specific ways in which nutrition affects immunity from TB and other diseases). Notwithstanding the gaps, these new findings already have significant implications on future research and development (e.g., pathogen-specific vaccines for diarrheal diseases), and interventions designed to tackle major diseases, both at country and global levels.

The burden from non-communicable diseases (NCDs) is overtaking that from infectious diseases
In many low and middle income countries, recent economic growth and the strengthening of healthcare systems have led to a reduction in the overall burden of infectious diseases. Higher life expectancy, along with demographic shifts like increasing urbanization, unhealthy diets, and less physical activity, are leading to a surge in the incidence of non-communicable, chronic conditions like obesity, diabetes and cardiovascular disease. In India, for example, cardiovascular disease now is the leading killer of both men and women, followed by respiratory diseases. In most developing countries, healthcare systems were primarily focused on controlling infectious diseases and not NCDs. This shift in disease profile seriously impacts their ability to combat the growing menace of these chronic diseases.
SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS THAT CAN TRANSFORM GLOBAL HEALTH OUTCOMES

Achieving step changes in population-level health outcomes is extremely challenging, but technological breakthroughs will continue to play a major role in bringing about dramatic improvements. The following is a summary of major breakthroughs which can lead to fundamental improvements in the health of low income populations around the world. Please note that this list is a subset of the longer list of breakthroughs identified in the chapters that follow, and only includes the ones we believe to be the most significant.

1. **Vaccines that can effectively control and eventually help eradicate the major infectious diseases of our time—HIV/AIDS, Malaria and TB.**

   These vaccines do not yet exist because of the intrinsic complexity of the pathogens and a lack of complete understanding of the specific mechanisms through which our immune systems can protect against these diseases.

2. **Single dose, or short course, TB treatment drugs that will lead to significant improvements in treatment adherence, and curb the spread of drug resistance.**

   Currently, treating drug-sensitive TB with the typical cocktail of antibiotics takes more than 6 months; as a result, patients often stop treatment prematurely, causing drug resistance.

3. **Microbicides to provide a method of protection against HIV/AIDS for those who are otherwise vulnerable to infection through sexual contact with their partner.**

   Women often struggle to get their male sexual partners to use condoms. Vaginal or rectal microbicides, if effective, can be a viable alternative for controlling the spread of HIV/AIDS and other sexually transmitted diseases.

4. **Improved, longer-lasting antiretroviral therapy (ART) formulations to control HIV viral replication, and increase patient adherence.**

   ART formulations currently on the market require continuous, long-term treatment, the cost of which is difficult for low income populations to bear. Reformulation of current ART drugs for higher effectiveness, simplified treatment regimens (e.g., single fixed-dose pill), and reduced toxicity can help significantly increase access and adherence.

5. **A complete cure drug for Malaria that eliminates all malarial parasites, at every stage of the lifecycle, from the human body.**

   Existing drugs for treating malaria do not completely destroy the parasite from the patient’s body, and lead to an asymptomatic reservoir among patients who have been successfully treated. This in turn contributes to continued transmission of the disease through malarial vectors. A complete cure—which eliminates all malaria parasites in the patient’s body—will be a valuable tool in eradicating malaria.

6. **An easy to operate, affordable, integrated, and solar-powered suite of medical devices specifically for maternal, child and primary care in low resource settings.**

   Currently, building a reasonably equipped clinic costs more than US$100,000. In addition, essential devices are often difficult to install, complicated to use and expensive to maintain. A suite of devices that are
integrated for ease of installation and use (e.g., as a ‘clinic-in-a-box’)”—integrating the 10-15 key medical devices, costing around $10,000—can serve as a building block for expanding health coverage to rural, low income areas. Integration needs to happen with respect to power supply and management, data, imaging, computation and communication.

7 Automated and multiplex diagnostic immunoassays, leading towards an integrated single diagnostic platform.
Affordable point-of-care immunoassays that can use different types of samples (e.g., blood, urine, sputum), and test for multiple biomarkers (and diseases) from a single patient interaction, represent a major breakthrough in diagnosing and treating vulnerable populations. Ideally, such tests will be micro-scale, will integrate and automate complex steps, and require limited power. In the long run, the ultimate diagnostic breakthrough will be a bench-top platform that integrates a variety of individual platforms (e.g., optical readers, chemistry analyzers, nucleic acid tests, etc.).

8 New long-lasting, non-chemical, low cost spatial mosquito repellents (or attractants) that provide community level protection.
Currently, the most common mechanisms to keep mosquitos from biting people are bed-nets and insecticide sprays. These tools are only effective indoors, or when people are sleeping under the nets. Spatial repellents, which irritate the mosquitos (e.g., based on sensory sensitivities), can supplement existing tools; non-chemical repellents which do not require regular replenishment will be even more valuable. While some sound-based devices are on the market, it is not clear they are based on rigorous science.

9 Low cost, portable, solar-powered refrigerators, or other thermo-stabilizing mechanisms, for preserving vaccines and other temperature sensitive life saving pharmaceuticals.
Vaccines and a number of other pharmaceuticals are highly temperature sensitive, making it very difficult to administer them in remote, low resource settings. The current approach to use boxes with freezer packs is highly ineffective. An affordable, portable, solar-powered refrigerator can enable delivery to such settings. In the long run, the likely solution is to obviate the need for refrigeration, e.g., with stabilizing additives which render the pharmaceuticals less sensitive to extreme temperatures.

10 A new generation of homes with advanced construction material especially for the urban poor: durable, light weight, and affordable, with integrated solar-powered lighting, ventilation, and toilets.
The majority of the urban poor live in densely packed shacks made with found material, with very limited light, fresh air, running water, and sanitation. This heavily contributes to a range of diseases such as pneumonia, TB, respiratory conditions, and diarrheal diseases. Improving living conditions through a new kind of home, with the characteristics listed above, can significantly improve quality of life and health. Reinventing the home is critical to improving health outcomes.

11 Nutrient-dense and culturally appropriate foods for infants, to supplement breastfeeding.
Malnutrition, caused by the lack of diverse and nutrient-rich foods during childhood, underlies almost half of all childhood deaths in sub-Saharan Africa and South Asia. Affordable, nutrient-dense, and culturally appropriate foods for infants, as a complement to breastfeeding, can make marked improvements in the crucial early years of life.
More than most other topics covered in this study, new technologies for health depend heavily on a range of required trials and approvals, policy reforms, behavior change on the part of users, and improvement in the level of technical skills of care providers. In this context, first, it is important to remember that without an adequate number of trained healthcare workers and clinicians, as well as fundamental changes in how healthcare is sought and administered, there is a significant risk that many of these technologies will simply not have a market.

Second, conditions like diarrheal disease, pneumonia and TB, can benefit from individual technological breakthroughs. However, the underlying risk factors involved—particularly in densely populated urban settings—can only be alleviated through structural changes in how people, especially those at the lower end of the income spectrum, live. As long as the poor continue to live in squalid conditions, most medical technologies will only serve as a means to provide reactive interventions. For interventions to be proactively preventive, it is important to think beyond individual technologies and move towards a more integrated and long-term solution.

Third, not all health conditions can be battled through a breakthrough technology. This is particularly true of the rapidly escalating threat of non-communicable diseases—obesity, diabetes, and cardiovascular diseases. While technology can play a role in effective treatment, incidence is primarily due to lifestyle and behavioral choices. Managing this burgeoning health challenge relies primarily on raising awareness and behavior change interventions.

In this section, we look at the major health conditions contributing to highest mortality and DALYs globally, their clinical underpinnings, and the key challenges to overcoming them. These conditions, each a dedicated chapter, include:

- HIV/AIDS
- Pulmonary tuberculosis
- Malaria
- Maternal and neonatal health
- Pneumonia and lower respiratory infections
- Diarrheal diseases, often referred to as WASH—water, sanitation and hygiene—diseases
- The major non-communicable diseases—diabetes and cardiovascular disease
- Nutritional deficiencies

In addition, we examine two important systemic issues:

- Diagnostics
- Healthcare delivery

**Note:** In this section, childhood health (and related conditions) typically refer to children under 5.

‘Resource-poor settings’ refers to contexts in which low income populations do not have access to clinics with basic amenities (e.g., reliable electricity, running water, and functioning medical devices), or to adequately trained healthcare providers; this could be in rural or urban settings. ‘Remote settings’ usually refers to rural areas which are difficult to access due to the absence of reliable roads and/or transport. ‘Peripheral clinics’ refers to barely functioning healthcare facilities which serve populations in resource-poor or remote settings. Finally, ‘point-of-care’ describes services which are provided at or near where the patients are, rather than at laboratories or healthcare facilities which are far away from where the patients live and work.
HIV is a retrovirus that causes AIDS, a disease which leads to the progressive deterioration of the immune system. Left untreated, it leads to death. HIV/AIDS represents a serious global pandemic and is the 6th largest cause of mortality in the world. Over 35 million people around the world are living with HIV/AIDS; about 70% of them are in sub-Saharan Africa. Each year, more than 2 million people contract the virus, and over 1.6 million people die due to AIDS-related causes.

HIV is primarily transmitted through unprotected sexual contact, contaminated needles, and from infected mother to child (in utero, at birth or through breastfeeding). There is neither a vaccine to prevent HIV infection, nor a cure for it. Consequently, targeting risk-reducing behaviors is important for preventing HIV infection and controlling the spread of the disease.

Antiretroviral treatments (ARVs) are widely available. While they do not cure the disease, they control disease progression and are able to dramatically reduce transmission. However, enabling early diagnosis and widespread access to ARVs is a significant challenge, especially in the developing world. Treatment is life-long and very costly, and preventing patient dropoff during treatment is difficult.

Given the above challenges, there are 5 technological breakthroughs that can help reduce the burden of HIV in developing countries.

► A safe and efficacious vaccine that offers long-lasting protection for those immunized

► Microbicides to provide a method of protection for those who are otherwise vulnerable to infection by their sexual partner

► PrEP, or pre-exposure use of antiretroviral therapy (ART), to reduce the risk of HIV infection via sexual exposure

► Improved, longer-lasting antiretroviral formulations to control viral replication and increase patient adherence

► Point-of-care diagnostic for viral-load testing, to monitor treatment failure
HIV/AIDS is a serious ongoing global pandemic. In 2011, it was the 6th largest cause of mortality in the world, and the 2nd leading cause of death in low income countries (WHO, 2013). Concerted global efforts to curb transmission and the development and distribution of antiretroviral drugs have substantially reduced mortality, and have gradually converted HIV into a chronic disease. Today, there are an estimated 35.3 million people living with the virus globally (UNAIDS, 2013). While the overall number of new HIV infections has fallen 33% since 2001 (UNAIDS, 2013), the pandemic is far from over.

**CORE FACTS AND ANALYSIS**

Human immunodeficiency virus (HIV) is a retrovirus that causes acquired immune deficiency syndrome (AIDS), a disease characterized by progressive deterioration of the immune system. The diminished immune function of HIV/AIDS patients puts them at greater risk for a variety of infections, which, without treatment, leads to death.

In 2012, 2.3 million people contracted the virus, and 1.6 million people died of AIDS-related causes (UNAIDS, 2013). Young people between the ages of 15-24 years now account for almost half of all new HIV/AIDS infections. In 2012, there were 780,000 new HIV infections among this age group and 260,000 new infections among children under 15 (WHO, 2014). Young women are particularly vulnerable because of social and physiological reasons; the prevalence rate is 8 times higher for young women than for young men (UNAIDS, 2010). Importantly, those living with HIV have a 20-37 times higher risk of developing TB (WHO, 2012).

The HIV/AIDS pandemic poses an enormous economic burden on countries with high incidence and prevalence rates, especially in light of higher prevalence in younger individuals. The resulting disability and death among workers and young parents has devastating effects on household income, and it also decreases productivity and growth at the national level, leading to an estimated 1.5% annual loss in gross domestic product (GDP) in the worst-affected countries (Greener, 2004). The care of children orphaned by the virus further adds to the economic burden of the worst-affected countries. Globally over 16 million children are defined as AIDS orphans (UNAIDS, 2010). Put together, these factors create downward spirals of poverty and social disruption in regions severely affected by HIV/AIDS.
Sub-Saharan Africa is the center of the HIV/AIDS pandemic

Although HIV is prevalent across the world, sub-Saharan Africa is home to 25 million of the 35 million people living with HIV worldwide (UNAIDS, 2013). In sub-Saharan Africa, HIV/AIDS is the second largest cause of disease burden, representing 10% of all DALYs (IHME, 2010). It is also the single most important contributing factor in the overall disease burden among the adult population in Southern and Eastern Africa. In some countries like Swaziland, Botswana and Lesotho, HIV affects over 20% of the population between the ages of 15-49 years (UNAIDS, 2010). Table 1 illustrates the total number of people living with HIV and the number of new HIV infections and deaths in 2012 (UNAIDS, 2013).

<table>
<thead>
<tr>
<th>Region</th>
<th>People living with HIV (% population)</th>
<th>New HIV infections, annually</th>
<th>Deaths due to AIDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>sub-Saharan Africa</td>
<td>25 million (4.7%)</td>
<td>1.6 million</td>
<td>1.2 million</td>
</tr>
<tr>
<td>Middle East &amp; North Africa</td>
<td>260,000 (0.1%)</td>
<td>32,000</td>
<td>17,000</td>
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<tr>
<td>South &amp; Southeast Asia</td>
<td>3.9 million (0.3%)</td>
<td>270,000</td>
<td>220,000</td>
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<td>East Asia</td>
<td>880,000 (&lt;0.1%)</td>
<td>81,000</td>
<td>41,000</td>
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<tr>
<td>Caribbean</td>
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<td>Eastern Europe &amp; Central Asia</td>
<td>1.3 million (0.7%)</td>
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<td>Latin America</td>
<td>1.5 million (0.4%)</td>
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<tr>
<td>Oceania</td>
<td>51,000 (0.2%)</td>
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</tr>
<tr>
<td>Total</td>
<td>35.3 million (0.8%)</td>
<td>2.3 million</td>
<td>1.6 million</td>
</tr>
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</table>

*Table 1:* Global HIV/AIDS mortality figures suggest that AIDS continues to be a huge medical problem.

In terms of prevalence, South and Southeast Asia are second to sub-Saharan Africa with a total of 3.9 million individuals living with HIV/AIDS (UNAIDS, 2013). However, in contrast to sub-Saharan Africa, HIV/AIDS is only the 17th largest cause of disease burden in South Asia, behind lower respiratory infections, preterm birth complications and diarrheal diseases, among others, and represents 1.43% of all DALYs (IHME, 2010).
HIV/AIDS attacks immune cells and is transmitted person-to-person

HIV is a member of the genus Lentivirus within the Retroviridae family. The virus infects immune cells, such as T cells, which bear the surface molecule CD4. HIV can also infect other immune cells, such as macrophages, which may serve as both a reservoir for the virus and a means of viral spread to other body tissues.

After entry into a permissive cell, a viral enzyme called reverse transcriptase converts the RNA genome into double stranded DNA. This DNA becomes integrated into the cellular genome by a second HIV enzyme, integrase. Once integrated, the HIV provirus takes advantage of host cell enzymes to transcribe and translate its genetic material into the viral proteins, which, together with its genetic copies, assemble into new viral particles and bud from the infected cell. The body’s defenses weaken when subsets of immune cells such as T cells are infected and destroyed. Once a patient develops AIDS, they are highly susceptible to a wide variety of opportunistic infections (BVGH, 2012).

HIV/AIDS transmission in some ways parallels the transmission patterns of other sexually transmitted diseases such as syphilis, gonorrhea, and of diseases such as Hepatitis B, which are also transmitted via blood transfusion or intravenous drug use. HIV transmission requires unprotected and close contact with body fluids of other infected individuals, primarily through exposure to blood, semen, vaginal secretions, and breast milk. As a result, the major routes of infection are through sexual contact, contaminated needles, and from infected mother to child in utero, at birth or through breastfeeding.

Interventions have revolved around preventing transmission, and treatment with antiretroviral therapy (ART)

In addressing the HIV/AIDS pandemic, there are two key avenues for intervention: first, the prevention of transmission, and second, diagnosing and treating the virus (WHO, 2013).

In contrast to some other infectious diseases, there is neither a vaccine to prevent HIV infection nor a cure for it. Available antiretroviral drugs (ARVs) require life-long treatment and only control viral replication and disease progression. While antiretroviral drugs do dramatically reduce HIV transmission, enabling early diagnosis and widespread access to ARVs is a significant challenge in the developing world. Consequently, targeting risk-reducing behaviors is important for preventing HIV infection.

Interventions aimed at preventing transmission

Condoms and abstinence
Sexual transmission of HIV can be reduced by consistent and correct use of male and female condoms, limiting the number of sexual partners, or abstaining from sexual activity all together. Consistent use of condoms reduces the risk of contracting or transmitting HIV by about 80% (Weller & Davis-Beaty, 2011). Despite this, in 2013 only 41% of adults with multiple sexual partners report having used a condom during the last time they had sex. Condom use is particularly low among adolescent girls in Africa and among men who have sex with men (WHO, 2014).

Male circumcision
Medical male circumcision (the surgical removal of the penis foreskin), has been recognized since 2007 by the WHO, UNAIDS and other major health organizations as an effective component of the global strategy to end the HIV/AIDS pandemic. Clinical trials have demonstrated that male circumcision can reduce a
man’s risk of acquiring HIV from his female infected sexual partner by at least 60 percent (Wawer, et al., 2008). Modeling studies show that this would also have ‘vaccine-like’ efficacy, in that each man who is protected via circumcision would therefore not be capable of transmitting to a subsequent partner; thus women stand to derive some long-term benefit from circumcision due to lower probability of being exposed to, and infected by, HIV. Voluntary male circumcision has been promoted in 14 priority countries in Africa since 2007, and by the end of 2012 more than 3.2 million men had undergone the procedure. The number of annual circumcisions rose from 900,000 in 2011 to more than 1.7 million in 2012, and uptake has been greatest among younger populations (WHO, 2014).

Treatment as Prevention (TasP)
In 2011, an international study showed that ART can prevent the sexual transmission of HIV among heterosexual couples where one partner is HIV infected and the other is not. UNAIDS described the result as a “serious game changer” for HIV prevention (The Lancet, 2011). The WHO has embraced TasP as a key element of HIV prevention and as a major part of the solution to ending the HIV pandemic.

In 2011, a nine country trial called HPTN 052 panning Africa, Asia, and South America demonstrated that treating an HIV positive person with ART successfully decreases the amount of virus present in their bodies and reduces HIV transmission rates during sexual intercourse by 96% (WHO, 2012). In 2012, the WHO issued guidance recommending that HIV positive partners in serodiscordant couples (where one partner is HIV positive and the other is HIV negative) start ART. After working closely with countries to define TasP guidelines for use, by April 2014, 26 out of 59 surveyed high-burden countries had adopted the provision of ART for serodiscordant couples into their treatment guidelines (WHO, 2014). A recent WHO-led review of global TasP research concluded that there are currently more than 50 ongoing or planned field trials and analyses of TasP, which include a number of large randomized controlled studies (WHO, 2012).

Pre-exposure prophylaxis (PrEP)
In November 2010, the results from a clinical trial showed promise for a new HIV prevention strategy called pre-exposure prophylaxis or PrEP. This involves the use of antiretroviral drugs by HIV negative people who are at a high risk of contracting HIV, to reduce the risk of HIV infection. The trial, iPrEx, demonstrated that daily use of Truvada (a combination ART) reduced the risk of HIV dramatically among men who have sex with men. While PrEP is not recommended for roll-out yet, several oral PrEP effectiveness trials have shown promising results. In 2012–2013, WHO published guidance on oral PrEP for serodiscordant couples, as well as for men and transgender women who have sex with men, recommending that this intervention be rolled out as demonstration projects in a limited number of countries. However, it should be noted though that PrEP has failed in large studies. The VOICE study (reported earlier in 2013) included a Truvada arm that was stopped in the early stages due to futility. This is a continuing limitation to PrEP’s potential as a widespread and effective HIV intervention.

Drug counseling, treatment, and clean needles
Intravenous injection of illicit drugs is a high-risk behavior for HIV/AIDS transmission, as the virus can be passed on through contaminated needles. Prevention of drug use is targeted through counseling and treatment. Programs that have supplied drug users with clean needles have markedly reduced their risk of infection. In addition, post-exposure prophylactic treatment with ART can sometimes prevent infection if administered within 72 hours of potential exposure.

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1 In 2011, the HPTN 052 trial showed that, among HIV serodiscordant couples, ART given to the HIV positive partner with a CD4+ count <550 cells/mm3 decreased HIV transmission by 96% when compared with those who started ART at CD4+ counts <350 cells/mm3.
Interventions aimed at controlling viral replication

Diagnosis of infected patients

Generally, diagnosis of infection occurs in two stages. First, a screening test or first-line test is used for presumptive diagnosis. Such tests are generally immune-based enzyme-linked immunosorbent assays (ELISAs) that measure the presence of antibodies, and may have high sensitivity but low specificity. Patients who receive a positive diagnosis from the first-line screening test then receive a higher specificity confirmatory test that verifies HIV infection. Simplified, instrument-free, immune-based assays are available for rapid HIV screening in settings without access to laboratory facilities. More than 25 commercially available rapid tests for HIV screening have been independently evaluated by the WHO and many have demonstrated acceptable sensitivity, specificity, and suitability for use in resource-poor settings (WHO, 2009). Confirmatory diagnosis can be performed using western blot, line immunoassays, or for high prevalence areas by using a minimum of 2-3 different rapid assays. The choice of confirmatory test depends on HIV prevalence in the population, as well as by the cost and availability of laboratory services.

Treatment of infected patients

The WHO recommended treatment for HIV/AIDS is a combination of ART, and management and treatment of opportunistic infections that may result from HIV-related immune suppression. The ART strategy most widely used is called Highly Active Antiretroviral Therapy (HAART) and consists of combination treatment with two nucleoside reverse transcriptase inhibitors (NRTIs), co-administered with a third drug with a different mechanism of action, such as a non-nucleoside reverse transcriptase inhibitor (NNRTI), a protease inhibitor, or an integrase inhibitor. There are currently 35 HIV products approved by the U.S. Food & Drug Administration (FDA) including individual drugs and fixed dose combinations (FDA, 2013). The new WHO guidelines call for all adults starting ART to take the same daily single fixed-dose combination pill, which represents a simplified and safer treatment regimen than previously recommended therapies.

ART is required for life because the virus integrates and forms a reservoir in human tissues and left uncontrolled will replicate rapidly. Since HIV drugs result in toxicities from long-term use, and treatment is life-long, eligibility guidelines set forth by the WHO use CD4+ cell counts in parallel with clinical staging to determine when ART should be initiated. Decreases in the CD4+ T-lymphocyte-cell population are indicative of progression of HIV to AIDS. Current WHO guidelines, released in June 2013, recommend all individuals with a CD4 count equal to or below 500 cells/mm³ should receive ART. In addition, all serodiscordant couples, pregnant and breastfeeding women with HIV, those with TB and HIV co-infection,

Preventing mother to child transmission of HIV/AIDS (PMTCT)

The risk of mother to child transmission (MTCT) of HIV is directly linked to maternal viral load. ART use has led to the virtual elimination of perinatal HIV cases in the United States, and different regimens are being successfully used to decrease the risk of such transmission worldwide. The 2010 WHO guidelines for PMTCT recommended ART options for pregnant women with CD4+ counts of greater than 350 cells/mm³. The 2013 WHO guidelines recommend starting all HIV infected pregnant and breastfeeding women on life-long ART, regardless of their CD4+ count (WHO, 2013). This could have a significant impact on the prevention of HIV transmission both to newborn children and to sexual partners. Substantial progress in PMTCT has been achieved in countries like Botswana where mother-to-child HIV transmission has come down from 20-40% in 2001 to less than 7% in 2007 (Botswana Ministry of Health, 2013). Such success is an indication that developed world paradigms for HIV control can be successfully implemented in developing countries. Despite the progress, a survey of 81 low and middle income countries showed that in 2012, an average 16% of children of mothers living with HIV acquired the virus (WHO, 2014).

2 Also known as viral burden, viral titre or viral titer, is a measure of the severity of a viral infection, and can be calculated by estimating the amount of virus in an involve body fluid. For example, it can be given in RNA copies per milliliter of blood plasma.
those with hepatitis B virus (HBV) and HIV co-infection with severe chronic liver disease, and all children under 5 with HIV are recommended to receive ART regardless of CD4 count (WHO, 2013).

It is estimated that in low and middle income countries, ART averted an estimated 5.5 million deaths between 1995 and 2012 (WHO, 2014). Without treatment, patients infected with HIV/AIDS have an expected lifespan, or net median survival time, of 11 years (UNAIDS, 2007). However, if treatment begins when patients have undetectable viral load and CD4 counts above 500, they face no increased risk of death. Deferring ART until CD4 count declines puts a patient at greater risk of morbidity and mortality, and the magnitude of CD4 recovery is directly correlated with CD4 count at the start of ART. Many of those who start treatment with CD4 counts less than 350 cells/mm³ never achieve counts greater than 500 cells/mm³ after several years on treatment (AIDSInfo, 2014). In some countries, such as the United States, the policy has shifted to ‘Test and Treat’ so that all individuals diagnosed to be HIV positive are put onto ART. This more inclusive policy, if applied globally, would increase the number of infected individuals from low and middle income countries eligible for treatment to 32 million. Reasons for not widening eligibility worldwide include the additional burden this may put on the already strained health services in resource-poor countries (WHO, 2012), and the social stigma of being identified as being HIV positive in several others. If an HIV positive individual is asymptomatic, beginning a treatment course presents an ethical dilemma. Access to ART is already insufficient, especially in low and middle income countries, even when applying narrower eligibility criteria.

Viral load testing to monitor treatment efficacy

Viral load testing is the most sensitive method to monitor patients for ART failure and determine the need to progress to second-line treatment regimens. The majority of tests today use nucleic acid amplification techniques to detect the presence of viral nucleic acid. Treatment failure occurs when viral load either does not drop or repeatedly rises after having dropped previously, in what is called virologic failure. However, viral load testing is typically not done in developing countries because it is cost-prohibitive and requires sophisticated laboratory equipment and highly trained personnel.

Monitoring patient adherence

Treatment interruption leads to a large and quantifiable increase in viral load and dramatically increases chances of disease progression and transmission (Bangsberg, et al., 2001). Lack of treatment adherence is a leading predictor of HIV/AIDS mortality globally. There are numerous reasons for patients falling out of treatment, which are described in detail further in this chapter, and include social stigma, cost of treatment, and transportation constraints. Additionally, once patients begin treatment and start to feel better, they may become lax about their treatment. The support from friends and family, who have made it possible for a patient to make it to a clinic for starting treatment, may begin to wane. Numerous approaches are being explored to increase patient adherence, including the development of long-lasting treatment formulations, mobile-health solutions such as SMS reminders to patients to take their medicines (Siedner, et al., 2012), and realtime adherence monitoring devices that are linked to a patient’s pill boxes and can transmit information back to a clinic about when patients have opened their medication boxes. These approaches are superior to current adherence monitoring methods that either rely on structured patient interviews and pill counts or tracking pharmacy refill information; these methods operate on an intermittent basis and missed doses go undetected for several weeks or months. Realtime, wireless monitoring mechanisms may offer the opportunity to proactively prevent virologic rebound and treatment failure, and prevent death (Haberer, et al., 2010) (DeSilva, et al., 2013).

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3 Applies to all countries except those where HIV subtype E accounts for the majority of infections. While the median net survival time in these countries is still under review, a few studies show estimates of nine years survival without treatment.
KEY CHALLENGES

While much has been done globally to tackle the HIV/AIDS pandemic, several scientific and social factors limit transmission control and finding a definite cure. Highlighted, below, are some of the major challenges in the fight to reduce HIV/AIDS related mortality.

A highly complex virus, which makes developing vaccines difficult

HIV mutates rapidly, and patients can be infected by numerous different strains of the virus. HIV is broadly classified as HIV-1 or HIV-2. The former is more virulent, causes majority of the infections, and can be divided into several distinct groups; these groups are further divided into subtypes (clades) that display distinct geographic patterns of infection. The acute diversity of HIV strains and the alacrity of the virus’ spread and mutation within the human body are the principle impediments to the development of new biomedical prevention tools. Once inside the body, the virus mutates so fast that the immune system simply cannot keep pace. Indeed, it is the immune system itself that is the target of the virus. After one week of infection, HIV is overwhelmingly found in the T cells of the gut—exactly the cells that have the capacity to defeat it. Because HIV is a retrovirus, it integrates into a person’s DNA. The problem of rapid integration is particularly crucial for a vaccine. Once the virus integrates, it has the ability to ‘hide’ from the immune system. Integration means that any vaccine must be able to act within the short interval between infection and before the integrated form of the virus takes over a substantial number of CD4 T cells.

An effective vaccine would be the single most transformational technology intervention to prevent HIV transmission, yet nearly two decades of R&D has led to scant success. In December 2009, the first hopeful clinical trial results were published; the results of the RV144 vaccine trial in Thailand. In this study more than 16,000 HIV negative volunteers received a series of priming vaccinations with a canarypox-based viral vector vaccine (Sanofi-Pasteur), followed by boosters with a recombinant protein vaccine containing subunits of the HIV surface glycoprotein gp120 (AIDSVAX B/E, VaxGen/GSID). The study showed approximately 31% protection against HIV infection as compared to the placebo control group, and the efficacy of this protective effect declined with time (Rerks-Ngarm, 2009). This study made clear that numerous basic science questions about the virus still remain unanswered.

The correlates of protection are unclear
In general, when developing a vaccine, an important input is an understanding of the natural history of a disease, and the immune response it elicits. In the context of HIV, there are no examples of natural immunity in the human environment. While there are examples of a few individuals who are genetically resistant to infection and those who control the virus at low levels for a long time, there is no population of people that have actually overcome the infection. This is a major obstacle to HIV vaccine development. The 2009 RV144 trial yielded additional questions about the immunological basis of protection in those people who received the vaccine. In 2012, more research on this topic provided some additional but not conclusive data on correlates of protection, indicating that the immune response was antibody-based (Haynes, et al., 2012). Ongoing studies are trying to understand the mechanism of immunity in the protected group using samples collected from patients throughout the RV144 trial.

It is difficult to elicit an antibody response that is durable over time
Progress has been made in developing new antigens and adjuvants capable of inducing longer-lasting antibody responses, yet there is little understanding of how the immune response may be manipulated to increase the durability of this antibody response. In 2012, researchers reported that during the RV144 trial, vaccine efficacy seemed to peak early; cumulative vaccine efficacy was estimated to be 60.5% through the 12 months after initial vaccination, but it declined to 31% after three years, a problem that is linked to waning antibody responses (Robb, et al., 2012). There remains a critical need to reliably elicit
durable antibody responses, and this is an important focus of current research in HIV vaccines (Global HIV Vaccine Enterprise, 2013).

Complex and inter-related drivers of transmission make disease control problematic. The number, complexity, and inter-related nature of the drivers of HIV transmission pose enormous challenges for HIV control, and in particular, for pinpointing and implementing preventative behavioral interventions (Exhibit 1).

Drivers of HIV transmission

Exhibit 1: HIV/AIDS transmission is complex (Boerma & Weire, 2005). The underlying sociocultural, socioeconomic and demographic determinants of HIV/AIDS transmission that drive sexual behaviors, in turn shape the downstream proximate determinants of transmission.

The key biological determinants that underlie HIV transmission include the contact rate (C), which describes the exposure of the susceptible to the infected, the efficacy of transmission per contact (β), and the duration of infectivity (D). Those with HIV infect others in line with the contact rate, but the development of HIV into AIDS can be prevented by early detection and treatment with ART. Each of these biological determinants of infection is in turn impacted by proximate determinants (Table 2).
### Biological and proximate determinants of HIV transmission

<table>
<thead>
<tr>
<th>Biological Driver</th>
<th>Proximate Determinants</th>
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| **Contact rate: Sexual Transmission** | • New sex partner acquisition: the frequency of engagement in sexual activity with a new partner  
• Coital frequency: the frequency of sexual activity  
• Sexual partnership mixing patterns: the extent to which subpopulations with different prevalence of infection engage in sexual partnership mixing with others of different levels of education, involvement in illicit drug use, concurrent sex partners, and incarceration  
• Concurrency: the existence of more than one long-term sexual partner  
• Type of intercourse |
| **Contact rate: Needle Transmission** | • Use of injected drugs  
• Frequency of blood transfusions  
• Frequency of medical injections |
| **Efficacy of transmission per contact (\( \beta \))** | • Prevalence of other sexually transmitted infections: STIs have been shown to increase the susceptibility of an individual to being infected, and also increase the virulence of the infection in an HIV infected person  
• Type of intercourse  
• Viral load of infected individual impacts efficacy of transmission  
• Biological susceptibility: Individuals can have different basic levels of susceptibility to HIV infection |
| **The duration of infectivity** | • Treatment with ART: Duration of infectivity is life-long without antiretroviral therapy |

**Table 2:** Biological determinants of HIV transmission and infection are impacted by several proximate determinants.

The underlying sociocultural, socioeconomic and demographic determinants of HIV/AIDS transmission that drive sexual behaviors shape the downstream proximate determinants of transmission. In recent years, increased understanding about human sexual behaviors and how they are shaped by social, economic, and legal-political structures, has made it indisputable that reducing HIV risk is embedded in structural change in economic opportunities, social norms, gender roles, and legal freedoms (Parkhurst, 2013). HIV prevention efforts are particularly challenging in situations where power is skewed structurally along gender divisions. Particular groups become extremely vulnerable, such as commercial sex workers and women in polygamous marriages. Based on our current understanding of the structural determinants of HIV infection, commonly identified high risk groups include: adolescents (in particular, underprivileged or street children), women (in particular, young women between the age of 15-24 years, and commercial sex workers), men and transgender individuals who have sex with men, truck drivers, displaced populations, and prisoners. Such populations represent the majority of people affected by HIV outside Africa, and a significant share of new infections within Africa (WHO, 2014).
Difficulty of getting people onto treatment

Improving access to ART in low and middle income countries is a key priority. According to the 2010 WHO guidelines, at the end of 2012 there were 16.7 million people living with HIV in low and middle income countries eligible for ART. Of those, only 9.7 million (or 58%) received treatment. This represented a significant increase over the 5.2 million patients in 2009 and 6.6 million patients in 2010 receiving treatment. However, if all of the recommendations in the WHO 2013 guidelines are fully implemented in all countries, the number of people eligible for ART in low and middle income countries increases from 16.7 million to 28.6 million, representing 86% of all people living with HIV in those countries. The 9.7 million patients on treatment, therefore, now represent only 34% of eligible individuals living with HIV (WHO, 2014) (Exhibit 2 and 3).

Exhibit 2: Based on the WHO 2010 guidelines, 58% of the roughly 16.7 million persons eligible for treatment in low and middle income countries received ART in 2012. With the new 2013 guidelines, however, the increase of eligible persons to 28.6 million persons reduces the ART coverage to below 40% (WHO, 2014).

Exhibit 3: If all of the recommendations in the WHO 2013 guidelines are fully implemented in all countries, the number of people eligible for ART in low and middle income countries increases from 16.7 million to 28.6 million, representing 86% of all people living with HIV in those countries.
The HIV/AIDS treatment cascade (Exhibit 4), is a way of showing the number of individuals living with HIV/AIDS who are actually receiving the full benefits of the medical care and treatment they need. Even in the United States only 1 in 4 HIV infected individuals are receiving the full care they need (Gardner, et al., 2011). While little comprehensive data is available about the treatment cascade in sub-Saharan Africa and other developing countries, it is generally agreed there is a high level of dropoff that occurs between diagnosis to initiation of ART. One meta analysis suggests a median completion rate of 17% for those who get from diagnosis to initiation of ART (Rosen & Fox, 2011).

**United States treatment cascade**

![United States treatment cascade (in millions)](image)

**Exhibit 4:** Even in the United States, only 1 in 4 HIV infected individuals is receiving the care they need (Gardner, et al., 2011).

There are a number of reasons for the rapid drop-off in the treatment cascade, as described below.

**Difficulty of identifying infected individuals**

Early identification of HIV infection is critical to treatment outcomes. However, HIV cannot be diagnosed through clinical symptoms. Two to four weeks after infection, patients may display flu-like symptoms accompanied by a rash and fever. Many patients are initially asymptomatic. This makes diagnosis difficult. Although the incubation period between infection and onset of AIDS is often cited as 7-10 years, disease course can be accelerated in low and middle income countries due to environmental factors, co-morbidities, and poor nutrition (BVGH, 2012). Social stigma also prevents many individuals from even getting tested for HIV.
Moving from diagnosis to care and patient retention, particularly if ART is not immediately required. Monitoring CD4+ counts generally requires expensive flow cytometry equipment and a highly trained laboratory workforce. Although simplified bench-top devices are available (e.g., FACSCount, BD; Guava EasyCD4; Partec Cyflow; PointCare), most of these machines are expensive to purchase, repair and maintain, and require regular electricity to operate, largely limiting their utility to centralized laboratory facilities in the developing world (WHO, 2007). As a result, CD4+ testing means patients seeking care in one clinic may need to be referred to a separate location to provide a blood sample for diagnosis, and a follow-up visit is typically required to receive results. Even after diagnosis and being linked to care, regular monitoring to determine ART eligibility may not be perceived as medically beneficial by patients. This is especially true for those patients who do not feel sick, particularly when weighed against the out-of-pocket costs of missing work, transportation costs to access the nearest testing facility, and the stigma of being identified as HIV positive within the community despite no outward symptoms. Some progress has been made recently towards simplifying diagnostic devices for monitoring CD4+ counts, including approved and licensed devices that are inexpensive and do not require reliable power or technical prowess to operate.

Availability of ART
While in the last few years the overall availability of ART has improved significantly, the demand-supply gap coupled with the new WHO eligibility guidelines means that today only 34% of those who need and are eligible to start ART are receiving ART. Availability of ART drugs varies from country to country depending on the drug (composition, manufacturer, government approval etc.), as well as health system resources. Apart from the upfront cost of making ARTs available and accessible for everyone in need, additional resources like adequate number of physicians within the healthcare system is essential since treatment must be administered by doctors. As described above, the recently updated WHO guidelines, which increased the numbers of patients eligible for treatment, have placed an additional strain on limited ART resources.

Patient adherence to treatment regimen
Side effects, constant necessity to be on medication (treatment is required for life) and costs involved, both medical and incidental costs to access medical care, can impact an individual’s inclination and ability to stay on treatment. Monitoring for treatment failure is extremely difficult in the developing world; currently prevalent diagnostics require expensive infrastructure and resources, making their widespread implementation in low resource settings very difficult. Additionally, there are no low cost tracking mechanisms that allow healthcare personnel to easily track those on ART to ensure they stay compliant.

Pediatric challenges
The challenges outlined above are intensified for pediatric patients. Of all individuals living with HIV, children are the most vulnerable; without ART, mortality approaches 50% at 2 years and 80% by 5 years. Of the estimated 2.1 million children in need of ART today, only 34% are receiving it (UNAIDS, 2013). Bottlenecks limiting pediatric treatment include poor access to diagnosis (early infant diagnosis is largely limited to urban areas), weak systems for patient retention, few healthcare facilities and providers equipped to deliver pediatric ART, and drug regimens that are more complex to administer than adult regimens (WHO, 2012). For young children on liquid ART formulations, dosage is important. Pediatric formulations are based on weight, and the risk of measuring and administering an inadequate dose is more likely than for adults. Increasingly, however, pediatric formulations are available in tablet form (FDA, 2012) (IFPMA, 2012). Nevertheless, pediatric patients are dependent on their caregivers to support adherence to treatment and for that it is essential that the caregiver is consistent and dependable.

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4 As per 2010 WHO guidelines. However, the eligibility criteria for children remains unchanged in the new guidelines.
SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

There is neither a vaccine to prevent HIV infection, nor a cure for it. As things stand, the only effective methods of combating the HIV/AIDS pandemic have been the prevention of transmission, and diagnosing and treating those infected. Drawing strength from a massive global effort, these interventions, despite the complexities involved, have shown results; since 2001, the total number of new infections has fallen substantially. Sustaining and accelerating this decline is now crucial in the fight against the virus.

A safe and efficacious HIV/AIDS vaccine that offers long-lasting protection for those immunized

The process of vaccine development—basic research on disease etiology, vaccine construction, pre-clinical and clinical testing—is technically challenging, expensive and time consuming (Francis, 2010). The extreme diversity of HIV strains, the rapid mutation of the virus inside the body, and the fact that HIV is a retrovirus which integrates into an infected individual’s DNA makes vaccine development for HIV particularly challenging. A vaccine must therefore act quickly in the short interval between infection and establishment of the integrated form in a substantial number of CD4 T cells. After nearly two decades of HIV vaccine R&D, little success has been achieved. Given the current lack of a promising candidate and the historical lack of success, it is clear that much research is needed before a vaccine offering long-lasting protection is a realistic aim. In particular, there is a need to better understand the correlates of protection and how to elicit a durable antibody response over time, as discussed further below.

Current vaccine research is largely focused on a preventative or therapeutic vaccine that elicits a ‘broadly neutralizing antibody’ (bNAB) response. After a few years of infection, a small number of HIV positive individuals are able to produce antibodies that can neutralize a broad spectrum of HIV variants. While this antibody response simply ends up playing ‘catch up’ with a virus that mutates ahead of it, it is believed that if such bNABs are induced before exposure to HIV, their presence could prevent infection. Another potential approach is gene therapy or gene transfer that involves identifying high-risk individuals and turning their cells into protein factories that can create and circulate antibodies that offer long-lasting protection. Since 2009, 19 new bNABs have been isolated and characterized. However, this is an area of very early research and a viable vaccine candidate is several years away. The ultimate vaccine is likely to rely on a multi-component, “prime boost” strategy, and will have to elicit multiple bNABs, increasing the technical difficulty of the development process. The vaccine will also need to overcome the problem of antibody durability to provide long-lasting protection so that individuals do not require frequent re-immunization.

If an HIV vaccine is developed, it can be deployed to children through existing—reasonably established—vaccine delivery channels. However, except for the new HPV vaccines, there are very few mechanisms for delivering a vaccine to adolescents and adults. HIV vaccine regimens are likely to be multi-component “prime-boost” regimens; this increases implementation complexity since there is more than one active agent, and stockpiles, distribution networks and patient tracking are more demanding. Further, vaccine delivery still remains a challenge in many remote locations (e.g., due to the absence of a robust cold chain). While the vaccine is expected to be made available to individuals at a low cost, this cost subsidy will have to be supported by national governments and international donors. Policy changes to support introduction and widespread distribution through public health systems will also have to be introduced at both country level and internationally. Based on the above assessment, the projected time to market readiness is 15-20 years, and the level of difficulty is COMPLEX.

5 In December 2009, the first hopeful clinical trial results were published; the RV144 vaccine trial results showed approximately 31% protection against HIV infection as compared to the placebo control group, and the efficacy of this protective effect declined with time (Rerks-Ngarm, 2009).
6 A large effort at research centers including International AIDS Vaccine Initiative (IAVI)’s Neutralizing Antibody Consortium (NAC), NIH’s Vaccine Research Center (VRC) and Duke University’s Center for HIV/AIDS Vaccine Immunology (CHAVI) have invested in this area. Since 2009, IAVI, the NAC, Theraclone and Monogram have collaborated to isolate and characterize 19 new broadly neutralizing antibodies from the Protocol G blood specimens.
**Breakthrough 1 – Difficulty of deployment**

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<thead>
<tr>
<th>Difficulty</th>
<th>Policies</th>
<th>Infrastructure</th>
<th>Human capital</th>
<th>Access to user finance</th>
<th>Behavior change</th>
<th>Existing demand</th>
<th>Market fragmentation/Distribution channels</th>
<th>Business model innovation</th>
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<tbody>
<tr>
<td>Extremely Challenging</td>
<td>Low-moderate need for human capital development</td>
<td>Requires some improvements to existing infrastructure</td>
<td>Financing not required</td>
<td>Minimal behavior change required</td>
<td>Moderate demand</td>
<td>Clear deployment models existing at scale</td>
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<td>Challenging</td>
<td>Regulated market with supportive policies</td>
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**Microbicides to provide a method of protection for those who are otherwise vulnerable to infection by their partner**

Women, especially those living in societies and situations plagued by gender and income inequality, are often limited in their ability to ensure that their sexual partners use condoms. This risk is exacerbated in places with high rates of sexual violence, and a high prevalence of polygamy. Specific high-risk populations, like sex workers and transgender people, also find themselves restricted in their ability to use protection during sexual contact.

Microbicides are currently under development as vaginal or rectal products designed to protect healthy men and women from HIV/AIDS infection. These products are being tested in multiple forms—vaginal and rectal gels that can be used at the time of sexual contact, and vaginal film, tablets or rings that can slowly release the microbicide drug to provide preventative coverage for up to a month. Unlike vaccines, an effective microbicide must be made into a commodity that individuals will want to and can safely use, on a regular basis. Ideally, microbicides would be discreet (socially acceptable), easy to use, long-lasting, and easy to distribute.

There are several different microbicide candidates currently being studied. In May 2013, 11 phase I trials, 1 phase I/II trial, and 4 phase III trials were underway (AVAC, 2013). Even if a phase III microbicide candidate is found to successfully prevent HIV infection, it will take a few years before it becomes available for use. Any successful product will have to first undergo review and licensing by regulatory agencies. It will also take time to work out the best formulation and dosage, find a suitable delivery method, and identify appropriate distribution channels before the product can be made available to the public.

Difficulty of deploying microbicides, once available, will depend on human factors, including how easy and convenient they are to use (microbicides require regular reapplication), and whether they are...
PrEP, or pre-exposure use of antiretroviral therapy (ART) to reduce the risk of HIV infection via sexual exposure

PrEP involves the use of ART by those at a high risk for HIV infection, to reduce the possibility of contracting the disease. Testing of Truvada (a combination ART) has demonstrated that daily use can reduce the risk of HIV infection by up to 92% among men who have sex with men, up to 90% among men and women in HIV discordant couples, and up to 74% among injection drug users. Based on such data, the US FDA announced its approval of Truvada for PrEP in May 2014. This is the first ARV drug to be approved for HIV prevention in HIV negative adults. In addition to Truvada, a range of oral and long-acting injectable drugs are now in development. Next-generation strategies will use longer-acting drugs, focusing on delivery methods that are not widely used for HIV treatment. These include TMC278LA formulated as a long-acting injectable, a vaginal ring containing dapivirine, and a vaginal ring combining dapivirine and maraviroc (AVAC, 2013). Despite these early, encouraging signs, much needs to be learned about the safety, effectiveness, and long-term implication of PrEP, and on how to enable large-scale adoption and use of PrEP, particularly among high risk populations. If the early results hold, the projected time to market readiness in developing countries is short—2-3 years.

However, most countries facing the full impact of an HIV/AIDS epidemic do not have the infrastructure or economic resources to implement a PrEP strategy. In wake of the new WHO guidelines that make millions more eligible for ART globally, and the fact that ART is not already available for everyone who needs it,
suggesting that decision makers in developing countries divert attention from HIV positive people to those who are at a high risk of infection, is not only problematic but an extremely sensitive subject as well. Based on the above assessment, the level of difficulty for deployment is EXTREMELY CHALLENGING.

**Breakthrough 3 – Difficulty of deployment**

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<thead>
<tr>
<th></th>
<th>Extremely Challenging</th>
<th>Challenging</th>
<th>Complex</th>
<th>Feasible</th>
<th>Simple</th>
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<td>Policies</td>
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<td>Infrastructure</td>
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<td>Market fragmentation/Distribution channels</td>
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<td>Business model innovation</td>
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<td>Highly regulated and controversial changes required</td>
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<td>Moderate need to train a limited number of people</td>
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<td>Limited financing required</td>
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<td>Major behavior change required, potentially on daily basis</td>
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<td>Low demand, needs to be built</td>
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<td>Clear deployment models existing at scale</td>
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<td>Fragmented market, weak distribution channels</td>
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</table>

**Improved, longer-lasting antiretroviral formulations to control viral replication and increase patient adherence**

While globally access to ART is improving, children and those living in rural areas with poor infrastructure are still particularly disadvantaged due to the demands of the treatment and associated costs and constraints. Reformulation of current ART drugs can improve ease of use, and in turn, access, especially for neglected populations. Improved and more effective drugs with simplified treatment regimens (e.g. single fixed-dose pill or easy to administer pediatric formulations) and reduced toxicity can help prevent treatment interruption and increase patient adherence. Long-acting ARTs can go a step further by helping reduce overall treatment costs.

These improved treatments should ideally be low cost, remain stable in high heat and humidity, require few supportive technologies to deliver the treatment, and offer improved safety profiles to allow use with minimal medical supervision. There are currently a handful of long-lasting injectable ARV drugs in development (e.g., S/GSK1265744 by Shionogi and GSK, which is in Phase II trials). Some of these new formulations are also being tested to see if they have a preventative effect in HIV negative individuals.

Cost is the main barrier to widespread availability of new formulations and treatment. A 2010 study that modeled long-term funding needs for HIV/AIDS control in developing countries estimated that in the absence of an HIV/AIDS vaccine, global HIV control programs would cost between $400 billion and $700 billion during 2009 to 2031, and approximately $22 billion to $24 billion annually by 2015.
depending on policy choices adopted by governments and donors (Hecht, et al., 2010). Today, in excess of $15 billion is spent on treating HIV positive people in the developing world, and drug prices are believed to be near bottom. The required investment to make improved therapies widely available is likely to be enormous.

Based on the above assessment, the projected time to market readiness is 7-10 years, and the difficulty of deployment is FEASIBLE.

**Breakthrough 4 – Difficulty of deployment**

<table>
<thead>
<tr>
<th>Extremely Challenging</th>
<th>Challenging</th>
<th>Complex</th>
<th>Feasible</th>
<th>Simple</th>
</tr>
</thead>
<tbody>
<tr>
<td>Policies</td>
<td>Infrastructure</td>
<td>Human capital</td>
<td>Access to user finance</td>
<td>Behavior change</td>
</tr>
<tr>
<td>Regulated market with supportive policies</td>
<td>Low-moderate need for human capital development</td>
<td>Minimal behavior change required</td>
<td>Strong existing demand</td>
<td>Fairly concentrated market and/or well defined channels</td>
</tr>
<tr>
<td>Dependent on existing infrastructure</td>
<td>Limited financing required</td>
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**Point-of-care diagnostic for viral-load testing to monitor treatment failure**

There is a need for simple, handheld devices that can monitor patients for treatment failure by giving a rapid and accurate viral load count. As noted earlier, virologic failure is detected using tests based on nucleic acid amplification techniques. However, viral load testing is typically not done in developing countries because these tests are cost-prohibitive and not available at point-of-care. An important breakthrough for HIV control will be an affordable point-of-care nucleic acid based test (NAT) for viral load testing. This will help in rapid diagnosis and reduce the chances of patient loss due to followup, and also simplify the process of monitoring patients for treatment failure.

Developing NAT for use at the point-of-care has proven extremely difficult. NAT typically involves three highly complex steps: sample preparation (consisting of sample collection and processing), signal amplification, and detection. Sample preparation is intrinsically time consuming and complex, and samples are subject to degradation and cross-contamination. Signal amplification is dependent on reliable power, expensive equipment high quality (reagent-grade) water, and refrigeration. Detection, most commonly based on fluorescence, requires complex optical instrumentation, stable power, and trained technicians.

A point-of-care NAT will have to integrate the steps above into a portable, user-friendly and affordable tool appropriate for use by minimally trained technicians. The test will have to be designed to operate in areas which lack access to stable electricity, running water, and ancillary laboratory equipment. It should
also be low cost and robust, so that frequent servicing is not required. NATs have been discussed in further detail in the chapter on Diagnostics.

Based on the above assessment, the projected time to market readiness is 4-6 years, and the level of difficulty for deployment is CHALLENGING.

Breakthrough 5 – Difficulty of deployment

- **Extremely Challenging**
  - Requires high level of training for large numbers of people
  - Limited financing required
  - Low demand, needs to be built
  - Clear deployment models existing at scale

- **Challenging**
  - Highly regulated market with policy changes required
  - Requires high level of training for large numbers of people
  - Moderate behavior change required with evidence of behavior change being viable
  - Limited financing required

- **Complex**
  - Limited financing required
  - Clear deployment models existing at scale

- **Feasible**
  - Clear deployment models existing at scale

- **Simple**
  - Clear deployment models existing at scale
Pulmonary Tuberculosis, also commonly referred to as TB, is an airborne bacterial infection of the lungs. It is one of the most pervasive infectious diseases in the world, with 8.6 million new cases and 1.3 million deaths annually. It is estimated that as much as one third of the global population has latent TB, which occurs when someone is exposed to TB but the immune system keeps the bacteria sequestered in the body.

Most TB cases can be treated with first line antibiotics, however, a full course of treatment lasts 6 months, which makes compliance with treatment challenging. Failure to complete full treatment has resulted in the emergence of TB that is resistant to first line drugs (referred to as multidrug-resistant TB or MDR-TB), which requires dramatically more expensive second line drugs taken over the course of 18-24 months. MDR-TB is becoming increasingly common and it is believed most cases of MDR-TB are now acquired directly, as opposed to being a result of failed treatment.

Diagnosis of TB poses an additional problem, both for drug-sensitive TB and for MDR-TB. Current diagnostic methods have low specificity and sensitivity and are unable to discriminate between drug-sensitive and MDR-TB. The lack of a precise diagnostic for MDR-TB is a critical challenge in stemming the disease's growth. In light of the above challenges, 4 technological breakthroughs can help reduce the burden of TB in developing countries.

- A vaccine for pulmonary TB
- A novel, more accurate TB diagnostic with the ability to identify drug resistance
- Shorter course TB treatments for both drug-sensitive TB and MDR-TB
- Biometric devices for tracking patients and compliance
Tuberculosis (TB) is a bacterial infection caused by Mycobacterium Tuberculosis (MTB). In its most prevalent form, it infects the lungs and is called Pulmonary Tuberculosis, also simply referred to as TB. It is one of the most pervasive infectious diseases in the world (Table 1), with 8.6 million new cases every year, and 1.3 million deaths annually (WHO, 2013).

**CORE FACTS AND ANALYSIS**

TB is a highly contagious airborne disease, and most commonly transmitted through coughing and sneezing (WHO, 2013). Along with those suffering from active TB infections, it is estimated that 2.3 billion people have latent TB, which is when the infecting MTB bacteria are sequestered by the body’s immune system and remain alive but are neither an active infection nor contagious. About 5-20% of individuals with latent TB will develop active TB in their lifetime, with the majority developing active TB within the first 2-5 years after infection (WHO, 2013).

**TB cases in 2013**

<table>
<thead>
<tr>
<th>Type of TB</th>
<th>Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latent TB</td>
<td>2,300 million total cases</td>
</tr>
<tr>
<td>Drug-sensitive TB</td>
<td>8.15 million new cases</td>
</tr>
<tr>
<td>Multidrug-resistant TB (MDR-TB)</td>
<td>450,000 new cases</td>
</tr>
<tr>
<td>Extensively drug-resistant TB (XDR-TB, a subset of MDR-TB)</td>
<td>43,000 new cases</td>
</tr>
</tbody>
</table>

*Table 1: TB cases are often classified based on drug resistance or susceptibility. The WHO estimates that 8.15 million people have drug-sensitive TB, which can be treated with a combination of first line drugs; 450,000 have multidrug-resistant TB, and 9.6% of these cases are considered to be extensively drug-resistant-TB (XDR-TB) (WHO, 2013).*

People with healthy immune systems when exposed to TB often only develop latent TB. However, individuals with compromised immune systems (e.g., due to malnutrition, HIV, aging, or other infections) are more likely to develop active TB upon initial exposure itself. They are also more likely to develop active TB from latent TB infections. For instance, people infected with latent TB who are also HIV positive are 21-34 times more likely to develop active TB compared with those without HIV infection (WHO, 2013).

In sub-Saharan Africa, HIV co-infection—found in 13% of new TB cases and 29% of TB-related deaths—is a major complication (WHO, 2013). Of all HIV-TB cases, 75% are found in the African region.
Healthcare systems, especially for diagnosing and treating TB, are weaker in sub-Saharan Africa than in South Asia. As a result, mortality rates, even for those without HIV co-infection, are higher in sub-Saharan Africa than in South Asia and Southeast Asia (WHO, 2013) (Table 2).

Malnutrition is a driver in both regions. Poor nutrition leads to weakened immune systems, which increases the likelihood that someone with latent TB or someone who is infected for the first time will develop active TB (Cegielski & McMurray, 2004). Many people, however, develop active TB even in the absence of these risk factors.

### Regional prevalence of TB and HIV-TB co-infection

<table>
<thead>
<tr>
<th></th>
<th>sub-Saharan Africa</th>
<th>South/Southeast Asia¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total cases</td>
<td>2.7 million</td>
<td>4.8 million</td>
</tr>
<tr>
<td>New cases per year</td>
<td>2.3 million</td>
<td>3.4 million</td>
</tr>
<tr>
<td>Mortality (excluding TB-HIV co-infection)²</td>
<td>230,000</td>
<td>450,000</td>
</tr>
<tr>
<td>HIV prevalence in new cases</td>
<td>36%</td>
<td>5%</td>
</tr>
<tr>
<td>% of new TB cases with MDR-TB</td>
<td>2.3%</td>
<td>2.2%</td>
</tr>
<tr>
<td>% of TB re-infection cases with MDR-TB</td>
<td>11%</td>
<td>16%</td>
</tr>
</tbody>
</table>

Table 2: The underlying factors driving the spread of TB and the effectiveness of treatment are different in South/Southeast Asia and sub-Saharan Africa (WHO, 2013).

¹ Southeast Asia is the region used in the Global TB Report which includes South Asia.
² Deaths among HIV-TB co-infected patients are classified by the WHO as HIV-related deaths.
KEY CHALLENGES

Although the epidemiology of TB is not fully understood, it is generally accepted that the spread of TB is facilitated by crowded, unhygienic conditions, both in homes and specific locations like public transport and hospitals. A critical role is also played by ‘pump’ populations such as miners, prisoners and migrants (WHO, 2008) (Stuckler, et al., 2010). The most significant hurdles in the path to TB control are outlined below.

1. There is no effective vaccine

The only available TB vaccine, Bacille Calmette Guerin (BCG), has so far proved effective only for preventing TB meningitis in children and severe Miliary TB, a form of the disease which tends to spread throughout the human body and cause small lesions. The vaccine has little to no efficacy in either preventing pulmonary TB infections or preventing the conversion of TB from latent to active infections in adolescents or adults. There is currently no TB vaccine specifically for adults.

2. Drug resistance is exploding into a massive crisis

Standard treatment of active TB consists of combination treatment with 4 drugs (isoniazid, rifampicin, pyrazinamide, and ethambutol), daily for 2 months followed by 2 drugs (isoniazid and rifampicin) for 4 months. All 4 drugs are generally available and relatively inexpensive. In many countries, complete treatment incurs a direct patient cost of $0-$20, with a provider cost of $100-$500. Costs, however, vary widely based on country and its healthcare system. Failing to complete this treatment regimen can lead to drug resistance in patients.

WHO-mandated DOTS protocol (directly observed treatment, short-course) has a patient monitoring component that ensures that patients complete the full treatment regimen. However, at least 34% of TB patients are either not diagnosed or do not undergo the complete DOTS treatment (WHO, 2013), which can cause resistance to first line drugs, leading to multidrug-resistant TB (MDR-TB). From a negligible number in 2000, MDR-TB cases rose sharply to an estimated 450,000 total cases in 2012. About 3.6% of new cases and 20% of retreatment TB cases are now estimated to be MDR-TB (WHO, 2013). Some experts believe—although there is no supporting data—that this increase in incidence reflects an improved ability of health systems to diagnose MDR-TB, which has been widespread, and perhaps the growth has not been as explosive as it seems.

MDR-TB is significantly harder to treat. It requires an array of second line drugs, at a total cost of $2,600-$4,700 to the provider, over a period of 18-24 months. Resistance to certain second line drugs is called extensively drug-resistant TB (XDR-TB), and has also sharply increased in recent years, with 92 countries reporting cases of XDR-TB in 2012 (WHO, 2013). Combining these reported incidents of XDR-TB, the WHO has estimated that the proportion of MDR-TB cases that are extensively drug resistant is 10% (WHO, 2013). Worryingly, MDR-TB appears to have transitioned from being primarily a developed condition in patients, stemming from not completing a full course of treatment, to a community-acquired disease where individuals are catching MDR-TB directly (Exhibit 1). It is believed that most cases of MDR-TB are now acquired, rather than developed due to lapses in treatment.
Known cases of drug-resistant TB have grown sharply over the past 10 years. Known cases are confirmed and are distinct from total estimated cases which are 10 to 15 times higher (WHO, 2012).

**Exhibit 1:** Known cases of drug-resistant TB have grown sharply over the past 10 years. Known cases are confirmed and are distinct from total estimated cases which are 10 to 15 times higher (WHO, 2012).

Current diagnostics are insufficient for both drug-sensitive and drug-resistant TB

Despite a variety of methods available for diagnosing TB, actual diagnosis remains suboptimal. There are no tests capable of yielding rapid, accurate, and affordable diagnosis at the point-of-care for active TB or latent TB and there is only one (expensive) diagnostic test that can identify drug resistance. Diagnostic challenges are further intensified in cases of HIV co-infection where existing diagnostic technologies are rendered largely ineffective. While progress has been made in developing and introducing new diagnostic tools, many new technologies are not only expensive but require elaborate and expensive biosafety infrastructure. This limits their use to district facilities and national reference laboratories, adding to delays in diagnosis and treatment. The lack of effective TB diagnostic tools poses significant risks to successful TB control. Challenges with specific types of tests are highlighted below.

**Sputum-Smear Microscopy (SSM)**

The WHO DOTS protocol for TB diagnosis calls for the use of SSM where specially stained sputum is examined through a microscope for the presence of acid-fast bacilli (AFB). The protocol emphasized the detection and treatment of sputum-smear positive cases of pulmonary TB (the most infectious cases). However, it is now widely recognized that this approach alone is insufficient for diagnosis because:

- SSM requires extensive training for those administering the test, and delivers low-throughput results.
- SSM is not highly sensitive; roughly 70% sensitive in TB patients and less than 50% sensitive in patients with HIV co-infection.
- SSM does not identify people who have smear negative forms of TB; smear-negative pulmonary TB is especially common among people who are HIV-positive.
Major challenges exist in the effective treatment of TB depending on whether an individual has drug-sensitive TB, MDR-TB or TB-HIV co-infection.

Bacterial Culture
To diagnose smear-negative and MDR-TB cases, sputum specimens can be cultured (grown) in laboratories, after which it is possible to diagnose or rule-out TB. While this is the most accurate TB diagnostic method, culture grown on solid media takes 3-4 weeks to yield a result. More recently the use of liquid culture and molecular technologies have been recommended to reduce diagnostic delays (Stop TB Partnership, 2013).

Rapid Serological Tests
In the developing world, there are numerous ‘rapid TB tests’ available on the market. In July 2011, however, the WHO recommended against the use of these rapid serological tests for active TB, calling them “inconsistent and imprecise” and potentially leading to “misdiagnosis, mistreatment, and potential harm to public health.” (WHO, 2011).

Nucleic Acid Amplification
The state-of-the-art method for TB diagnosis, newly recommended by the WHO, is highly precise and based on nucleic acid amplification technology (NAT), which identifies the presence of the bacterium at the DNA level. The leading product in this space, GeneXpert®, is capable of identifying rifampicin-resistant infections without bacterial culture, allowing it to accurately discriminate between drug-sensitive TB and MDR-TB. The technology is expensive. Each single-test disposable cartridge costs about $7-$8 and the back-end reader costs approximately $17,000. These prices, however, are changing rapidly. A number of less expensive NATs are on the horizon (UNITAID, 2012), and are expected to be market ready in 2-4 years.

Simple rapid diagnostic tools that can replace SSM at the lower levels of healthcare systems are urgently needed. These diagnostics should be effective in peripheral level health systems in diagnosing active pulmonary TB including sputum-smear negative TB, and detecting drug resistance (Stop TB Partnership, 2013).

SSM cannot be used to discriminate between drug-sensitive and drug-resistant forms of TB.

SSM cannot be used to detect extra-pulmonary TB.

Developed by FIND, Cepheid, Inc., and the University of Medicine and Dentistry of New Jersey with funding from NIH, and the Bill & Melinda Gates Foundation.

LIGTT analysis, based on expert interviews and literature cited throughout this report.
Of known TB deaths, the majority are patients who die in treatment. This reflects the fact that most individuals who develop TB do ultimately end up seeking care, but many patients do not receive treatment until the disease has become too advanced. This is caused by patient delays in seeking care, provider-caused delays in treatment, natural rates of treatment failure, and also the effects of HIV co-infection. Delays in patients seeking care are driven by a lack of awareness of early symptoms of TB, considerable community stigma, and insufficient access to healthcare. Provider-caused delays often arise in diagnostics and referrals. TB diagnosis is often clinical or done with methods that produce false negatives, and diagnostics can be slow to produce results, which means some patients ‘fall off’ before receiving their results and subsequently treatment, especially in rural sub-Saharan Africa where patient followup is particularly challenging. Patients visit an average of 3 clinics before receiving a positive diagnosis and care referral, creating a delay of 45-60 days (WHO, 2013). There is also a natural rate of failure with current drugs due to their interactions with the body and the disease, although most experts believe that this is a far less significant cause of mortality relative to delays in patients seeking care and provider-caused delays in treatment. Finally, the number of patients who die in treatment is influenced by patients with TB-HIV co-infection, and while this analysis looks specifically at the 7.1 million TB patients who do not have HIV, the percentages applied in the analysis are global figures, and include TB patients with HIV who have greater case fatality rates in treatment.

Roughly a third of patients do not receive DOTS-compliant treatment because they go to private practitioners or traditional healers. These patients receive non-WHO approved treatment which has lower rates of success.

6% of patients under DOTS coverage and 25% of patients outside of DOTS default due to the long treatment cycle, even if they are receiving treatment through DOTS-compliant facilities, because of insufficient compliance monitoring systems. This is a key contributor in the growth of MDR-TB, which is now driven primarily by transmission (WHO, 2013).
What drives drug-sensitive TB mortality

Exhibit 2: A break point analysis for drug-sensitive TB. The largest breakpoints involve mortality during treatment due to delays in seeking care, provider-caused delays in treatment, and non-WHO approved treatment by private health practitioners.⁵

MDR-TB

The major challenge in treating MDR-TB (Exhibit 3) is that it is typically misdiagnosed as drug-sensitive TB. Even if it is appropriately diagnosed, the antibiotics required for treatment are neither available nor affordable for most patients. Additionally, treatment is non-curative in almost half the patients. As a result overall mortality rate for MDR-TB is 35% (WHO, 2013).

The most significant driver of mortality from MDR-TB is a lack of positive diagnosis of MDR-TB, which in turn is driven by lack of diagnostics that can discriminate between MDR-TB and drug-sensitive TB. Only 5% of new TB cases and 9% of relapse cases are tested for MDR-TB, and undiagnosed cases account for over 90% of deaths from MDR-TB (WHO, 2013). It is worth noting that in our analysis we used calculated MDR-TB case detection rates that are much higher than global estimates. In order to reconcile global infection and mortality figures, and given the case notification rate through DOTS, and known outcomes of treatment, we calculated that 25% of new MDR-TB infections and 45% of retreatment MDR-TB cases were accurately diagnosed. This is much higher than global estimates, and reflects the lack of high quality data in MDR-TB global surveillance.

Only 82% of all MDR-TB patients notified of their TB condition receive appropriate treatment (WHO, 2013). This is primarily due to low coverage of MDR-TB treatment facilities and the high cost of second line drugs. Only 9% of TB management units have MDR-TB treatment services, while necessary

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⁵ All figures using data from 2012 are from the Global TB Report 2013 or the WHO’s database. See Data Notes at the end of this chapter for full explanation of data and sources.
drugs can cost 250 times as much as the first line drugs (WHO, 2010). The length and technical complexity of administering proper treatment for MDR-TB is a key reason for low coverage.

MDR-TB treatment is non-curative in more than half of patients. MDR-TB treatment has higher failure, default, and death while in treatment rates than drug-sensitive TB. This is due to a number of factors including that MDR-TB patients often receive appropriate treatment at a more advanced stage of disease (after a previous round of TB treatment, or after a series of misdiagnoses for drug-sensitive TB), and longer and more physically demanding treatment regimes (WHO, 2013).

What drives MDR-TB mortality

Exhibit 3: A break-point analysis of mortality due to MDR-TB shows that misdiagnosis of MDR-TB as drug-sensitive TB is the most significant problem. A second major concern is that even with accurate diagnosis, treatment is non-curative for over 50% of patients.\(^6\)

HIV co-infection

More than 1.1 million people around the world with active TB have HIV co-infection (13%). Of these cases, 75% percent are in sub-Saharan Africa, where 36% of the 2.3 million new TB cases in 2012 had HIV co-infection (WHO, 2013). In Africa, 74% of notified TB patients had a documented HIV test result as opposed to 46% across the world. Globally, only 57% of patients with TB-HIV co-infection were on antiretroviral

\[^6\] All figures using data from 2012 are from the Global TB Report 2013 or the WHO’s database. See Data Notes at the end of this chapter for full explanation of data and sources.
therapy (ART) and 80% were on preventative co-trimoxazole therapy (WHO, 2013). In most regions it is not standard practice to test for HIV when an individual is being tested for TB and vice versa. Moreover, if an individual has HIV, diagnosing a TB co-infection using a standard sputum smear test is even harder given the high false negative rate of the test. Further complicating the challenge is that HIV-TB co-infection is often extra-pulmonary and does not show up at all in SSM tests.

For those who do receive an accurate diagnosis, drug compatibility poses a challenge. Many TB treatments are incompatible with ARVs for HIV. Rifampicin, in particular, can cause some ARVs to be metabolized too quickly, reducing their effectiveness.
SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

Many interventions have proven effective in reducing the spread and burden of TB and warrant continued attention and expansion, for example, the DOTS protocol. Additional non-technology interventions include bringing down the cost of second line drugs through market coordination interventions, similar to those used for first line drugs, and interventions to reduce care seeking and provider-caused delays. As the spread of the disease is poorly understood, there are significant opportunities in better understanding the epidemiology and transmission of the disease to design effective public health interventions. These interventions would likely be focused on high transmission settings such as hospitals, public transportation, and potentially households in urban slums. In addition to these interventions, there are 4 major scientific and technological opportunities to reduce TB mortality.

A vaccine for pulmonary TB

There is currently no vaccine for pulmonary TB. If it were available, it could be one of the most effective ways to prevent the spread of the disease. There are multiple potential vaccination strategies including pre-exposure vaccination to create immunity to TB, post-exposure vaccination to delay development of latent TB to active TB, particularly for HIV positive patients, or therapeutic vaccination to kill TB bacteria.

The current focus is on pre-exposure vaccines for adults and adolescents as opposed to children. This is due to the higher projected impact of strategies targeting adolescents and adults over children, as well as the more advanced state of research on pre-exposure vaccines relative to post-exposure vaccines.

The lack of a basic scientific understanding of protection against TB is one of the major challenges in development of a vaccine. Specifically, the correlates of protection for TB are not understood—that is, the markers of immune response to a vaccine that correlate with protection from the disease (e.g., the presence of certain types of antibodies following a vaccination). Even with the BCG vaccine, which is efficacious against certain forms of TB in children, there is no complete and accepted understanding of what exactly are the changes in the body that cause or correlate with immunity.

Currently, 7 different vaccines are undergoing clinical trials, and all of these are either in Phase I or Phase II. Several more pre-clinical candidates exist as well. However, the success of any of these is uncertain, and experts estimate that in the absence of a major breakthrough, it will take 10-15 years before any vaccine is market ready.

While many developing countries have relatively robust coverage for vaccinations, existing immunization programs typically target infants and children. A successful vaccination campaign for adults would require significant coordination through the government, behavior change, and financial investment. Given these factors, the difficulty of deployment is COMPLEX.
A novel, more accurate TB diagnostic with the ability to identify drug resistance

TB is currently detected primarily through sputum smear microscopy (SSM) and clinical diagnosis. Both have low sensitivity and specificity and cannot differentiate between drug-sensitive and drug-resistant TB. A new, more accurate and quick, diagnostic is required to help administer timely treatment and curb the spread of the more dangerous drug-resistant versions of TB. A new diagnostic would need to be:

- Able to differentiate between drug-sensitive TB and MDR-TB, and ideally XDR-TB.
- Easy and safe to use for healthcare workers administering the test, specifically with respect to collection of the infected sputum sample, introduction of the sample into the diagnostic system, and the final diagnostic readout.
- Affordable, with respect to both (a) capital investment for any back-end devices (e.g., a cost of $500, compared to the over $10,000-$15,000 per machine for current state-of-the-art machines); and (b) disposable devices (e.g., less than $2-$3 per disposable test kit).
- Capable for delivering rapid results, ideally within minutes, rather than hours and days, as is currently the case.
- Appropriate for point-of-care at the clinic and ideally outpost level of care delivery including in off-grid areas with little or no access to electricity, running water, refrigeration or other amenities. The device should be portable and function across multiple heat and humidity ranges.

An ideal diagnostic would automate collection and tracking of relevant epidemiological data as well. This would most likely be achieved using a DNA-based test. Major advances in nucleic acid amplification test (NAT) technology have made the possibility of a novel TB diagnostic imminent. At least 1 major company expects to release an appropriate and relatively affordable diagnostic within the next 2-4 years.

As most TB cases are diagnosed clinically and the majority of non-clinical diagnoses are conducted using microscopes, it will be a challenge to get a critical mass of clinicians adequately trained and switched to new devices even if they are more effective. This will likely require government intervention.
Even if the technological breakthrough is achieved, it will be very difficult to deploy at scale. The projected time to market readiness is 2-4 years and the difficulty of deployment is CHALLENGING.

**Breakthrough 2 – Difficulty of deployment**

### Breakthrough 3

Shorter course TB treatments for both drug-sensitive TB and MDR-TB

Many challenges related to controlling TB are a function of long and demanding treatment regimens. Even though treatment duration of drug-sensitive TB has been brought down from 9-12 months to 6-9 months, this timeframe is still extremely long and creates major challenges. Second line drug regimens for MDR-TB take 18-24 months and are able to cure only about 50% of the cases. Treatment for drug-resistant TB sometimes exceeds 2 years. In addition, some current drugs are not easily co-administered with antiretrovirals (ARVs) for patients with TB-HIV co-infection.

These drug challenges lead to high rates of non-compliance, expensive delivery systems to provide treatment responsibly, and the growth of drug-resistant TB. New drugs that can treat drug-sensitive TB over the course of weeks as opposed to months, will dramatically alleviate many of the challenges of controlling TB. The TB Alliance highlights several drugs at various stages of clinical testing for both drug-sensitive and drug-resistant TB. Two drug regimens in Phase III trials for drug-sensitive TB could be available within a few years, reducing treatment time from 6 months to 4 months. A drug combination which recently completed Phase II trials could be used to treat drug-sensitive TB and certain forms of MDR-TB, including individuals with HIV-TB co-infection, in 4 months. The projected time to market readiness—depending on the drug—is 2-4 years and difficulty of deployment is FEASIBLE.
Biometric devices for tracking patients and compliance

Patient compliance is a major challenge in treating TB and preventing the development of MDR-TB. Biometrics, combined with data tracking and messaging systems, offer a low cost opportunity to increase compliance and reduce the likelihood of clinicians falsifying treatment documentation for patients. Many clinicians are paid based on the number of patients treated, and there is an incentive to claim to have properly treated patients who may actually have defaulted on treatment. Affordable biometric devices to track treatment compliance (e.g., thumb-print scanners) are already being deployed at a small scale. While in principle these technologies can be scaled up, large-scale deployment remains challenging. Broad coverage in any country will have to be mandated by government policy. The breakthrough is market ready and difficulty of deployment is COMPLEX.
Breakthrough 4 – Difficulty of deployment

- **Policies**: Regulated market with supportive policies
- **Infrastructure**: Low-moderate need for human capital development
- **Human capital**: Moderate behavior change required with evidence of behavior change being viable
- **Access to user finance**: Financing not required
- **Behavior change**: Moderate demand
- **Existing demand**: Deployment model(s) being tested
- **Market fragmentation/Distribution channels**: Moderate fragmentation of customers, under-developed channels
- **Business model innovation**: Dependent on existing infrastructure

- **Difficulty of deployment**: Simple, Feasible, Complex, Challenging, Extremely Challenging.
The data available for this analysis had many shortcomings. Required figures were often unavailable, incomplete, or inconsistent with other published figures. For example, The Global TB Report calculates that there were 450,000 new and re-treatment cases of MDR-TB in 2010, of which only 94,000 or 21% were detected. However, it also states that MDR-testing rates are 5% for new TB infections and 9% for re-treated infections, significantly below 21% inferred from the global new case and treated case figures.

In order to create as sound an analysis as possible, we began with the most definitive data available—the global number of new cases and global mortality, drawn from the Global TB Report 2013. From there we worked inwards, identifying the rate of DOTS vs non-DOTS treatment and mortality rates for various clinical scenarios. After this stage the data became increasingly unavailable or unreliable. In some cases we calculated figures (e.g. percentage of patients outside of DOTS who are successfully treated), in order to reconcile the resulting mortality rates with the global mortality rate. Specific figures and their sources are explained below. All decimal percentage points were rounded to the nearest percent and all incidence and mortality figures were rounded to the nearest thousand.

### Drug-sensitive TB

**New infections (7.1 million)**

The number of cases is the incidence of non drug-resistant, non-HIV-TB co-infection cases in 2012, as reported in the Global TB Report 2013.

**Tested, notified to DOTS and treated**

- **Global case detection rate (66%)** taken from the Global TB Report 2013. All notified patients were assumed to seek treatment.
  - Successfully treated: Reported as 87% in the Global TB Report 2013.
  - Died in treatment: Reported as 4% of all treated cases in the Global TB Report. The Global TB Report also states that 4% of treated cases were “not evaluated” and had no associated outcome. We distributed this 4% in a weighted manner across the Died in treatment, Failure and Default scenarios, bringing the Died in treatment rate to 5% of treated cases.
  - Failure: Reported as 1% of all treated cases in the Global TB Report. The report also states that 4% of treated cases were “not evaluated” and had no associated outcome. We distributed this 4% in a weighted manner across the Died in treatment, Failure and Default scenarios, bringing the Failure rate to 2% of treated cases.
  - Default: Reported as 4% of all treated cases in Global TB Report. The Global TB Report also states that 4% of treated cases were “not evaluated” and had no associated outcome. We distributed this 4% in a weighted manner across the Died in treatment, Failure and Default scenarios, bringing the Default rate to 6% of treated cases (this number is higher than the 5% in the Died in treatment scenario due to rounding).

**Tested outside of DOTS**

All individuals that were not among the 66% who were Tested, notified to DOTS and treated are assumed to have been tested outside the formal sector where DOTS is practiced. We assumed the number of patients who were never tested to be negligible.

- Correctly diagnosed/False negative: The false negative rate is assumed to be 20%, drawn from a literature review which highlighted very high (30%+) rates of false negatives in certain high TB burden regions (parts of South Asia and Africa), and a false negative rate of around 10% for non-DST tests such as skin tests elsewhere in the world.
- Treated non-DOTS program/Not treated: We found limited high quality data for patients treated outside of DOTS. We assumed 95% (i.e. the vast majority of patients), seek some form of treatment.
- Successfully treated/Died in treatment/Failure or default: We found limited high quality data for patients treated outside of DOTS. We assumed the rate of patients who died in treatment to be twice that of DOTS due to less...
regulated and less effective treatment outside of DOTS. We then calculated a 65%/25% split between successful treatment and failure and default rates in order to reconcile final mortality rates with global figures.

**Mortality rates**

**Successfully treated/Died in treatment**
Patients who are successfully treated by definition survive. See above for further explanation of 87% successful completion and 4% mortality in treatment figures for DOTS and 65% and 10% figures for non-DOTS coverage.

**Failure/Default/Not-treated**
WHO estimates 22.5% of untreated TB patients will die in the first 2 years (70% 10 year mortality rate for smear positive TB and 20% for smear negative TB). We assume smooth rates of infection and mortality such that while 22.5% of new infections will not die this year, the number who die last year and this year will be 22.5%. We initially ran the analysis with the figure 22.5% figure for treatment scenarios in which treatment fails, is not completed or is not initiated, and then increased this rate to 30% to reconcile mortality rates to meet global mortality figure of 840,000.

While this analysis is focused on drug-sensitive, non HIV-TB co-infection, the figures are calculated including patients with HIV-TB co-infection.

### MDR-TB

**Total new infections (450,000)**
The Global TB Report 2013 estimates 450,000 new cases of drug-resistant TB. This is the sum of new and relapse infections.

**New infections**
The Global TB Report states that 3.6% of all new TB cases are MDR-TB cases. With 8.6 million new TB cases per year, this implies 310,000 new MDR-TB cases.

**DOTS tested**
Global case detection rate is reported as 66% in the Global TB Report 2013. All patients not under DOTS coverage are assumed to go untreated, as MDR-TB testing is still uncommon in DOTS, and particularly outside of DOTS.

- Tested for MDR-TB: The Global TB Report 2013 reports 94,000 total MDR-TB cases known to have been detected across new and relapse MDR-TB cases. The report also states that 5% of new TB cases and 9% of relapse cases were tested for drug resistance. Given that 66% of patients are under DOTS coverage (297,000 MDR-TB infected individuals), and 94,000 patients were confirmed to have MDR-TB under DOTS, we infer that, among patients who are under DOTS coverage, 25% of new infection cases with MDR-TB were tested for MDR-TB, while 45% of retreatment cases with MDR-TB were tested for MDR-TB (25% to 45% ratio for testing in new cases vs. retreatment cases is based on the 5% to 9% ratio stated in Global TB Report). This is significantly higher than globally estimated case detection rates for MDR-TB reported in the Global TB report. These reconciliation challenges highlight the inconsistencies in the data available for MDR-TB.

  For this analysis, we have used these inaccurately high detection rates of 25% and 45% so that mortality numbers and reported infection numbers can reconcile, and have noted the underlying issues with these figures explicitly.

**TB re-treatment**
We calculated TB re-treatment cases by subtracting the number of new infections, 310,000 from the total number of estimated infections, 450,000, according to the Global TB Report.
DOTS tested
Global case detection rate is reported as 66% in the Global TB Report 2013. All patients not under DOTS coverage are assumed to go untreated, as MDR-TB testing is still uncommon in DOTS, and particularly outside of DOTS.

Tested for MDR-TB: See explanation under new infections.

Treated
The Global TB Report states that 82% or 77,000 patients were treated for MDR-TB, of the 94,000 who were tested and eligible.

Successfully treated
Reported as 48% in the Global TB Report 2013.

Died in Treatment
Reported as 15% of all treated cases in Global TB Report. The Global TB Report also states that 14% of treated cases were “not evaluated” and had no associated outcome. We distributed this 14% in a weighted manner across the Died in treatment, Failure and Default scenarios, bringing the Died in treatment rate to 20% of treated cases.

Failure
Reported as 9% of all treated cases in Global TB Report. The Global TB Report also states that 14% of treated cases were “not evaluated” and had no associated outcome. We distributed this 14% in a weighted manner across the Died in treatment, Failure and Default scenarios, bringing the Failure rate to 12% of treated cases.

Default
Reported as 14% of all treated cases in Global TB Report. The Global TB Report also states that 14% of treated cases were “not evaluated” and had no associated outcome. We distributed this 14% in a weighted manner across the Died in treatment, Failure and Default scenarios, bringing the Default rate to 20% of treated cases.

Mortality rate

Successfully treated/Died in treatment
Patients who are successfully treated by definition survive. See above for further explanation of 48% successful completion and 20% mortality in treatment figures.

All other scenarios
Mortality for untreated MDR-TB is calculated to be 40% (compared to 30% for untreated drug-sensitive TB), to fit the overall mortality figure in the Global TB Report.
Malaria has proven to be one the most persistent and lethal diseases in human history, responsible (by some accounts) for more deaths than any other disease. Each year, 219 million people around the world are infected with malaria, 660,000 of whom die. Disproportionately affecting vulnerable populations like pregnant women and children, malaria is the 3rd leading cause of death among children under 5. Malaria is transmitted from person to person through infective bites from female *Anopheles* mosquitoes. Its persistence and virulence is due to the behaviors of these mosquitoes, which makes them difficult to control, as well the highly complex and resilient nature of the parasites that they carry (*Plasmodium falciparum* in particular).

African countries are home to 90% of the malaria-related fatalities, with three countries—Nigeria, DR Congo and Burkina Faso—accounting for over 50% of them. Both caseload and fatalities have decreased markedly in recent years due to large-scale deployment of long-lasting insecticide-treated bed-nets (LLINs), indoor residual spraying (IRS) of insecticides, the introduction of rapid diagnostic tests (RDTs), and treatment with novel combination therapies.

However, a number of major challenges remain. These include the threat of vector resistance to insecticides and existing control methods; the development of parasite resistance to antimalarials, which results in a delayed or incomplete clearance of parasites from a patient’s body; and the presence of a large, asymptomatic reservoir of parasites in successfully treated and otherwise healthy individuals, who continue to carry the parasite in their bodies for years and contribute to malaria transmission in their communities. There are 5 scientific and technological breakthroughs which can help control, eliminate, and eventually eradicate malaria.

- An improved anti-infective vaccine for *P. falciparum*
- A single dose, complete cure for malaria
- Biological modification of mosquitoes (although this can have unpredictable long-term consequences)
- New long-lasting non-chemical spatial mosquito repellents or attractants
- New long-lasting chemical mosquito repellents delivered in novel ways
Malaria is one of the most persistent and lethal diseases in human history. The early records of malaria date back to 2700 BC in China (Cox, 2002). By some accounts, it has been responsible for more deaths in human history than any other disease (Shah, 2002). It is the 5th largest cause of mortality in the world, and the 3rd most deadly infectious disease. Each year, 219 million people around the world contract malaria, and 660,000 of these patients die (WHO, 2013).¹

**CORE FACTS AND ANALYSIS**

Malaria is caused by protozoan parasites of the genus *Plasmodium*, belonging to the parasitic phylum *Apicomplexa*. Mosquitoes act as the vector, transmitting the disease from one human to another. This disease disproportionately affects vulnerable populations like pregnant women and children. It is the 3rd leading cause of death among children under 5, who constitute over 85% (more than 560,000) of total malaria-related deaths worldwide (WHO, 2013).

Malaria-related deaths are highly concentrated in a small number of countries and population segments

As of 2013, malaria is endemic in 99 countries. An estimated 3.3 billion people are at risk of becoming infected with malaria, 670 million of whom reside in countries with a high malaria burden. In 2010, 32 countries were in the stage of eliminating malaria, and 67 countries were in the stage of controlling malaria (Feachem, et al., 2010).

**Geographic distribution of malaria cases and malaria-related deaths**

Exhibit 1: 80% of all malaria cases worldwide and 90% of all malaria-related fatalities occur in Africa. Over 50% of African fatalities are concentrated in Nigeria, DR Congo and Burkina Faso (WHO, 2013).

¹ Uncertainty range in mortality from 490,000 – 836,000.
Even though malaria is widespread, malaria-related deaths are highly concentrated in Africa. African countries are home to 90% of all malaria-related fatalities, with Nigeria, the Democratic Republic of Congo and Burkina Faso (Exhibit 1) accounting for 53% of all reported malaria deaths in Africa\(^2\) (WHO, 2013). If malaria-related mortality in the 10 worst-affected African countries were to be brought in line with the rest of sub-Saharan Africa, overall mortality would be reduced by almost 20% (WHO, 2013). There are three major reasons for the concentration of mortality and morbidity in Africa (Feachem, et al., 2010) as outlined below.

**Prevalence of Plasmodium falciparum, the most lethal form of the parasite**

Of the more than 200 known species of *Plasmodium* parasite (Rich & Ayala, 2006), 5 are known to cause human malaria. These are *P. falciparum*, *P. vivax*, *P. ovale*, and *P. malariae*; in addition, a species of primate malaria, *P. knowlesi*, has recently been documented to cause human infection and fatality in many countries of Southeast Asia (Aneshvar, 2009). Of the 4 common malaria species, *P. falciparum* is the most lethal and accounts for 90% of globally reported malaria mortality. The other species are known to usually cause sickness, and significant morbidity, but not death. *P. falciparum* is also far more prevalent in Africa than in other parts of the malaria-endemic world (WHO, 2013). An estimated 85% of malaria cases in Africa are due to *P. falciparum* (Exhibit 2), compared with around 50% in South and Southeast Asia, where the less fatal species, *P. vivax*, is also prevalent (WHO, 2013). It is interesting to note that *P. falciparum* is more virulent and causes significantly higher mortality in Africa, than in comparable communities in Southeast Asia. This may be partly due to lower transmission and earlier treatment outside of Africa, but may also be explained in part by epidemiological differences and variations in the pattern of disease across the two continents (Maitland & Williams, 1998).

**Contribution of the different parasites to malaria-related deaths**

<table>
<thead>
<tr>
<th>Percent of cases</th>
<th>sub-Saharan Africa</th>
<th>South/ Southeast Asia</th>
</tr>
</thead>
<tbody>
<tr>
<td>P. malariae</td>
<td>8%</td>
<td>48%</td>
</tr>
<tr>
<td>P. ovale</td>
<td>5%</td>
<td>52%</td>
</tr>
<tr>
<td>P. vivax</td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td>P. falciparum</td>
<td>85%</td>
<td></td>
</tr>
</tbody>
</table>

*Exhibit 2: Of the various malaria parasites in sub-Saharan Africa and South/Southeast Asia, *P. falciparum* is the dominant form, followed by *P. vivax*. The former is, by far, the leading cause of death (WHO, 2012) (WHO, 2013) (The Malaria Parasites, 2013).\(^3\)*

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\(^2\) Nigeria, India, DRC, Tanzania, Uganda and Mozambique combined make up 50% of all malaria cases. India accounts for 11% of all cases but only 4% of all deaths.

\(^3\) Numbers represent % of reported malaria cases. Numbers for Africa presented here differ slightly from those in the WHO World Malaria Report, which does not track *P. ovale* or *P. malariae*. In Asia, *P. malariae* and *P. ovale* are sporadic, and *P. knowlesi* is rare but geographically concentrated and can account for up to 70% of malaria cases in areas of Southeast Asia where it is present.
WHO defines the following “high risk” groups, based on vulnerability to infection and death: pregnant women, infants and children under five, HIV/AIDS patients, and migrant or mobile populations.

Dominance of resilient and highly efficient malaria vectors
There are 3,500 known species of mosquitoes, across 41 genera. Of these, females of only 30-40 mosquito species (from the genus Anopheles), transmit malaria in humans, and only 7 have been found in Africa. The major malaria vectors in Africa are the Anopheles gambiae and Anopheles funestus. These vectors are particularly difficult to control because they occur in high densities in tropical climates, live in close proximity to human populations, and have a strong preference for feeding on humans. They have relatively long life spans, and breed readily in water bodies of varying size, from lakes to tiny puddles (White, et al., 2013). The Anopheles gambiae can lay viable eggs in bodies of water as tiny as animal hoof prints, which means that there can be thousands of such water accumulations—after every rainfall—in even the smallest village. This makes larval control in Africa extremely difficult. There are also numerous secondary vector species prevalent in sub-Saharan Africa. The unique behavioral traits of these different Anopheles species, the difficulty of distinguishing between them, and the existence of multiple species in a single geography adds to the complexity of developing effective vector control strategies.

Conflict has historically been a driver of malaria
Conflict displaces entire populations (a key driver of malaria transmission), erodes health systems, and thus poses significant impediments to any large-scale efforts to control the disease. With the notable exception of Burkina Faso, most of the countries with high caseloads and mortality rates in Africa (e.g., Nigeria, the Democratic Republic of Congo, Mozambique, Cote d’Ivoire, Chad, and Uganda), have witnessed very destructive civil wars in recent years. Malaria also disproportionately affects specific, vulnerable populations (WHO, 2002) (WHO, 2013). Over 85% of malaria deaths globally were among children under 5. Children have low immunity and are particularly susceptible to malaria. Malaria during pregnancy causes as many as 10,000 maternal deaths each year. P. falciparum infection during pregnancy increases the chance of maternal anemia, abortion, stillbirth, prematurity, intrauterine growth retardation, and low infant birthweight—the greatest risk factor for death in the first month of life. 8-14% of all low birthweight babies, and 3-8% of all infant deaths in certain parts of Africa are the result of malaria during pregnancy.

Current and historic interventions have targeted both mosquito and parasite

WHO defines Malaria elimination as “a reduction to zero of the incidence of infection caused by human malaria parasites in a defined geographical area as a result of deliberate efforts.” Malaria control is defined as “reducing malaria morbidity and mortality to a locally acceptable level through deliberate efforts using the preventive and curative tools available today.” Globally, between 2000 and 2010, both malaria caseload incidence and mortality rates have decreased markedly, by 17% and 26%, respectively (WHO, 2013). This is largely as a result of both institutional and individual interventions described below.

Interventions aimed at preventing transmission

Bed-nets, particularly long-lasting insecticide treated bed-nets (LLINs)
In such nets, particular insecticides (deltamethrin, alphacypermethrin, or permethrin) are either incorporated into the fibers of the net (during extrusion of the polymer), or coated with a binder onto

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4 WHO defines the following “high risk” groups, based on vulnerability to infection and death: pregnant women, infants and children under five, HIV/AIDS patients, and migrant or mobile populations.
the surface of the netting fabric. Currently, 11 manufacturers make WHO-recommended LLINs. These nets provide both individual and household levels of protection, especially against vector species that predominantly bite at night or rest indoors. The netting protects the individuals sleeping underneath from mosquitoes that are either killed or repelled by the insecticide. By killing mosquitoes, the household as a whole is offered some protection. While high coverage of LLINs has been associated with some level of community-wide protection, LLINs cannot protect individuals from being bitten when they are outside the net. Further, a key challenge with LLINs is emerging insecticide resistance. Because LLIN campaigns to date have mostly targeted children, caseloads may shift towards older individuals in the future. Still, scale-up of LLINs is credited with having made a significant contribution to the overall reduction in malaria cases and fatalities by targeting the most vulnerable section of the population—children.

**Indoor residual spraying (IRS)**

Small pre-defined amounts of insecticides (like dichlorodiphenyltrichloroethane, pyrethroids, carbamates, or organophosphates), are sprayed indoors and on the walls of dwellings. As in the case of LLINs, IRS is only effective indoors and is credited with a significant contribution to the reduction in caseload and fatalities. However, its full potential is realized only if at least 80% of houses in the targeted areas are sprayed. One challenge with IRS is that it requires repeated applications, which may not happen. Once the sprayed insecticide weakens, mosquitoes quickly reappear. Indoor spraying is effective for 3-6 months, depending on the insecticide used and the type of surface on which it is sprayed. Newer formulations of pyrethroids and organophosphates can last up to 9 months, and DDT can in some cases be effective for 9-12 months. A big challenge for all insecticide-based interventions, including LLINs and IRS, is that mosquitoes develop resistance to insecticides. In some malaria-endemic areas, resistance to all four classes of insecticides has been detected. While this has not yet translated into large-scale operational resistance or significant reduction in the effectiveness of LLIN and IRS interventions, operational resistance to pyrethroids in particular is a huge risk (Ranson, et al., 2010), especially in high-burden countries like Senegal, Sudan, Benin, Burkina Faso, Ghana and Cote d’Ivoire where indications of reduced efficacy of interventions resulting from insecticide resistance have already been seen.

**Skin repellents**

These include sprays and ointments, and are used extensively for personal protection (though not malaria control) in many parts of the world, with varying levels of efficacy depending on the brand. Some of them are available at a price point that can be affordable for low-income families. However, adoption in communities not accustomed to using such repellents will likely be difficult, and efficacy will be highly dependent on education, behavior change, and compliance with instructions for use. A recent randomized control trial testing the effectiveness of skin repellents in combination with LLINs found that topical repellents are not an effective incremental intervention, if LLINs are already in place (Chen-Hussey, et al., 2013).

**Spatial repellents**

These include flammable incense and coils, and are used extensively around the world with varying levels of effectiveness. Such repellents tend to give off an unpleasant smell and can increase the risk of respiratory disease. An alternative is the use of vaporizing mats or small cardboard tablets which, when heated in a small electrically-powered device, release a pyrethroid vapor. This is more effective than coils but is significantly more expensive and can only be used where electricity is available (Pates, et al., 2002). Importantly, while skin and spatial repellents have proven effective for personal protection, neither have demonstrated community-level protection against malaria.

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5 WHO-certified LLIN manufacturers include the following; Full Recommendations: BASF, Vestergaard Frandsen, Sumitomo Chemical, Yorkool; Interim Recommendations: Care Plus, Clarke, Bayer, V.K.A. Polymers, Bestnet, Disease Control Technologies.

6 WHO defines insecticide resistance as the ability of an insect to withstand the effects of an insecticide by becoming resistant to its toxic effects by means of natural selection and mutations. The Insecticide Resistance Action Committee (IRAC) defines operational resistance as a heritable change in the sensitivity of a pest population that is reflected in the repeated failure of a product to achieve the expected level of control when used according to the label recommendation for that pest species.
Large-scale draining of water bodies and swamps
This has been a key component of elimination strategies in high income countries. However, this method only works when the vector mosquitoes primarily breed in larger bodies of water, and where potential breeding sites are easy to map and treat. Some targeted efforts to reduce large mosquito breeding grounds, like controlled irrigation of rice fields, have shown promise. However, the *Anopheles gambiae* can lay viable eggs in very tiny pools of water, making large-scale draining irrelevant to the African context. Recently, there have been some efforts to educate populations about how to identify and eliminate small, but obvious, breeding sites.\(^7\)

Improved housing construction
This has contributed to the elimination of malaria in high income countries, where most homes also have window screens which can keep mosquitoes out. Unfortunately this remains a luxury the poor cannot afford.

There have been only two interventions aimed at the parasite itself

Treatment of infected patients
The WHO recommended treatment for *P. falciparum* infection is Artemisinin-based Combination Therapy (ACT).\(^8\) Originally derived from sweet wormwood, *Artemisia* can now be manufactured synthetically. In this treatment regimen, artemisinin administered in combination with another antimalarial (amodiaquine, lumefantrine, mefloquine, sulfadoxine-pyrimethamine, dihydroartemisinin-piperaquine), reduces the likelihood that the parasite will develop resistance to an individual drug, as had happened earlier with antimalarial treatments such as chloroquine (which is now largely inefficacious in much of the malaria-endemic world). Resistance represents an acquired (or selected) genetic difference in parasite population structure, and occurs by selecting out a subpopulation of parasites with drug pressure. Emergence of resistant parasite strains also happens when individuals with low immunity and a heavy parasite load receive small amounts of drugs, especially through monotherapy (treatment with a single drug). The biggest challenges in malaria treatment include the continued use of poor-quality or counterfeit treatments, the use of monotherapies, and lack of patient compliance to treatment regimens. All of these factors lead to the development of drug resistance and all are common in Africa, where the majority of patients with fever and other malaria symptoms seek treatment through informal channels or unregulated street vendors.

Use of malaria rapid diagnostic tests (RDTs)
Related to the treatment challenges described above, treatment with antimalarials has tended to be presumptive rather than relying on a confirmed diagnosis. A significant portion of antimalarials dispensed are used for non-malarial illnesses. A recent study conducted in Gabon found that 30% of children with fever received unprescribed antimalarials, and that 80% of these children were not actually infected with malaria (Mawili-Mboumba, et al., 2013). These children failed to receive the treatment they required, and the antimalarials were wasted on non-malarial illness. To address this challenge, the WHO has launched a new initiative—T3: Test, Treat, Track—to ensure that all suspected malaria cases are tested and that only confirmed cases are treated with quality-assured antimalarials. This initiative is also expected to slow the emergence of drug resistance to ACTs.

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\(^7\) For example, the Student Leaders Against Malaria (SLAM) initiative.

\(^8\) The recommended treatment regimen during pregnancy is different.
KEY CHALLENGES

There are a number of reasons why malaria has been among the most resilient and lethal diseases in human history, and why achieving a sustained reduction in disease transmission, and deaths, has been difficult.

The two-part lifecycle of *P. falciparum*

Exhibit 3: Malaria parasites have two separate life cycles: in the human between being bitten and having the parasite fully mature into *gametocytes*, and in the mosquito between the *gamete* and *sporozoite* stages.

A highly complex parasite makes developing vaccines and medications difficult

The *Plasmodium* parasite has two different lifecycles: in the mosquito, and in the infected human (Exhibit 3). In both lifecycles, it goes through significant transformations. To this day, there are considerable gaps in the understanding of the basic immunology and host response to the disease.
Transmission intensity is determined by a complex and variable set of factors:

- The parasite can use antigenic switching under selective immune pressures, to evade the immune system. In other words, it changes the antigens it expresses, while maintaining the same underlying genetic composition.
- The parasite is intracellular, and hence not exposed to the immune system consistently through its lifecycle.
- Infection does not automatically result in future immunity. Partial immunity against malaria builds slowly over time, is developed over years of exposure, and never provides complete protection. Further, immunity can be lost in a few years if individuals move outside of endemic areas.
- Different parasitic loads can lead to dramatically different levels of sickness in different individuals. Many infected individuals remain asymptomatic and hence are not aware they have malaria, or that they are capable of transmitting it. Mosquitoes first become malaria vectors only after biting an infected human. In the long-term, if asymptomatic infection is not addressed, the reservoir of infection will continue to grow, and malaria resurgence will be inevitable.

Mimicking the antigen under such complexities in order to produce a protective, artificial immune response has proven extremely difficult. As a result, developing an effective vaccine has proven elusive. New vaccine development programs are focused on either blocking parasite transmission from infected humans to mosquitoes, or on preventing gametes from developing in the mosquito gut itself.

Transmission intensity is thus central to the design and implementation of effective malaria control measures. In low transmission areas, symptomatic patients account for the vast majority of the infectious reservoir, and declines in transmission rates translate proportionally to a decline in malaria incidence and prevalence. By contrast, in high transmission areas, much larger declines in transmission rates are needed to reduce overall malaria incidence and prevalence, and targeting symptomatic individuals alone is unlikely to achieve this (WHO, 2010). The implication is that while they may have a major impact on mortality reduction, drug strategies to reduce malaria prevalence will be effective in high transmission areas only if used among the known complexities are:

- The parasite can use antigenic switching under selective immune pressures, to evade the immune system. In other words, it changes the antigens it expresses, while maintaining the same underlying genetic composition.
- The parasite is intracellular, and hence not exposed to the immune system consistently through its lifecycle.
- Infection does not automatically result in future immunity. Partial immunity against malaria builds slowly over time, is developed over years of exposure, and never provides complete protection. Further, immunity can be lost in a few years if individuals move outside of endemic areas.
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Transmission intensity is determined by a complex and variable set of factors.
in combination with other effective interventions targeting the vector. Drug strategies increase in importance for overall malaria control only as transmission intensity declines, and the majority of patients become symptomatic. Programs then need to adapt to target the remaining parasite reservoirs, by finding and treating individual infections (Sturrock, et al., 2013).

Today, only half the countries of sub-Saharan Africa have data available on transmission intensities. What data is available, suggests that EIRs and malaria transmission intensity appear to vary greatly based on the presence of different Anopheles species, the extent of urbanization, land use, population density, elevation, and climate. Improved and standardized data on EIRs, and an increased understanding of the drivers of differences in transmission intensity across neighboring geographies is critical to the design and effective monitoring of malaria control interventions (Hay, et al., 2000).

The dominant Anopheles mosquito vectors are pervasive, adaptable and resilient

A mosquito’s lifecycle has 4 stages: egg, larva, pupa, and adult (Exhibit 4). The first 3 stages are aquatic and last 5-14 days. The mosquito becomes a vector only once it reaches adulthood, and only females are vectors. Adult females feed on sugar sources for energy, but require a blood meal to develop eggs. After a full blood meal, the female rests for a few days while the blood is digested and eggs are developed. In tropical conditions, this takes 2-3 days. Once the eggs are fully developed, the female lays them and resumes host seeking. If—and only if—the mosquito has taken a blood meal from a human infected with the malaria parasite and survives the 10-14 days it takes the parasite to complete the incubation period and render the mosquito infectious, does the mosquito become an active malaria vector.

Female Anopheles mosquito life-cycle

Exhibit 4: Female Anopheles gambiae become a vector about a month after being laid as eggs. What little data there is, suggests, that fewer than 10% survive to become vectors.
The dominant vector, *Anopheles gambiae*, has a number of characteristics that make it an extremely efficient malaria vector.

**Strong preference for human blood, combined with highly efficient feeding habits**
Most *anopheles* mosquitoes are neither strongly anthropophilic (i.e., prefer feeding on humans), nor zoophilic (i.e., prefer animal blood). However, *Anopheles gambiae* are strongly anthropophilic, and therefore highly efficient malaria vectors. They are also endophilic (i.e., they rest indoors) and nocturnal, which means that they have unfettered access to humans while they sleep, unless they are under appropriate bed-nets or are otherwise well-protected.

**Relatively long life span**
Adult *Anopheles gambiae* females tend to live (a relatively long) 1-2 weeks in nature (Kileen, et al., 2000), and studies in Tanzania showed *Anopheles gambiae* mosquitoes have a 77-84% daily survival rate. Extrapolating from this limited evidence, fewer than 10% of female *Anopheles gambiae* are likely to survive longer than the 14-day extrinsic incubation period it takes for them to become malaria vectors. If, however, actual daily survival rates were 90%, more than 20% of mosquitoes would survive longer than this extrinsic incubation period (CDC, 2014). The long life span of the *Anopheles gambiae* is therefore a major factor in the intensity of malaria transmission in endemic countries.

**Thousands of breeding sites, which are very difficult to eliminate (CDC, 2014)**
Each adult female lays 50-200 eggs per oviposition, directly on water. These eggs have floats on their sides, and hatch in a few days. Larvae of *Anopheles gambiae* (unlike those of most other species), can breed in very diverse habitats: fresh or salt-water marshes, mangrove swamps, rice fields, grassy ditches, edges of streams, and small, temporary rain pools such as tire tracks. Without repeated and large-scale spraying, or other such expensive and environmentally destructive methods, it is extremely difficult to eliminate all these breeding sites. Recent studies have explored other methods for targeting oviposition and gravid (carrying eggs) females as a vector control strategy. Some have suggested that shiny, sticky surfaces may attract gravid females because they can be visually mistaken as aquatic habitats, and this could potentially be exploited in the development of gravid traps or novel mosquito trapping strategies (Dugassa, et al., 2012).

**Mosquitoes may be capable of behavioral plasticity**
Numerous anecdotal reports of mosquitoes changing their behavior and adapting feeding patterns as a result of IRS and LLINs exist. There is insufficient data to assess whether these are genetic or adaptive responses (Ranson, et al., 2011). The implication of such adaptability is that the effectiveness of LLINs may diminish over time, if, in order to minimize contact with indoor insecticides, the *Anopheles gambiae* mosquitoes begin feeding earlier in the day, or do not remain exclusively endophilic. If this does happen, new control tools and strategies may be required.

The complex distribution of primary, secondary and tertiary *Anopheles* vector species makes design of effective vector control strategies difficult

*Anopheles* mosquitoes can be divided into several species complexes, which are composed of several morphologically indistinguishable sibling species. The *Anopheles gambiae senso stricto* is a complex of at least seven morphologically indistinguishable, but behaviorally distinct, sibling mosquito species, which include two genetically distinct species of *Anopheles gambiae senso strictu* (*Anopheles gambiae A* and *Anopheles gambiae S.*), and *Anopheles arabiensis*, three of the dominant vector species in sub-Saharan Africa.\(^{11}\)

\(^{11}\)This species complex consists of: *Anopheles arabiensis, Anopheles bwambae, Anopheles merus, Anopheles melas, Anopheles quadriannulatus, Anopheles gambiae senso stricto.*
Anopheles funestus is also a dominant vector species, and further complication is introduced by the existence of primary, secondary and even tertiary vector species existing in sympatry within a single geography. Effective control strategies depend on proper identification of the mosquito vector(s) and an understanding of each species’ distinct feeding and biting preferences. Interventions need to be properly adapted to the local environment, taking into account the behavior and ecology of the main vector species as well as the resistance status of both parasite and vector. The importance of this is underscored by the fact that neighboring villages can have vastly different malaria transmission intensities, depending on number of mosquito vectors present in that location. Where Anopheles funestus vectors are present alongside Anopheles gambiae, malaria transmission rates have been found to be twice as high. In Senegal, a village only 5 kilometers from its neighbor was found to have transmission rates 10 times as high, due to the presence of Anopheles funestus (Kelly-Hope & McKenzie, 2009). Further, Anopheles arabiensis —also endemic in much of Africa—have become more prevalent after broad introduction of bed-nets and IRS (Bayoh, 2010), likely because they have less preference for feeding and resting indoors. Today, large knowledge gaps exist about mosquito ecology and behavior in many highly endemic areas, due to the difficulty of identifying and monitoring mosquito vectors in the field.

Limitations of treatment with antimalarials

Effective treatment with ACTs is a key component of reducing malaria-related mortality. The biggest challenges in malaria treatment include the continued use of poor quality or counterfeit treatments that are abundant in the marketplace, the use of monotherapies, and lack of patient compliance to treatment regimens. All of these factors favor the development of drug resistance and are particularly common in Africa.

Yet another limitation of treatment strategies for broader malaria control efforts is the fact that symptomatic individuals constitute only a portion of the infectious reservoir, an important determinant of the number of infectious mosquitoes in an area and therefore the EIR. In a high transmission area, there are a large number of asymptomatic individuals due to the development of partial immunity resulting from frequent infectious bites. Targeting symptomatic individuals alone is unlikely to achieve large declines in transmission rates or a reduction in overall malaria incidence and prevalence (WHO, 2010). In low transmission areas, symptomatic patients account for the majority of the infectious reservoir, and declines in transmission rates are proportional to a decline in malaria incidence and prevalence. Clearly, drug strategies to reduce malaria prevalence will be effective in high transmission areas only if used in combination with other effective interventions targeting the vector. Drug strategies increase in importance for overall malaria control only as transmission intensity declines, the majority of patients become symptomatic, and programs adapt to target remaining parasite reservoirs—finding and treating asymptomatic individuals (Sturrock, et al., 2013).

Limitations of LLINs and IRS

As described earlier, LLINs and IRS—despite their effectiveness when scaled up sufficiently—have drawbacks with respect to the breadth and longevity of the protection they offer, and carry the risk of emerging longer-term operational insecticide resistance. Managing resistance is particularly challenging when an intervention is dependent on a single chemical class as in the case of LLINs. Even in the case of IRS, which relies on 4 currently available insecticide classes (resistance has been reported to all 4 of these in some populations of Anopheles gambiae), managing resistance and providing sustainable vector control with existing chemicals is unlikely (Ranson, et al., 2011). In addition, there are significant portions of
affected populations in remote areas, which are proving difficult to reach with these tools. New classes of insecticides and delivery tools are urgently needed to maintain the gains achieved over recent years.

Large-scale programs to control or eliminate malaria require heavy, sustained public investment and coordination.

Gains against malaria have historically relied on scale-up of successful interventions, and these gains have proven to be highly fragile. This is particularly true in high transmission settings, which have large asymptomatic reservoirs of infection (Stresman, et al., 2010). Although malaria transmission can be dramatically reduced with effective control strategies, resurgence is inevitable in the absence of sustained interventions. The common denominator among instances of malaria resurgence has been the weakening of malaria control programs due to reduced funding (Cohen, et al., 2012). The economic sustainability of interventions is, therefore, critical to maintaining any gains achieved in mortality reduction.
Global malaria efforts have necessarily had a dual focus, control in highly endemic regions, and elimination on the margins. The widely accepted malaria eradication strategy is two-pronged: it relies on aggressive control strategies to reduce transmission intensity and mortality in high-burden countries, and on progressive elimination of malaria from the endemic margins, to shrink the malaria map (Feachem, et al., 2010). To achieve dramatic results, the dual aims of control and elimination are being considered in parallel. Short-term interventions—no matter how successful in reducing mortality—will inevitably fail to control malaria in the long run, due to the inevitability of malaria resurgence (Feachem, et al., 2010) and the possibility of cross-border transmission. Regional elimination is a long way from being a reality in much of sub-Saharan Africa, and malaria eradication will likely take several decades.

It should be recognized that as sustainable malaria control is achieved and malaria transmission intensity is reduced in highly endemic countries, the character of malaria in these countries may change. In the long-term, if *P. falciparum* incidence is controlled, the relative proportion of *P. vivax* may increase, along with the proportion of malaria affecting adult men. New challenges will require dramatically different strategies and technologies, in order to:

- Move towards elimination by targeting *P. vivax*, including addressing new populations of affected individuals.
- Identify and address remaining (asymptomatic) reservoirs of malaria parasites.
- Manage emerging parasite species, in particular, the simian malaria species *P. knowlesi*, which has been infecting humans in Southeast Asia.
- Control cross-border malaria transmission to sustain regional elimination.
- Sustain funding (e.g., for surveillance and response), through elimination.
- Better identify and monitor mosquito species in the field.

In the meantime, there continue to be large numbers of malaria-related fatalities, especially among children in African countries. As described above, the investment required to maintain and scale-up current interventions is unlikely to be sustainable in the long-term. The limitations of current interventions need to be addressed with new solutions targeted for high-burden countries and populations. As such, this analysis focuses on identifying technologies with the highest potential to reduce malaria mortality in high transmission settings, while recognizing that these may need to evolve over time as malaria transmission rates decline in high-burden countries.

### Development of an improved anti-infective vaccine specifically for *P. falciparum*

Given the difficulty in controlling *Anopheles* mosquitoes, it is clear that children will continue to be bitten and infected. Therefore, providing artificial protective immunity in the form of an anti-infective vaccine specifically for the *P. falciparum* parasite represents a significant breakthrough in the area of malaria control.

Vaccines, in general, have a very long development lead-time; vaccines for malaria have proven particularly elusive. As noted previously, there are a number of complexities which increase the difficulty of developing a malaria vaccine that offers immunological protection. These include antigenic switching by the parasite under selective immune pressures to evade the immune system, the complex lifecycle and intracellular nature of the parasite, and the lack of natural long-lasting immunity in humans against malaria.

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12 WHO defines Malaria elimination as “a reduction to zero of the incidence of infection caused by human malaria parasites in a defined geographical area as a result of deliberate efforts.” Malaria control is defined as “reducing malaria morbidity and mortality to a locally acceptable level through deliberate efforts using the preventive and curative tools available today.”
the parasite. Consequently, mimicking the antigen to produce a protective but artificial immune response has proven extremely difficult. To account for the differential expression of antigens across the parasite lifecycle and to deepen understanding of effective or ineffective immune responses, a range of approaches to vaccine development are underway. However, to date, only one has reached Phase III trials, with limited effectiveness. Given the current lack of a vaccine developmental candidate and the historical lack of success, experts believe it is 20 years or more away.

A different approach currently being explored is the development of transmission-blocking vaccines. These would reduce the number of blood stage parasites, and specifically limit the presence and expansion of the infectious gametocyte form of the parasite in the mosquito, thus blocking ongoing transmission. Such vaccines will not offer protection to the immunized individual, but will prevent the individual from passing parasites onto others, which represents an important breakthrough for dramatically lowering malaria transmission rates.

If a malaria vaccine is developed, it can be deployed through existing, reasonably established, vaccine delivery channels. However, even today vaccine delivery remains a challenge in many remote locations where supporting infrastructure like cold storage facilities are either few or non-existent. While the vaccine is expected to be made available to patients at a low cost, financing for the vaccine by national governments or international donors would need to be secured in order to support widespread distribution. Policy changes would also need to support its introduction and distribution through public health systems. If any ultimately successful vaccine is transmission-blocking, adoption by individuals is uncertain, given that the immunized individual will not be offered protection from the vaccine. Based on the above assessment, we believe that the projected time to market readiness is 20 years, and the level of difficulty for deployment is FEASIBLE.
A single dose, complete cure for malaria

Effective treatments for malaria exist. The majority of safe medications for malaria target the blood stage of the parasite, but not stages of the parasite lifecycle such as the *gametocyte* stage. The persistence of the *gametocytes* following treatment creates a human reservoir of parasites, which remain viable for years in an otherwise asymptomatic and healthy person. While this does not cause disease directly, it does pose challenges for malaria control and elimination. As such, a single dose, complete cure to eliminate all malaria parasites in the human body—both blood stage and liver stage, and both sexual and asexual—represents a significant breakthrough in malaria control.

There is a fairly well developed pipeline for improved antimalarial treatments, including drugs that are targeting other stages of the parasite lifecycle. Experts believe that the time to market readiness for a single-dose cure, or fixed dose combination cure, is 4-6 years.

Once available, the drug will need to be approved by the WHO and incorporated into international and national level malaria treatment guidelines. As many of those who will require treatment are asymptomatic, the drug will likely need to be introduced in combination with a highly sensitive rapid diagnostic test that can help identify these asymptomatic individuals. Finally, sustained funding for these interventions will need to be secured. Based on the above assessment the difficulty of deployment is FEASIBLE.
Biological modification of mosquitoes

Biological modification of mosquitoes to control malaria could be achieved through genetic modification. Such modification can render mosquitoes incapable of carrying the falciparum parasite, can prevent the parasite from developing in the mosquito gut, or can be used to sterilize males to reduce reproduction, thereby reducing the total mosquito population.

The idea of genetically modifying mosquitoes to create a breed that is *P. falciparum*-resistant, and has a longer life span, has gained traction in recent years. The general idea is that these ‘stronger’ mosquitoes, released into the wild, will ultimately replace the mosquitoes which today carry *P. falciparum*. Some experiments, however, have shown that such genetic modification can carry a fitness cost (e.g., reduce mosquito strength and viability over generations). Other studies have successfully demonstrated that genetically modified mosquitoes can live longer and lay more eggs than their malaria-infected counterparts, thereby replacing non-modified mosquitoes over several generations. However, all such experiments to date have been small, and no large-scale experiment has yet been conducted (Imperial College, 2013) (Bian, et al., 2013). A key challenge with implementing such a strategy is the fact that multiple vector systems (sympatric populations and sibling species) exist in a single geography, which is a challenge to the sustainability of genetic engineering strategies. Clearly, the unintended consequences of such an intervention also need to be carefully considered before such experiments or interventions are taken to scale. Critical concerns include the impact on other animal populations, the risk that the mosquito population could develop in unpredictable ways, and the risk that the parasite will simply adapt to the new genetic makeup of the modified—and now, stronger and longer-living—mosquito. Ethical concerns and political willingness to implement such an intervention are also factors that may limit the potential of such an approach.

Another related approach is the release of sterilized male mosquitoes to reduce the mosquito population, typically achieved through irradiation. This technique was pioneered in the 1950s and has been implemented successfully to eradicate the screw-worm fly (*cochliomyia hominivorax*), in areas of North America, and to control some species of fruit flies. It has been implemented in the African context to eradicate the tsetse fly from Zanzibar in order to control human African trypanosomiasis (African sleeping sickness), and is being explored for its applicability to *Aedes* mosquito vectors responsible for spreading diseases like dengue and chikungunya (Rodriguez, et al., 2013). As with genetic modification, applying this approach to *Anopheles* mosquito vectors poses several challenges. In the past, successful sterile releases have been done with insects that have a much lower reproductive rate than mosquitoes (and are therefore likely to have a higher impact). Further, radiation is not a highly specific technique—it can unintentionally mutate multiple genes. Therefore, radiation could in fact carry a fitness cost to mosquitoes, such that sterilized insects are actually at a disadvantage when competing for females.

Genetic modification is a highly complex and controversial approach. Given the multiple vector systems existent in Africa, such species-specific approaches pose significant scientific challenges. As things stand, even the core science of breeding dominant *P. falciparum*-free or sterile mosquitoes is not resolved. By the time these issues are resolved and adequate tests are conducted, especially to understand longer term impacts, it will likely take more than 10 years.

Once available, there are significant policy decisions that need to be resolved before such a controversial technology is unleashed into natural mosquito habitats. Moreover, issues of financing for such large-scale engineering and release of modified mosquitoes must also be addressed. Based on the above assessment, the projected time to market readiness is 20 years, and the level of difficulty for deployment is EXTREMELY CHALLENGING.
New long-lasting non-chemical spatial mosquito repellents or attractants

High coverage of spatial repellents can enhance the impact of existing interventions such as LLINs and IRS, particularly in areas where mosquitos are biting individuals outdoors. Non-chemical repellents or attractants also have the potential to overcome the challenge of insecticide resistance.\(^\text{14}\)

Non-chemical spatial repellents (e.g., based on sound) exist in the market, but have not proven effective, particularly at the community-level. It is unclear whether these products are based on rigorous science. Effective spatial repellents can be difficult to design, and their benefits to individual households need to be considered in the context of benefits to the community (Achee, et al., 2012). In particular, a repellent that is very effective in a household setting may simply drive the mosquitoes to other areas and households which do not have an equally effective repellent, potentially intensifying malaria in less protected, likely poorer, areas. Therefore, such repellents should ideally be used through a ‘push-pull’ mechanism (Takken, 2010), which would ‘push’ mosquitos away from at-risk households, and ‘pull’ them towards an area where they can easily be destroyed. Alternatively, attractants can offer the potential to easily ‘lure and kill’ mosquitos. Methods to do so by exploiting mosquito mating behaviors (e.g. pheromones, wing beat frequency), and sensory sensitivities (odors) are being explored.

Any new breakthrough repellents or attractants must not need frequent replenishment and be designed as an energy efficient and long-lasting device (possibly powered by ambient light), that targets the mosquito’s sensory sensitivities. Ideally such a device would be able to run uninterrupted for several months. The technology will have to be very low cost and incorporated into something that individuals already use or can easily adopt (e.g., a light-bulb that also acts as a repellent). These new repellents should be optimized for the most lethal African vectors—*Anopheles gambiae*, *Anopheles arabiensis* and *Anopheles funestus*—but will ideally be effective across all primary and secondary vector species.

\(^{14}\)Even non-chemical repellents are not certain to overcome the challenges of resistance; some crawling insects treated with diatomaceous earth have managed to develop resistance to by thickening their cuticle—others have even developed resistance to their own hormones.
As the sensory sensitivities of mosquitoes are better understood, developing repellent and attractant technologies (e.g., based on sound or other senses) can be more easily developed. However, to be effective, the use of spatial repellents will need to be considered in the broader context of the community, and not just the individual household. This will likely require some form of governmental coordination. Community-level protection will need to be demonstrated, and this will require significant investment in operational research. Furthermore, optimum usage may require some training (depending on the nature of the repellent), and adherence to appropriate protocol. Importantly, these non-chemical repellents should be designed such that they do not require frequent replenishment or investment in supply chain infrastructure. Based on the above assessment, the projected time to market readiness is 7-10 years, and the difficulty of deployment is CHALLENGING.

Breakthrough 4 – Difficulty of deployment

- **Extremely Challenging**
  - Low role of policy / regulation
  - Requires high level of training for large numbers of people
  - Major behavior change required, potentially on daily basis
  - Low demand, needs to be built
  - Fragmented market, weak distribution channels

- **Challenging**
  - Limited financing required
  - Low demand, needs to be built
  - Clear deployment models existing at scale

- **Complex**

- **Feasible**

- **Simple**
New long-lasting chemical mosquito repellents delivered in novel ways

It is unlikely that existing chemicals will provide sustained control while limiting the development of resistance. New classes of long-lasting chemical repellents are required, and need to be delivered through novel mechanisms that are easy to use and adopt. Delivery strategies must provide community-level protection, and should ideally be optimized for *Anopheles gambiae* and *Anopheles funestus* but be effective across all *Anopheles* species.

Research is already progressing in this field and some existing chemicals (e.g., transfluthrin) are showing promise. Recent efforts aimed at providing individual-level protection include transfluthrin-treated strips (Ogoma, et al., 2012), and the under-development Kite Patch™ that relies on chemicals to disrupt a mosquito’s carbon dioxide receptors. However, these devices have not yet been sufficiently field-tested and their potential for long-term spatial efficacy has not been demonstrated.

Novel and long-lasting delivery mechanisms and strategies will be needed to enable community-level protection (e.g., through sufficient scale-up or by luring mosquitos away from human targets and into insect traps). Similar to the spatial repellents described previously, deployment of the technology will likely require some form of governmental coordination, significant investment in operational research, and training on usage (depending on the nature of the repellent). Based on the above assessment, the projected time to market readiness is 5-7 years, and the difficulty of deployment is COMPLEX.

**Breakthrough 5 – Difficulty of deployment**

- **Simple**
  - Policies
  - Infrastructure
  - Human capital
  - Access to user finance
  - Behavior change
  - Existing demand
  - Market fragmentation/Distribution channels
  - Business model innovation
  - Regulated market with supportive policies
  - Requires high level of training for large numbers of people
  - Moderate behavior change required with evidence of behavior change being viable
  - Moderate fragmentation of customers, under-developed channels
  - Clear deployment models existing at scale

- **Feasible**
  - Moderate financing needed, viable mechanisms available
  - Moderate demand

- **Challenging**
  - Moderate behavior change required with evidence of behavior change being viable

- **Extremely Challenging**
  - Requires high level of training for large numbers of people
Maternal and neonatal mortality are caused by multiple independent medical conditions, which result in 287,000 and 3.1 million deaths, respectively, every year. The vast majority of these deaths occur in developing countries.

Maternal mortality is caused by 6 major conditions—hemorrhage, hypertensive disorders, unsafe abortion, sepsis, indirect causes and other direct causes. Hemorrhage and hypertensive disorders are the largest causes of mortality, accounting for 35% and 18% of mortality respectively. Neonatal mortality is caused by 3 main conditions, preterm birth complications, infections, and birth asphyxia, which represent 35%, 24%, and 23% of mortality respectively. Underlying all of these conditions are 3 broad challenges—most births take place at home without skilled birth attendants, most mothers do not receive sufficient antenatal care, and many mothers are malnourished. Most of these medical conditions can be treated effectively with a skilled birth attendant and proper equipment, but given the wide range of potential conditions, interventions to address specific conditions are limited in overall impact.

Interventions need to be targeted at bringing adequate care and treatment to mothers, and their infants, in an integrated, rather than condition specific manner. In light of the above challenges, 1 technological breakthrough can help reduce maternal and neonatal mortality in developing countries.

A suite of integrated, low cost, off-grid medical devices for maternal and neonatal health, including an ultrasound, sterilizer, medical refrigerator, appropriate diagnostics, phototherapy, and devices to care for preterm infants. Integration likely needs to include power management, patient data/history, and communication.
Maternal and neonatal health have been an important global health priority. As the following discussion shows, the specific conditions and root causes of mortality and morbidity are structural, and there are no ‘silver bullets’ that can make a substantial difference by themselves.

**CORE FACTS AND ANALYSIS**

Each year, maternal and neonatal medical conditions cause 287,000 (WHO-UNICEF, 2012) and 3.1 million deaths respectively (Liu, et al., 2012), the vast majority of which—99% in the case of maternal deaths—occur in developing countries. The Global Burden of Disease study estimated that neonatal conditions are the largest cause of disease burden in developing countries and maternal health is the 21st highest cause of disease burden; although this seemingly lower rank does not reflect the large impact of maternal mortality on the infant or the family (IHME, 2012).

Most births in developing countries take place at home, administered by untrained health workers

More than half the childbirths in developing countries take place at home, with the assistance of traditional birth attendants, who, unlike skilled birth attendants, have limited or no formal training. This frequency of home birth is particularly high for the poor in these countries (Exhibit 1). A 2011 study found that in sub-Saharan Africa and South Asia, 74% and 84% of women in the bottom two quintiles gave birth at home, compared with 21-22% in the top quintile (Montagu, et al., 2011). That said, there is an increasing trend towards more facility births. Some countries, like India, have seen dramatic changes within a few years after the government started providing cash incentives to women opting for facility births.

**Location of birth by income quintile**

**sub-Saharan Africa**

<table>
<thead>
<tr>
<th>Income Quintile</th>
<th>Private / Religious facility</th>
<th>Public facility</th>
<th>Home</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poorest</td>
<td>18%</td>
<td>7%</td>
<td>78%</td>
</tr>
<tr>
<td>Poorer</td>
<td>23%</td>
<td>10%</td>
<td>60%</td>
</tr>
<tr>
<td>Middle</td>
<td>43%</td>
<td>31%</td>
<td>42%</td>
</tr>
<tr>
<td>Richer</td>
<td>22%</td>
<td>43%</td>
<td>54%</td>
</tr>
<tr>
<td>Richest</td>
<td>5%</td>
<td>42%</td>
<td>54%</td>
</tr>
</tbody>
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Private / Religious facility | Public facility | Home
Exhibit 1: Births in lower income populations take place overwhelmingly at home (Montagu, et al., 2011).

Expectant mothers do not receive antenatal care and are often malnourished

Across the largest countries in sub-Saharan Africa and South Asia, 71% of women receive at least 1 antenatal care visit, but only 37% receive the WHO recommended 4+ antenatal visits (UNICEF, 2012). This figure is higher in Countdown to 2015 priority countries, but even among this group, only 55% of women in the median country receive 4+ visits (Exhibit 2). This indicates critical missed opportunities to identify risk factors, provide treatment for basic conditions, provide nutritional supplements, and educate mothers on what they can do to improve their own health and the health of their children (WHO-UNICEF, 2012).

Rates of malnutrition amongst women in developing countries are high. It is estimated that nearly half of pregnant women in developing countries have anemia (WHO, 2012), and a significant number are stunted or undernourished, which can lead to delivery complications and preterm births.

Antenatal care in the 10 largest countries in South Asia and sub-Saharan Africa

Exhibit 2: Roughly 70% of mothers receive at least 1 antenatal care visit. Only 37% receive the WHO recommended 4+ antenatal care visits (UNICEF, 2012). ¹

Maternal mortality is driven by multiple conditions

Maternal mortality and morbidity is driven by fewer than 10 medical conditions (Exhibit 3). While maternal mortality has many underlying causes, approximately half of the 287,000 maternal deaths are caused by post-partum hemorrhage (PPH) and hypertensive disorders of pregnancy. Other conditions which cause maternal mortality in developing countries are unsafe abortion (9%), sepsis (8%), and indirect causes such as HIV and malaria (18%) (WHO-UNICEF, 2012).

Importantly, each of these causes of maternal mortality have different clinical needs. The underlying causes and treatment needs of the 2 leading clinical conditions of maternal mortality are listed below.

### Conditions leading to maternal mortality

- **Post-partum hemorrhage**: Characterized by excessive blood loss following childbirth, post-partum hemorrhage is the largest cause of maternal mortality, accounting for 35% of all maternal deaths. The primary cause of PPH is uterine atony, which occurs when the uterus does not contract and help stop post-partum bleeding. PPH can also be caused by abruption, retained placental tissue, coagulation abnormalities, and other factors.

  - The WHO recommended approach to prevention of PPH is Active Management of the Third Stage of Labor (AMTSL), which includes the administration of an uterotonic that makes the uterus contract. The WHO recommends Oxytocin as the first line uterotonic, but using it at many low resource facilities is problematic since it must be kept refrigerated. Other thermostable uterotonic like Misoprostol are possible alternatives. However, due to its use in abortions, Misoprostol is heavily regulated or banned in several countries. Adequate community-level care, training birth attendants to administer AMTSL and sufficient distribution of uterotonic are additional challenges to reducing PPH. It is important to note that uterotonic work in less than half of PPH cases, indicating a need for secondary treatments like balloon tamponades, anti-shock garments and hemostatic agents.

### Exhibit 3: There is no single cause of maternal mortality. It is caused by several different clinical conditions, of which post-partum hemorrhage (PPH) and hypertensive diseases are the largest. However, even these causes of mortality are caused by a broad range of underlying conditions and influenced by numerous risk factors (WHO-UNICEF, 2012).
Hypertensive disorders of pregnancy

Hypertensive disorders of pregnancy constitute the 2nd leading cause of maternal mortality—18% of deaths—and are a range of complications linked to high blood pressure. The major hypertensive conditions are preeclampsia, when a pregnant woman develops high blood pressure and protein in the urine after the 20th week of pregnancy, and eclampsia, which is characterized by seizures.

The placenta is a highly vascularized organ, and while it is believed that issues in the formation of blood vessels in the placenta are what lead to hypertensive diseases of pregnancy, the specific mechanisms are poorly understood. The prevalence of hypertensive diseases in pregnancy is no different in developing countries compared to developed countries, and there is no definitive treatment even in developed countries, except inducing early birth. If diagnosed early, the mother can be prescribed hypertensive medications, and the WHO has recommended prevention through calcium (where calcium intake is low), and/or aspirin supplements. However, traditional birth attendants in developing countries do not have the training or equipment to detect hypertensive diseases, administer appropriate medicines, or induce early birth.

Three conditions are responsible for 82% of neonatal mortality

The health of newborns is affected by many of the same underlying factors that influence maternal health—malnutrition in expectant mothers, the lack skilled birth attendants with appropriate equipment, and the lack of antenatal care.

As a category, neonatal conditions are the single largest cause of disease burden in developing countries, responsible for 202 million DALYs (IHME, 2012) and 3.1 million global deaths each year (Liu, et al., 2012). Three conditions—preterm birth complications, birth asphyxia and infection—are responsible for 82% of neonatal mortality (Liu, et al., 2012) (Exhibit 4).

Three major conditions impact neonatal health

Exhibit 4: Preterm births, infections (pneumonia, sepsis, and meningitis), and birth asphyxia cause 82% of all neonatal deaths (Liu, et al., 2012).

\(^1\) Liu, et al., report “intrapartum-related complications” and note “intrapartum-related complications were formerly referred to as birth asphyxia.”
Preterm birth complications

Births are considered preterm when the infant has completed fewer than 37 weeks of gestation. Each year, preterm birth complications cause 1.1 million infant deaths. Preterm infants are vulnerable to an array of conditions including respiratory distress, difficulty feeding orally, hypothermia, and infection (most commonly sepsis and pneumonia), among others. The frequency and severity of complications increase as the duration of gestation decreases (Exhibit 5). Infants born very preterm (28-32 weeks of gestation), are particularly prone to respiratory distress syndrome, which is characterized by under-developed lungs that lack surfactant—a lipoprotein complex that helps lungs expand and contract. The weight of the infant at birth is another important indicator. Even infants who are born at or near full-term can be low birthweight and require special care.

The causes of premature birth are not well understood, even in developed countries. It is believed to be associated with multiple pregnancies, infections, chronic conditions such as diabetes and high blood pressure, and genetic factors (WHO, 2012). Though it is best to prevent preterm birth, this is difficult given the limited understanding of risk factors and the lack of antenatal care in developing countries. Since preterm birth is difficult to predict or prevent, it is more effective to focus on treating the complications at each level of prematurity.

Exhibit 5: Infants born before 37 weeks experience an array of complications which require specialized care (WHO, 2012).
Infections

Major infections including pneumonia, sepsis and meningitis, are the 2nd leading cause of neonatal mortality, responsible for 718,000 deaths annually (Liu, et al., 2012). These major infections are often considered separately from tetanus and diarrhea, which cause another 58,000 and 50,000 deaths respectively, as they often have very different transmission pathways. Pneumonia, sepsis and meningitis are classified as early onset or late onset, depending on when the symptoms occur. Early and late onset infections are often contracted through different pathways.

The leading cause of neonatal infection is exposure to bacteria immediately before or during delivery. This occurs primarily when bacteria ascend from the birth canal during prolonged rupture of membranes and are aspirated by the infant. Infants can also be exposed to pathogens during birth due to unhygienic delivery practices such as use of dirty equipment, unwashed hands during delivery, and improper cord care. Symptoms of early onset infection occur within 7 days of birth. In late onset sepsis and pneumonia, symptoms occur 8-30 days after birth and can arise from community acquired infection or from bacteria contracted during birth.

Birth asphyxia

Birth asphyxia is defined as the inability to establish breathing at birth and is referred to in some studies as intrapartum-related events or complications or neonatal encephalopathy. Birth asphyxia is responsible for 717,000 deaths (Liu, et al., 2012) and an estimated 1.2 million stillbirths (Joy E, et al., 2011).

During birth, blood flow to the placenta is disrupted by contractions, which does not present a problem when the mother and fetus are healthy and labor progresses normally. Various conditions such as severe anemia and prolonged labor can exacerbate this disruption of blood and oxygen flow, however, leading to insufficient oxygen reaching the fetus and causing brain damage and death. Intrapartum complications are often addressable but require access to skilled care and equipment. Specifically, when a fetus is deemed to be in danger of intrapartum asphyxia due to prolonged labor or another cause, asphyxia can usually be prevented through emergency cesarean section. This is often not an option in many developing countries due to lack of obstetric skills and equipment.

Newborns sometimes also need assistance in establishing breathing immediately after birth. It is estimated that 10% of newborns require some form of assistance in initiating breathing (Healthy Newborn Network, 2014), usually through simple resuscitation devices like self-inflating bags and masks or suction devices, to remove amniotic fluid that may be in the newborn’s airway. These devices are inexpensive, but coverage is low and they require training to be properly used.
KEY CHALLENGES

The challenges in maternal and neonatal health are systemic: there are too few adequately equipped clinics, too few adequately trained clinicians, and little regulation. Beyond the challenges of access to basic health services, it is important to note that there are also significant cultural barriers in many communities, which compel women to rely exclusively on informal, at-home care. As a result, even when adequate clinics exist, the demand for them isn’t necessarily guaranteed. This broad lack of access to basic care leads to a number of essential issues.

1. **The majority of births in developing countries still take place at home**, administered by poorly trained and poorly equipped traditional birth attendants. There is a widespread lack of skilled birth attendants.

2. **Although facility birth rates are increasing, access and quality remains a concern.** In low resource settings, even where facilities are available, they tend to be overburdened and poorly equipped, lacking reliable electricity, lighting, necessary equipment, and access to clean water and sanitation.

3. **Mothers do not receive adequate antenatal care.** Only 55% of mothers in developing countries receive the WHO recommended 4+ antenatal care visits, and this number is even lower in large countries in sub-Saharan Africa and South Asia.

4. **Poor maternal nutrition and anemia during pregnancy make both mother and child more vulnerable to complications.** Poor nutrition prior to the pregnancy itself can also affect maternal and neonatal health. Stunting in girls, occurring as early as the first 2 years of life, for example, increases the risk of preterm delivery and PPH later in life.
SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

Maternal and neonatal mortality and morbidity is driven by fewer than 10 conditions, the majority of which are treatable by a skilled clinician with appropriate equipment. Currently, there is a shortage of both. Medical equipment in particular needs significant technological innovation and cost reduction to reach low income populations, especially in rural areas.

A suite of integrated, low cost, off-grid medical devices for maternal and neonatal health

While a number of reduced cost devices have been released over the past several years, and new devices continue to enter the market, broad deployment of these devices has not been achieved due to the reasons listed below.

Affordability
Even though these newer devices are a fraction of the cost of models that are used in developed countries, costs for many devices remain high and unaffordable for developing countries. For example, recently released low cost ultrasound machines still cost several thousand dollars.

Power consumption
In many cases, energy needs are optimized at the device level, as opposed to facility level. This means that even when fully equipped, a low resource facility in an area with little access to reliable electricity is often not able to utilize multiple devices that have individual power needs or that they must overspend on solar power equipment.

Limited supplier distribution
Many companies distributing low cost medical devices have not established large distribution channels and there is significant fragmentation, with many new entrants in the low cost medical device segment offering only 1 or 2 devices. This forces facilities and governments to source both devices and services from multiple vendors, adding to overall costs and complexity.

In particular, standardization of medical devices to a single, off-grid energy platform will help promote the introduction of new devices for facilities. Even more beneficial would be the integration of devices, which utilize the same energy platform, information communication technology (ICT) infrastructure, and could be procured and serviced by single suppliers (as opposed to a different supplier for each device). The ideal low cost and off-grid devices required to fully equip facilities to provide basic antenatal care, basic emergency obstetric care, and intensive care for neonates, are:

> Diagnostic devices for relevant maternal medical conditions including malnutrition, anemia, malaria, HIV, syphilis and hypertensive disorders.
> Sterilization devices for equipment.
> Ultrasound devices.
> Medical lighting.
> Neonatal intensive care devices including CPAP (continuous positive airway pressure) or ventilator devices, provision of warmth if Kangaroo mother care is not possible, and phototherapy.
> Refrigeration, particularly to store Oxytocin or other thermosensitive pharmaceuticals.
> Small ICT/mobile devices for tracking patient data and coordinating antenatal care.
Even if the devices are successfully developed for at-scale distribution, broad deployment will depend on other important factors like financing, training, infrastructure, and service models for maintenance. The projected time to market readiness is 2-6 years, and the difficulty of deployment is CHALLENGING.

Breakthrough 1 – Difficulty of deployment

Breakthrough 1 – Difficulty of deployment

Even if the devices are successfully developed for at-scale distribution, broad deployment will depend on other important factors like financing, training, infrastructure, and service models for maintenance. The projected time to market readiness is 2-6 years, and the difficulty of deployment is CHALLENGING.
Pneumonia is an infection of the lungs and is the leading cause of mortality in children under 5, causing an estimated 1.2 million childhood deaths each year. Most mortality from pneumonia is caused by 2 bacteria, pneumococcus and Hib, which are extremely common. Pneumococcus, in particular, is frequently found in the nose and throats of otherwise healthy children in developing countries. As a result of the ubiquity of these bacteria, risk factors that make children more susceptible to infection are critical drivers of pneumonia. Smoke inhalation, particularly from biomass, is believed to underlie 50% of pneumonia deaths. If identified early, antibiotics are an effective treatment, although only 1 in 5 caretakers in developing countries recognize the key warning signs of pneumonia—a major impediment to adequate care. Once infections are advanced, antibiotic therapy is less effective and oxygen therapy becomes necessary but is rarely available. Vaccines for both Hib and pneumococcus exist and are being rolled out globally. The pneumococcus vaccine, in particular, is expensive and provides protection only against a limited number of strains. In light of the above challenges, 3 technological breakthroughs can help reduce the disease burden from childhood pneumonia in developing countries.

- Low cost, off-grid oxygen concentrators
- An improved, lower cost vaccine for pneumococcus
- Low cost, novel diagnostics
Pneumonia, an infection of the lungs, is the leading cause of mortality in children under 5, globally. An estimated 1.2 million children die from pneumonia each year (Liu, et al., 2011), with the vast majority of these deaths occurring in developing countries.

**CORE FACTS AND ANALYSIS**

Pneumonia is part of the broader category of lower respiratory infections (LRIs), which can also occur in the trachea and bronchi. Upper respiratory infections (URIs) such as the common cold, occur in the nose, pharynx and larynx. LRIs are far more severe than URIs and are responsible for nearly all disease burden that results from respiratory infections in developing countries.

Children under 5 are most affected by LRIs (Exhibit 1). The Global Burden of Disease 2010 study estimates that 71% of disease burden from LRIs in developing countries occurs in children, with 51% occurring in children less than a year old (IHME, 2012). LRIs re-emerge as a major cause of mortality later in life, particularly for the elderly, but its impact on overall disease burden is low due to the reduced number of life years lost from mortality occurring later in life.

<table>
<thead>
<tr>
<th>Age Group</th>
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<tbody>
<tr>
<td>0-6 days</td>
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<tr>
<td>7-27 days</td>
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<td>28-364 days</td>
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<td>75-79 years</td>
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**Exhibit 1:** Disability adjusted life years (DALYs) for LRIs in South Asia and sub-Saharan Africa are highly concentrated in children under 5 (IHME, 2012).

Pneumonia is caused primarily by bacteria and viruses, with bacterial infections causing most severe cases, and viruses causing most non-severe cases. Often, pneumonia begins after an upper respiratory tract infection, with symptoms of pneumonia manifesting after 2 or 3 days of a cold or sore throat. The most common bacterial pathogens causing severe pneumonia in developing countries are *Streptococcus pneumoniae* (pneumococcus) and *Haemophilus influenza* type B (Hib). The WHO and UNICEF estimate that pneumococcus may be the cause for more than half of severe cases of pneumonia and Hib could be responsible for 20% of the severe cases (WHO-UNICEF, 2006). It is estimated that as of 2000, pneumococcus and Hib were responsible for 41% and 16% of pneumonia deaths, respectively, in

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1 Hib is a bacterial infection and is distinct from the family of viruses that cause influenza.
children (Izadnegahdar, et al., 2013). The same study also noted, however, that vaccine studies indicate the importance of pneumococcus may be much larger. One vaccine study in The Gambia, for example, noted that vaccination against pneumococcus led to a 16% reduction in all cause mortality (i.e. a 16% reduction in all childhood mortality, not just from pneumonia). The next most important pathogen is respiratory syncytial virus (RSV), which is an extremely common cause of pneumonia but generally causes less severe infections.

Prevalence of specific pathogens varies across regions, as do strains (more technically, serotypes) of pneumonia, but pneumococcus and Hib are considered to be the major drivers of mortality. The rollout of vaccines for these 2 bacteria will lead to the etiology of pneumonia shifting in coming years, likely toward more viral causes or toward non-vaccine strains. Worldwide, only 15 developing countries account for three-quarters of childhood pneumonia cases, with the highest incidence concentrated in South Asia and sub-Saharan Africa (Exhibit 2).

**Cases of childhood pneumonia across countries**

*Exhibit 2:* Just 15 countries account for roughly three-quarters of childhood pneumonia cases (WHO-UNICEF 2006).
KEY CHALLENGES

The burden of pneumonia is driven primarily by the ubiquity of the infecting pathogens and risk factors that increase susceptibility, especially among children, to these pathogens. Once children are infected, low awareness of the disease and its symptoms by caretakers and limited access to treatment are critical drivers of mortality. Vaccination efforts against the 2 most important pneumonia causing bacteria will markedly reduce disease burden in the coming years.

Many children are already carriers of pathogens which can cause pneumonia

The pathogens that cause pneumonia are highly contagious, and very prevalent in the population. Pneumococci and Hib in particular colonize the nose and throat, where they reside harmlessly until the bacteria have an opportunity to penetrate the body’s defense system and travel into the lungs, blood, or cerebrospinal fluid. This is often spurred by another infection, usually URIs, or inflammation of the lungs from smoke inhalation. Poor populations in sub-Saharan Africa and South Asia often live in crowded and poorly ventilated conditions, which facilitates the spread of bacteria. Newborns can also become infected by exposure to microbes in the birth canal during delivery. The ubiquity of these pathogens is evident in the fact that children develop pneumonia very frequently. In the developing world, a child will develop an average of 0.29 episodes of pneumonia per year, compared with 0.03 episodes per child per year in developed countries (WHO-UNICEF, 2006).

Several risk factors increase vulnerability of children to respiratory infections and worsen health outcomes

Smoke and household pollution
Atmospheric pollution, household pollution, and tobacco smoke cause inflammation of the lungs, which increases susceptibility to infections. The Global Burden of Disease study estimates that more than 50% of childhood pneumonia burden can be attributed to indoor air pollution from solid fuels (IHME, 2012). In developing countries, 52% of the population relies on biomass fuels for cooking (IEA, 2006), which are burned indoors without chimneys or adequate ventilation, causing high levels of particulate matter inside homes. Smoking is also highly correlated with increased rates of pneumonia. Incidence rates for pneumococcus are 1.9-4.1 times higher for active smokers and 1.9 times higher for children of smokers relative to non-smokers (van Zyl-Smit, et al., 2011).

Suboptimal breastfeeding
Breast milk provides infants with antibodies that help protect them until their immune systems develop more fully. The WHO recommends exclusively breastfeeding infants for the first 6 months of life, and partial breastfeeding for the following 18 months accompanied with age appropriate foods. Infants who are not breastfed in the first 6 months are 6 times more likely to die from pneumonia as children who are even partially breastfed (Black, et al., 2013) (Exhibit 3). Suboptimal breastfeeding contributes to 44% of all neonatal LRI-related deaths and in 18% of LRI-related deaths in children under 5 (World Lung Foundation, 2010). Globally, less than 40% of infants are exclusively breastfed (WHO, 2013).

HIV
Children with HIV, due to increased susceptibility to pathogens, are 40-50 times more likely to contract pneumonia, and 3-6 times more likely to die of the disease (World Lung Foundation, 2010). In sub-Saharan Africa alone 2.9 million children are living with HIV.2

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2 UNAIDS defines children as under 15 years, while most global health studies and this analysis consider childhood mortality as mortality in children under 5.
Malnutrition
Malnutrition weakens a child’s still-developing immune system, making him more vulnerable to pneumonia (Caulfield, et al., 2004). Childhood underweight is estimated to be a factor in as many as a quarter of childhood deaths from LRIs in developing countries (World Lung Foundation, 2010).

Sickle cell disease
Sickle cell disease is associated with increases in bacterial infections. Patients with pneumococcus and Hib were found to be 36 and 13 times more likely to have sickle cell disease respectively (Ramakrishnan, et al., 2010). Sickle cell disease is particularly common in areas of Africa where *P. falciparum* Malaria is endemic. It is estimated that in some countries such as Nigeria and Gabon, 25% of the adult populations are a carrier of the sickle cell trait (Ramakrishnan, et al., 2010).

Relative risk of mortality from pneumonia for children who are suboptimally breastfed in the first 5 months of life

Exhibit 3: Children who are not breastfed are 6 times more likely to die from pneumonia than those who are partially breastfed and 15 times more likely to die than children who are exclusively breastfed (Black, et al., 2013).

Low vaccination coverage, particularly for pneumococcal pneumonia
Vaccines are available for both Hib and pneumococcus, the latter of which is fairly new and in the process of being scaled globally. While the rollout for the pneumococcus vaccine—pneumococcal conjugate vaccine (PCV)—has been rapid, its coverage remains low relative to the large potential benefit it can deliver, due to costs and supply constraints. Although the price of PCV has already been brought down by roughly 90%, it still costs $3.50 per dose, compared with other vaccines that cost between a few cents to a dollar. According to one manufacturer, it takes nearly 2.5 years to make a dose of multi-valent conjugate vaccines from start to finish. Currently 2 companies supply GAVI with PCV, but total demand exceeds their production capacities. To help these companies ramp up production GAVI, in 2010, introduced the Advanced Market Commitment to provide guaranteed purchasing and create demand stability. With these measures, the supply situation is expected to improve in the coming years.
Caretakers do not recognize early symptoms and seek treatment or medical care only when the infection is too advanced

Parents often do not recognize the most common early symptoms of pneumonia—difficult breathing and fast breathing. Only 1 in 5 caregivers recognize these 2 key early warning signs of pneumonia (WHO-UNICEF, 2006). This is driven by the subtlety of these symptoms, and further compounded by the fact that often pneumonia begins as a URI, with obvious symptoms of pneumonia presenting only after a few days. Parents are more likely to react to severe symptoms such as fever or altered mental state, at which point antibiotic therapy is less effective and children may need more supportive care such as oxygen therapy. An additional challenge is that even when a child is recognized to have pneumonia, lack of access to affordable healthcare and lack of awareness about the severity of the disease means that the child may still not be taken to receive appropriate treatment. It is estimated that only half of children under 5 in the developing world are taken to an appropriate care provider when symptoms present (WHO-UNICEF, 2006).

Medical facilities do not have equipment to provide oxygen therapy

Oxygen therapy is a powerful intervention for children with severe pneumonia and has been shown to reduce case fatality rates by as much as 35% in developing countries (Duke, et al., 2008). However, current oxygen delivery systems are not appropriate for low resource settings. Oxygen cylinders are difficult to transport, liable to run out and require a logistics system to ensure ongoing supply to healthcare facilities, especially for those in remote areas. Oxygen concentrators, the alternative, are expensive and require a reliable energy source, training for use, and ongoing maintenance that hospital staff are rarely able to perform. Administering oxygen requires ongoing patient monitoring, which most clinics and hospitals in small towns and villages lack the staff for. Either system requires a pulse oximeter to measure oxygen in the bloodstream and a splitter so oxygen can flow from a single source to multiple patients. Cheap pulse oximeters exist on the market, but are rarely found in hospitals or clinics. Splitters by contrast are expensive and can be challenging to find. Notably, oxygen therapy is rarely seen as a high priority need. This explains its scarcity in hospitals and near absence from clinics. Most concentrators, particularly in sub-Saharan Africa, have been donated with insufficient training imparted to those operating them.

Medical facilities lack equipment necessary to make an accurate diagnosis

Chest radiographs are considered the gold standard for diagnosing pneumonia but are not practical in low resource settings. Instead, care providers rely on clinical diagnoses, and while this practice does not drive mortality (as clinical diagnosis is usually sufficient) it does tend to result in over-treatment. In particular, cases of viral pneumonia and upper respiratory infections may be prescribed antibiotics, which are ineffective and can lead to drug resistance. Improved diagnostics will also allow better understanding of the epidemiology of the disease and its variations across geographies.
As the above analysis shows, mortality is largely driven by behavioral risks and can be addressed through education and awareness, including teaching parents and caregivers to recognize and act on early symptoms of pneumonia, and encouraging breastfeeding.

The most promising non-breakthrough opportunity is reducing indoor air pollution. Indoor air pollution is driven largely by cooking activities, particularly with solid fuel sources. Amongst devices that can help reduce indoor air pollution are improved traditional cookstoves, which either use biomass pellets or have a blower (necessary to achieve air pollution reductions large enough to cause health benefits), LPG stoves, electric water heaters, and electric rice cookers in regions with high rice consumption.

Vaccinations are an effective solution for stemming pneumonia cases but are dependent on increasing coverage, which is primarily a policy and supply issue. Quick gains can be made by further reducing the cost of PCV, which is driven by the complexity of the manufacturing process as well as the fact that it is proprietary. While the price of PCV has been brought down dramatically, additional efforts are needed to bring it down further from its current cost of $3.50 a dose. An additional and significant challenge will soon emerge for countries that graduate out of GAVI support and must then finance the purchase of vaccines independently.

**Low cost, off-grid oxygen concentrators**

Oxygen concentrators are an existing technology that need to be redesigned to be more appropriate for low resource settings. Concentrators create oxygen-enriched airflow from ambient air, and are often the most practical solution to provide critically needed oxygen therapy at hospitals, clinics and potentially even outposts (as opposed to oxygen cylinders which require robust logistics systems). Despite the fact that oxygen therapy reduces case fatality rate of children with severe pneumonia by as much as 35% in developing countries (Duke, et al., 2008), there is a noticeable lack of awareness of the opportunity that oxygen therapy could provide. Many hospitals often do not realize that pneumonia is one of their biggest killers, or understand the sheer reduction in case fatality they could achieve with oxygen therapy.

Oxygen concentrators usually cost several hundred to over a thousand dollars, need constant energy supply to operate and require sophisticated maintenance. A novel oxygen concentrator would have to be dramatically cheaper, robust, and easy to maintain, or delivered in tandem with a service model. It should be able to provide oxygen in the absence of reliable grid power. This may require an oxygen storage system or a battery. Oxygen provision needs to be delivered alongside oxygen measurement. An effective oxygen concentrator could also incorporate an oximeter.

While there are no major fundamental scientific or engineering challenges that need to be overcome, design must be approached from a perspective of cost, durability, ease of maintenance and minimal dependence on infrastructure.

Given the lack of priority for oxygen therapy at the healthcare policy level as well as on-ground at clinics and hospitals, the current market is small, and demand will have to be built. At the clinic level, distribution channels are not well defined, and while there is some centralization for purchasing through ministries of health, achieving wide-scale distribution is challenging. Compared with oxygen cylinders, oxygen concentrators are sophisticated and expensive devices and will require a greater element of training and financing.

The projected time to market readiness is 4-6 years. Based on existing and emerging technologies, the difficulty of deployment is CHALLENGING.
An improved, lower cost vaccine for pneumococcus

Pneumococcus (streptococcus pneumonia) is considered the most important pathogen causing pneumonia mortality and disease burden in developing countries. UNICEF and the WHO estimate that pneumococcus may be the cause for more than half of severe cases of pneumonia. One vaccine study in The Gambia, for example, noted that vaccination against pneumococcus led to a 16% reduction in all cause mortality (i.e. a 16% reduction in all childhood mortality, not just from pneumonia). In 2007, the WHO recommended that vaccination against pneumococcus should be added to all national immunization programs, and particularly in countries with high child mortality.

The current vaccine for pneumonia—pneumococcal conjugate vaccine (PCV)—is a complex vaccine, designed to provide protection against multiple strains of pneumonia. More than 90 strains of pneumonia (referred to as serotypes) exist. Each of these present different antigens, which the immune system uses to recognize the bacteria and mount a defense. Consequently, vaccination against one strain often does not provide protection against another. To provide broader protection, PCV contains antigens for multiple strains (generally polysaccharides), which are attached to a carrier protein molecule. This conjugation process is complex and hence the vaccine is expensive relative to other types of vaccines. Currently available vaccines provide protection against as many as 13 strains depending on the manufacturer.

The availability of low cost PCV and its roll-out to developing countries is a significant advancement and has the opportunity to save an estimated 1.5 million lives through 2020. There are 3 manufacturers of PCV, 2 of which have entered into a supply agreement with GAVI. However, PCV deployment and adoption faces 2 critical challenges.

First, the current conjugate vaccines are very expensive, costing $3.50 per vaccination. While this is 90% less than the cost they are sold at in developed countries, PCV remains the single most expensive
vaccine GAVI provides. Other vaccines, by contrast, can cost as little as a few pennies. This high price is due to the complexity of the conjugation process and the fact that there are just 3 manufacturers. Moreover, these manufacturers currently lack sufficient capacity to meet GAVI’s needs, although supply capacity is now being expanded. While the cost may be a manageable challenge for GAVI, it poses a significant problem for countries that graduate out of GAVI support, and must then procure vaccines on their own.

Second, current vaccines do not provide protection against all strains of pneumonia. These strains, and the importance of each strain, vary by region. This means that protection against pneumonia is incomplete on an individual level, and in some regions strain coverage is suboptimal. There is also concern about strain replacement; strains that are currently less significant causes of mortality may become more important as a result of protection against strains that are included in the vaccine.

These challenges can be addressed in 2 ways. The first would be an advancement in the conjugation process. This will allow manufacturers to provide the vaccine at a lower cost, and increase the likelihood that other manufacturers will be able to offer competing vaccines. It may also allow the development of vaccines that can provide protection against a larger number of strains.

The second possibility is the development of an entirely new type of vaccine. This would not be a conjugate vaccine, and instead would produce immunity through another mechanism, most likely through a ‘common protein’ that is present in all strains of pneumonia. While this opportunity could be revolutionary, providing broader protection and likely a lower cost, the appropriate protein has not been identified yet. Significant primary research still needs to be conducted.

Once developed, either of these vaccines should be fairly easy to distribute. Major vaccine delivery channels exist, and are being developed further by GAVI. The time to market readiness for either approach is projected to be 10-15 years and the difficulty of deployment, for both, is FEASIBLE.

### Breakthrough 2 – Difficulty of deployment

<table>
<thead>
<tr>
<th></th>
<th>Policies</th>
<th>Infrastructure</th>
<th>Human capital</th>
<th>Access to user finance</th>
<th>Behavior change</th>
<th>Existing demand</th>
<th>Market fragmentation/Distribution channels</th>
<th>Business model innovation</th>
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- Regulated market with supportive policies
- Dependent on existing infrastructure
- Low-moderate need for human capital development
- Financing not required
- No behavior change required
- Strong existing demand
- Highly concentrated market or well defined channels
- Clear deployment models existing at scale
Low cost, novel diagnostics

Pneumonia is currently diagnosed clinically, making it difficult for care providers to identify different clinical scenarios such as whether a patient has viral or bacterial pneumonia or quickly determine the infecting pathogen, which can help indicate the potential severity of the illness. While the gold standard for diagnosis is a chest x-ray, it is not practical for clinics in developing countries. Most diagnoses are made based on evaluation of respiratory rate and chest in-drawing.

The technological challenges and time to market for a novel pneumonia diagnostic vary depending on what the clinical goal of the diagnostic would be. A urine-based diagnostic for pneumococcus bacteria, for example, may be available within a year. But a diagnostic that can discriminate between bacterial and viral pneumonia, and severe and non-severe pneumonia, is much more technologically complex; in some cases biomarkers have not been identified yet. The primary benefit of diagnostics that provide deeper information about the infecting pathogen would likely be a better understanding of the disease and its epidemiology, as opposed to reduced mortality.

Reducing mortality from severe pneumonia would likely rely on improvements in pulse oximetry and respiratory rate timers. Both are effective technologies, and while they could be refined further, the key challenge is distribution to and adoption at the clinic level, as opposed to major improvements in either the cost or technology. However, even the impact from better oximetry and respiratory rate timers are likely muted, as a reduction in mortality will only happen if patients seek care, are diagnosed in time, and in some cases have subsequent access to oxygen therapy which is currently rare.

Ease of deployment varies by the type of diagnostic. In general, simpler devices like improved respiratory rate timers and pulse oximeters have fewer deployment barriers; they need less access to grid energy, less access to financing and less training. In each case however, lack of existing demand and market fragmentation are major hurdles in achieving scale. There is currently no existing base for deployment of pneumonia diagnostics to rural clinics where they are most needed, so distribution of a new diagnostic would require creation of new channels as well as educating healthcare workers on the need and value of pneumonia diagnostics. Since clinical diagnosis generally remains effective, and the downside to clinical diagnosis (i.e. drug resistance) is neither immediate nor obvious, and it will be challenging to convince healthcare funders and clinicians to devote scarce resources to purchasing and using pneumonia diagnostics.

Diagnostics for pneumonia range from market ready (pulse oximeters and respiratory rate timers), to 7-10 years away (molecular based platform). The difficulty of deployment is CHALLENGING.
Breakthrough 3 – Difficulty of deployment

- **Extremely Challenging**
- **Challenging**
- **Complex**
- **Feasible**
- **Simple**

**Policies**
- Low role of policy / regulation
- Dependent on existing infrastructure

**Infrastructure**
- Moderate need to train a limited number of people

**Human capital**
- Limited financing required

**Access to user finance**
- Moderate behavior change required with evidence of behavior change being viable

**Behavior change**
- Low demand, needs to be built

**Existing demand**
- Fragmented market, weak distribution channels

**Market fragmentation/Distribution channels**
- Deployment model(s) being tested

**Business model innovation**
- Business model innovation
Diarrheal disease is responsible for 710,000 childhood deaths while soil-transmitted helminths (STH) affect roughly 1.5 billion people globally. In addition to mortality, the indirect burden of diarrheal disease and STHs is significant; they are a major contributor to malnutrition, which in turn is believed to underlie 45% of all childhood deaths.

Diarrheal disease is transmitted through the fecal-oral pathway, which is traditionally addressed through interventions targeting water quality, water supply, sanitation, hand hygiene, and food hygiene. Diarrheal disease burden can also be reduced through vaccination, nutritional interventions and oral rehydration therapy. Mortality from diarrheal disease has decreased dramatically over the past two decades. Over the same time, access to improved water, improved sanitation, vaccines, and oral rehydration therapy, all increased, and malnutrition decreased. However, the extent to which reduction in mortality can be attributed to specific interventions or demographic trends is a subject of debate. Despite these gains, factors such as high population growth and decreasing water supplies are expected to exacerbate diarrheal disease in the future.

Sustainability of interventions and adherence of beneficiaries (e.g. are people consistently washing their hands), have remained major challenges in diarrheal disease prevention. Behaviors around practices such as eating and defecation have deep cultural roots and can be hard to influence. There is no shortage of failed interventions and technologies in addressing this issue. While there have been demonstrated reductions in diarrheal disease from small-scale interventions, there has been limited success in bringing these interventions to scale. There are 5 technological breakthroughs for reducing mortality and morbidity from diarrheal disease.

- Resource recovery systems for fecal waste
- Next generation toilets or homes with in-home toilets, especially for the urban poor
- Additives to facilitate the breakdown and/or disinfection of fecal sludge in pit latrines
- Water pumps that automatically purify with chlorine
- Extremely simple point-of-use water treatment systems
Diarrheal disease is the 3rd leading cause of childhood mortality worldwide, behind only neonatal conditions and pneumonia (Liu, et al., 2012). It is responsible for 710,000 childhood deaths, almost all in developing countries (Liu, et al., 2011) (Exhibit 1).

**CORE FACTS AND ANALYSIS**

Defined as passage of three or more loose or watery stools per day, diarrhea is usually caused by an intestinal tract infection, which can be caused by many different pathogens including bacteria, viruses and protozoa. These are generally spread through contaminated food, drinking water or person-to-person contact (WHO, 2013).

Soil-transmitted helminths (STHs) are parasitic nematodes (worms) that feed on the host tissue or compete with the host for nutrition. Many STHs are contracted when children ingest eggs that were excreted in fecal matter of infected individuals. STHs are estimated to infect some 1.5 billion people globally (WHO, 2013). The most common and important STHs are roundworm, whipworm, and hookworm. While these infections are rarely fatal, STHs can cause intestinal distress, malaise or weakness, and impaired cognitive and physical development. The severity of symptoms is directly related to the number of worms an individual harbors.

Both diarrheal disease and STHs lead to malnutrition in the host (Table 1). Diarrheal disease can reduce an individual’s ability to absorb nutrients in the intestines and the effects of the disease last well beyond the diarrheal episode. STHs feed on host tissue, including blood, or compete with the host for nutrients. This leads to a loss of iron and protein and, similar to diarrheal disease, also causes malabsorption of nutrients. Recently, a condition known as environmental enteropathy has been proposed to explain, in part, malnutrition that results from sustained exposure to fecal pathogens, even in the absence of diarrheal episodes. A 2008 WHO study concluded that as much as 50% of childhood underweight and malnutrition could be associated with repeated diarrhea or soil-transmitted helminth infections (Prüss-Üstün, et al., 2008).

**Contribution to childhood mortality by health condition**

![Graph showing contribution to childhood mortality by health condition](image)

*Exhibit 1:* Diarrheal disease is the 3rd leading cause of childhood mortality in sub-Saharan Africa and South/ Southeast Asia (Liu, et al., 2012).
Key diarrheal pathogens and soil-transmitted helminths

<table>
<thead>
<tr>
<th>Pathogen class</th>
<th>Important pathogens</th>
<th>Effect</th>
</tr>
</thead>
</table>
| Diarrheal pathogen          | Globally important pathogens: Rotavirus, Cryptosporidium parvum, Shigella, ST-enterotoxigenic E. coli (ST-ETEC) Additional pathogens important in some specific regions: Aeromonas, V. cholera, C. jejuni | • Diarrhea, which causes dehydration and can lead to mortality  
• Reduction in ability to absorb nutrients (lasting beyond the diarrheal episode)  
• Environmental enteropathy (prolonged reduction in ability to absorb nutrients, can occur without diarrhea) |
| Soil-transmitted Helminths  | Roundworm (Ascaris lumbricoides), whipworm (Trichuris trichiura), hookworm (Necator americanus and Ancylostoma duodenale) and certain types of tapeworm (Taenia) | • Enteric inflammation, general malaise and weakness, and impaired cognitive and physical development  
• Anemia (hookworm only)  
• Increased malabsorption of nutrients  
• Loss of appetite |

Table 1: A handful of pathogens are responsible for the majority of severe diarrhea and STH infections. Rotavirus, Cryptosporidium parvum, Shigella, and ST-ETEC are the four most important diarrheal pathogens globally (Kotloff, et al., 2013).

Diarrheal disease and malnutrition share a complex link

The relationship between diarrheal disease, soil-transmitted helminths and malnutrition is recognized, but not entirely understood. Focusing specifically on diarrheal pathogens, the common belief for decades was that diarrhea itself caused a reduced ability for the body, specifically the small intestine, to absorb nutrients, and this effect could last significantly longer than the diarrheal episode itself. One meta analysis found that probability of stunting at age 2 increased by 2.5% per diarrheal episode, and 25% of all stunting was attributable to having 5 or more episodes of diarrhea (Checkley, et al., 2008).

Recently, the scientific community has begun to propose a more complex explanation, which is not related to diarrhea per se, but exposure to high levels of fecal pathogens. This condition is often referred to as ‘environmental enteropathy’ or ‘environmental enteric dysfunction’. Environmental enteropathy is a poorly defined condition, but is generally characterized by “villous atrophy, crypt hyperplasia, increased permeability, inflammatory cell infiltrate, and modest malabsorption” of nutrients (Humphrey, 2009). The underlying causal mechanism has not been specified yet. One proposed model is that high enteric pathogenic bacterial exposure in the small intestines creates an immune response, which in turn causes the common characteristics of enteropathy such as atrophy of intestinal villi (small finger-like structures on the surface of the intestines that increase surface area for absorption of nutrients). The effects are twofold. First, as a result of reduced surface area in the intestine, the small intestines have a reduced ability to absorb nutrients. Second, nutrients are repartitioned away from growth to support the immune system. This is an ongoing area of research.

Enteropathy could help explain why sanitation has stronger associations with achieving gains in infant and child growth, rather than reduction in diarrhea (Brown, et al., 2013). For example, a study in
Peru found that diarrhea could explain 16% of stunting, while access to sanitation and water services could explain 40% (Brown, et al., 2013).¹

STHs do not trigger the same immune response as diarrheal disease. It is believed that they affect nutrition by feeding directly on intestinal contents or blood, leading to nutrient loss and anemia (WHO, 2013). STHs and their effects on nutrition and growth have increasingly become a debated topic. In 2007 and 2012, The Cochrane Collaboration reviewed evidence for mass deworming initiatives and found that the evidence linking deworming programs to gains in nutrition and growth indicators was weak. Leaders from evaluation groups including Innovations for Poverty Action (IPA), the Center for Effective Global Action (CEGA), and the Abdul Latif Jameel Poverty Action Lab (J-PAL), have criticized these studies for excluding important randomized trials and ignoring the effect of deworming on improvements in education outcomes.

**Diarrheal disease is primarily a childhood disease**

Children under 5 represent 68% of the diarrheal disease burden (IHME, 2012). Children are generally more susceptible to diarrheal disease, due to their developing immune systems, and a high rate of malnutrition or other immune-suppressant risk factors. Children are also at higher risk for life-threatening diarrheal disease due to the higher composition of water in a child’s body relative to adults, relatively higher metabolic rates and lower capacity of their kidneys to conserve water (WHO-UNICEF, 2009).

The past two decades have seen a large drop in childhood mortality caused by diarrheal disease (Exhibit 2). The Child Health Epidemiology Reference Group (CHERG) estimates that childhood mortality fell by 31% between 2000 and 2010 (Liu, et al., 2012). The WHO and UNICEF estimate that in 1990 mortality was as high as 5 million (WHO-UNICEF, 2009). While it is widely accepted that the global burden has dropped significantly over the past two decades, the specific reasons for this decline are not well understood. The primary drivers are believed to be improvements in nutrition, improved case management, particularly the widespread use of oral rehydration therapy, increased coverage of immunization for measles and rotavirus, and increased access to clean water and sanitation.

**Global reduction in childhood diarrheal disease mortality in recent years**

Exhibit 2: Global mortality from diarrheal disease has decreased from nearly 1.1 million to less than 0.75 million per year, since 2000. However specific causes of this reduction remain unclear (Liu, et al., 2012).

¹ While many experts have come to take these positive associations between WASH interventions and health as conventional knowledge, some skeptics have noted the risk of confounding in this type of analysis, and a recent Cochrane review did not, in fact, include this particular study due to questionable methodological quality (See: Dangour, et al., 2013. The effect of interventions to improve water quality and supply, provide sanitation and promote handwashing with soap on physical growth in children).
While mortality from diarrheal disease has decreased, morbidity has remained more or less constant (Kosek, et al., 2003). This implies that the global health community has made major strides in case management and control of at least some pathogens that are responsible for moderate to severe diarrhea, but relatively little progress has been made in controlling the general transmission of diarrheal pathogens.

Diarrheal disease burden is highly concentrated in a small number of countries (Exhibit 3), with 10 countries representing 78% of deaths. Even within these countries, variability in the rate of diarrheal disease mortality is high (Exhibit 4).

**Exhibit 3:** 10 countries account for 78% of childhood deaths from diarrheal disease.

**Exhibit 4:** Mortality per 100,000 people varies greatly, even across high burden countries.

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2 This opinion is not universally held, and some experts note that cross-sectional surveys used to gather this data are unreliable (Luby, 2011)

3 These estimates are based on childhood mortality rates from 2010 CHERG data and population data from the CIA World Factbook, which contains data from various years. Note that deaths are for children only, while population figures are national. Thus, mortality rate for children specifically would be higher in all cases.
Diarrheal disease and intestinal nematodes are caused by 4 types of pathogens

The various pathogens causing diarrheal disease and intestinal nematodes behave in different ways. Some bacteria, for example, are believed to be seasonal. There are major spikes in bacterial infections during the wet seasons, which highlights the importance of water as a transmission pathway. In contrast, viruses, particularly rotavirus, show seasonal spikes in the drier, colder seasons. This indicates that person-to-person transmission is an equally or more important transmission pathway (Levy, et al., 2009). Unlike viruses, bacteria can also reproduce outside of the human body (e.g., on food left at room temperature), thus becoming more likely to produce disease after ingestion. STHs on the other hand must mature in soil, eliminating person-to-person transmission as a major pathway. Further description of the different types of pathogens can be found in Table 2.

The Global Enteric Multicenter Study (GEMS) identified 4 important specific pathogens that represent a disproportionate percentage of disease burden in developing countries: Rotavirus, Shigella, ST-ETEC, Cryptosporidium (Kotloff, et al., 2013).

### Major classes of pathogens and their characteristics

<table>
<thead>
<tr>
<th>Pathogen type</th>
<th>Important pathogens</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viruses</td>
<td>Rotavirus</td>
<td>Viruses are infectious pathogens that can only replicate after infecting other living cells. Rotavirus is the single most important pathogen associated with diarrheal disease.</td>
</tr>
<tr>
<td>Bacteria</td>
<td>ST-Enterotoxigenic E. coli, Shigella, Aeromonas, V. cholera, C. jejuni</td>
<td>Bacteria can grow on food and in water and sewage under the right conditions. Some bacteria are seasonal, with major spikes in the wet season.</td>
</tr>
<tr>
<td>Protozoa</td>
<td>Cryptosporidium Parvum</td>
<td>Protozoa are advanced organisms that are transmitted through cysts that are extremely robust, able to survive for long periods outside of the body and resistant to chlorine purification.</td>
</tr>
<tr>
<td>Soil-transmitted Helminths</td>
<td>Roundworm (Ascaris lumbricoides), whipworm (Trichuris trichiura), hookworm (Necator americanus and Ancylostoma duodenale) and certain types of tapeworm (Taenia)</td>
<td>Soil-transmitted helminths (STH) are parasites that do not cause diarrhea, but rather live in the body, generally the intestines, and cause enteric inflammation. Eggs must mature in soil before becoming infectious to humans, however, they are extremely persistent and can survive for weeks to months on crops and soil, and years in fecal matter.</td>
</tr>
</tbody>
</table>

Table 2: Each of the different types of pathogens travels along the fecal-oral pathway, but have different characteristics affecting their transmission and susceptibility to different interventions.
Traditionally, the flow of pathogens has been described through the F-diagram. Diarrheal disease and STHs are transmitted from person-to-person along the fecal-oral pathway, in which individuals ingest pathogens that have been excreted in fecal waste by other infected individuals and sometimes animals. The pathway is complex and can follow many routes, which vary in importance from location to location. This pathway has historically been represented with the F-diagram, which describes the flow of pathogens from fecal matter to new hosts (Exhibit 5).

The F-Diagram representing the Fecal-Oral Pathway.

Exhibit 5: The F-diagram has historically been used to describe the fecal-oral pathway (Brown, et al., 2013).

While this diagram is useful as a descriptive tool, it is limited in its usefulness for informing interventions. Drinking water or fluids, for example, can be contaminated in a number of ways including contamination at the source, either from flooding or direct runoff from inadequate sanitation systems, contamination in transit through water pipes with intermittent supply, or contamination in the household from poor storage practices.

A more nuanced fecal-oral pathogen flow model

In order to provide a more nuanced conceptual framework for problem and intervention analysis, we have developed the Pathogen Flow Model (Exhibit 6). This five-stage model maps major transmission pathways, allows identification of major breakpoints, and provides a view of which challenges must be solved in unison. Each stage of a pathway presents unique challenges, which are responsive to different types of interventions.

Stage 1 - Pathogen hosting

The transmission of fecal pathogens begins with individuals who are carrying diarrheal disease causing pathogens in their gut. These individuals may be suffering from diarrheal disease, or they may be asymptomatic carriers. In both cases, but particularly for individuals suffering from diarrheal disease, the disease-causing pathogens grow and replicate. This can also occur with asymptomatic carriers who carry potentially disease-causing organisms, but do not suffer from diarrhea. While humans can be infected by pathogens that come from animal hosts, the majority of infections responsible for the overall diarrheal and STH disease burden in children are likely acquired from other human hosts.¹

¹ One notable exception is Taenia which is often carried in cows or pigs.
Stage 2 - Defecation points

Following infection and the replication of pathogens in the body, pathogens are then excreted into the environment at defecation points. These defecation points, such as open fields, sewers, and pit latrines represent high-density sources of persistent diarrheal pathogens. The challenges associated with defecation points vary from urban to rural locations but generally revolve around the lack of sustainable and scalable sanitation systems. It is often taken as common knowledge that sanitation interventions are positively correlated with reduction in diarrheal disease and childhood growth. A meta analysis of sanitation interventions found an average relative risk reduction in diarrheal disease of 37% (Waddington, et al., 2009). A recent Cochrane review, however, found there was insufficient evidence to link sanitation interventions to childhood growth (Dangour, et al., 2013).

Stage 3 - Transmission pathways

When there are insufficient sanitation systems, diarrheal pathogens spread through transmission pathways such as crops and water sources. There are many possible transmission pathways, and targeting any single pathway in isolation is unlikely to create major improvements in health. Interventions at this stage have generally displayed less effectiveness than interventions at earlier or later points in the pathway. For example, water quality interventions at the source—a transfer point—are associated with an 11% reduction in diarrheal disease, while interventions at the household lead to a 35% reduction (Fewtrell, et al., 2005).

Exhibit 6: This five-stage model maps major transmission pathways for diarrheal disease and soil-transmitted helminths. It is important to note that different pathways are applicable in different contexts, e.g., rural vs. urban settings.
Stage 4 - Exposure

Pathogens enter the body in three ways: through drinking water, through food, and directly from hands.

Drinking water
Drinking water is generally contaminated at three main points—at the source, in transit (such as through pipes), and in the home (through improper storage). Major interventions focusing on drinking water are generally source protection (prior to the exposure stage), water purification, and safe household storage.

Food
Food can be contaminated in fields when farmers use wastewater for irrigation, when feces are deposited in fields due to open defecation or as fertilizer, in markets due to unhygienic conditions, or in the home through a mother’s hands while preparing food, a child’s hands while eating, or by flies that land on food and deposit pathogens. The ability of bacteria to reproduce rapidly on food has led to food, and particularly complementary (weaning) food, gaining increased importance in reduction of diarrheal disease. Food hygiene generally focuses on hand washing before preparing food and eating, appropriate food preparation practices including washing or disinfecting and then properly cooking food, appropriate storage of leftover food, and reheating food that had been previously prepared.

Hands and fingers
Hands and fingers can be contaminated during defecation, caring for an infant, and through contact with the soil and environment. Hand hygiene is focused primarily on hand washing with soap.

Interventions at the exposure stage tend to be moderately effective. Studies have found a 31% reduction in diarrheal disease from hygiene interventions and a 42% reduction from water quality interventions (Waddington, et al., 2009).

Stage 5 - Infection

Exposure does not necessarily lead to disease. Rather children who are malnourished, not optimally breastfed, or are HIV positive are more likely to develop diarrhea after exposure to pathogens. Vaccination is also effective in reducing the risk of diarrhea following exposure to some pathogens.
KeY CHALLenGes

Diarrheal disease is a condition that is driven by some of the most fundamental human activities—eating, drinking, preparing food, and defecating. In the absence of adequate sanitation systems, fecal pathogens contaminate the environment, food, and water both through environmental mechanisms and through human activities. Pathogens are then ingested, and in individuals who are susceptible, produce disease, at which point lack of adequate care becomes a major driver of mortality.

Key challenges in breaking the fecal-oral pathway, reducing susceptibility to disease through improved nutrition and health care, and improving care for those who fall sick are outlined below.

1. High rates of infection amongst the population lead to a constantly replenishing and growing supply of diarrheal pathogens and STHs in the environment

Rates of infection in many developing countries are extremely high. There are 1.7 billion cases of diarrhea globally per year, with an average of 2.9 episodes per child per year (Brown, et al., 2013), indicating that diarrheal pathogens are constantly being excreted into the environment and in massive quantities.

2. Lack of adequate, sustainable sanitation systems enables wide-scale environmental contamination with fecal pathogens

There are a number of systemic, multifaceted problems which expose low income populations to fecal pathogens. These include poor infrastructure, lack of public sanitation services, and the absence of sustainable business models for private sanitation.

Lack of sanitation infrastructure
Sanitation infrastructure such as sewerage and treatment facilities, the most common approach to clean environments in developed countries, is severely underdeveloped in most developing countries. The gold standard of closed sewage systems where wastewater is treated before being returned to the environment is highly uncommon. Sanitation systems generally only reach small portions of the population and are underdeveloped or in disrepair, leaving most individuals using alternative sanitation systems or practicing open defecation.

Lack of sustainable, scalable models for community or household sanitation systems
One of the key challenges with sanitation systems is maintenance—keeping the toilets at an acceptable level of cleanliness while removing waste—which is dependent on an effective business or public utility model. In most developing countries, government-funded sanitation systems have limited reach, often excluding the poor. In the absence of public models, private or hybrid models are being developed, although none have yet been fully proven. In the absence of an effective model which generates revenue, either from usage of the toilet or through sale of the fecal sludge, sanitation systems inevitably become unsanitary and go into disuse.

Existing urban and rural systems have major shortcomings, which lead to environmental contamination
In urban areas, particularly for the poor, sanitation systems are generally pit latrines and open sewers, which have several major shortcomings. First, both are prone to flooding which leads to widespread contamination. Second, open sewers in particular are often located in areas with high population density where they cause extensive contamination. Third, pit latrines often fill up faster than the waste decomposes, which means that they must be emptied. Often pit latrines are emptied by private parties who dispose of the fecal sludge improperly, usually very close to urban populations, where the diarrheal pathogens can contaminate water sources or soil, and come in easy contact with children. In rural areas, sanitation
Environmental conditions are conducive to the persistence and spread of pathogens

Bacterial pathogens can survive in water over 10-60 days and in soil for many months, and STH eggs can survive in soil for 27-35 days in summers, and up to half a dozen months during the winter season in temperate zones (Ensink & Fletcher, 2009). Both can survive significantly longer than their average lifespan in fecal waste.

In the absence of sanitation systems, there are a large number of ways in which food and water can become contaminated, or children can be exposed to pathogens directly

When there are insufficient sanitation systems, diarrheal pathogens flow through multiple transmission pathways, which brings them in direct contact with potential human hosts. There are many possible transmission points, and therefore many breakpoints in the transmission pathway to consider.

Distributed water sources including surface water, shallow wells and boreholes
Surface and shallow water sources, especially in rural areas, can be contaminated through flooding and runoff of fecal matter and pathogens. Deeper groundwater, in both urban and rural areas, can be similarly contaminated through episodic flooding, particularly when boreholes are constructed poorly (without a concrete block at the surface to prevent fecal matter from reaching the aquifer through and around the pipe).

Centralized water sources (water pipes)
In urban settings, water distribution pipes and sewage pipes or ditches are often constructed near each other. Pipes are inherently leaky, with even well maintained western systems losing roughly 15% of system water. Piping systems in developing countries are dramatically worse and often have only intermittent water supply. When the water supply is shut off, it creates reverse pressure, and if there is fecal matter around the pipes it can leach into the water pipes. This re-contaminates water even if it has already been purified.

Crops
It is estimated that 10% of the world’s food supply is irrigated with wastewater (Jimenez, 2006). Use of untreated wastewater for irrigation deposits pathogens, particularly on vegetables, which can then be ingested if the produce is not cleaned and cooked properly before eating.

Flies
Some flies are born and breed in fecal matter and carry pathogens on their exoskeleton or through their gastrointestinal system. Flies also tend to proliferate in hot and humid conditions, especially the rainy season, when there are more pathogens in the ecosystem.

Soil and environment
Soil and the broader environment are contaminated from open defecation, disposal of fecal sludge, runoff from inadequate sanitation systems, from wastewater that is used for irrigation, and from episodic flooding.
Diminishing water availability leads to utilization of lower quality water sources
As water sources become over-abstracted or are replenished at slower rates due to changes in hydrological patterns, the quality at these sources tends to degrade. Individuals then have to use lower quality water sources. This exacerbates existing challenges with nearly all water sources in water-poor areas, including most of South Asia and sub-Saharan Africa. This is also expected to become increasingly critical as the global population grows and hydrological patterns continue to change.

Children are exposed to diarrheal pathogens either directly from pathogens on their hands or through consumption of contaminated food or water

Exposure to diarrheal pathogens is enabled by food and personal hygiene habits as well as insufficient water purification systems.

Hand hygiene
Mothers and children do not wash hands with soap after contact with fecal matter, either through defecation or care for a child or infant who has defecated.

Food hygiene
Mothers often do not wash their hands with soap before preparing food and children do not wash their hands prior to eating. Weaning foods are prepared under unhygienic conditions and stored at room temperature. Several studies have found that the second 6 months of life are the period with the highest rate of diarrheal disease (Motarjemi, et al., 1993). One study found that 41% of weaning food items were contaminated with E. coli (Black, et al., 1982). Weaning foods have been found to be more contaminated than food prepared for adults, due to storage of weaning foods at high ambient temperatures (Black, et al., 1982). Apart from weaning food, previously cooked food is often not reheated before consumption later. Storage at room temperature can lead to exponential bacterial growth in cooked food. Studies have found that bacterial contamination on food greatly exceeds that found in drinking water (Black, et al., 1982).

Water quality and supply
There are several challenges in providing safe water to children. First, water delivery infrastructure is often poorly developed and in some cases absent in developing countries, particularly in rural areas. While most individuals in urban areas have access to water, access in rural areas, particularly in sub-Saharan Africa and India remains low. In both regions, only about half of the population has access to an improved water source. When there is no national level water infrastructure, community level systems are often employed; however, these systems need ongoing maintenance models and require an adequate service model to be sustainable.

There are various models, which have proven effective, but most proven community-level water distribution systems exist in rural areas with relatively high population densities. New models that can serve communities with lower population densities are required. For the household level, there are an abundance of point-of-use water purification systems; however these tend to have low compliance, due to the complexity and time involved when using them. Numerous studies have found point-of-use purification systems effective at reducing microbial contamination at the household level as well as diarrheal disease in children under 5 by up to 42% (Clasen, 2003).

However, studies have found significant heterogeneity in results from point-of-use water treatment systems, which is likely related to compliance (Clasen, et al., 2007). In one study of the poor in urban Bangladesh, even with bi-monthly visits to educate families about the dangers of untreated drinking water, only 30% of families used the most popular treatment system they tested, with lower rates of compliance for other systems (Luoto, et al., 2011). The low rate of adequate water treatment is also greatest
Increased susceptibility due to poor nutrition

Diarrheal pathogens are opportunistic. Development of active infection following exposure, like with many diseases, is driven by the strength of an individual’s immune system. Malnourished children, in particular, have higher susceptibility. Children who are stunted are 1.6 times more likely to die from diarrheal disease than those who are not stunted (Black, et al., 2008); Vitamin A deficiency causes a 60-70% increase in diarrhea prevalence (el Bushra, et al., 1992), and zinc deficiency has been found to increase diarrhea prevalence by 15-24% (Bhutta, et al., 2008). Suboptimal breastfeeding also contributes to childhood susceptibility to diarrheal pathogens. Infants under the age of 6 months who are not breastfed are over 10 times as likely to die from a diarrheal infection as those who are breastfed (Lamberti, et al., 2011).

Low vaccine coverage for rotavirus

An effective vaccine exists for rotavirus, which is the most common cause of moderate-to-severe diarrhea in children under 2, and makes up over 40% of all incidences of moderate-to-severe diarrhea in children under 1, more than double the next highest cause (Kotloff, et al., 2013). However, childhood coverage for this vaccine is still low due to its fairly recent introduction as a global priority and its high cost relative to other vaccines.

Lack of vaccines for Shigella, ST-ETEC, Cryptosporidium and soil-transmitted helminths

With the exception of rotavirus, there is no effective vaccine for any of the other major pathogens that cause diarrheal disease, and there are major scientific challenges to many of these pathogens (Jones, et al., 2003). There are many strains of ST-ETEC, and an effective vaccine would have to produce immunity against an array of antigens. Developing vaccines for parasitic diseases is challenging due to the increased complexity of antigen analysis of higher life forms, as is the case with Cryptosporidium and helminths. The challenge of developing a vaccine against STHs is compounded by the diversity of helminth organisms (Harris, 2011). Many experts believe that the development of additional vaccines is likely a high-cost, time-consuming opportunity relative to existing interventions.
Children do not receive adequate care during a diarrheal episode due to the low coverage of oral rehydration therapy

ORT is a proven intervention and can reduce mortality by 69% but coverage remains low (Bhutta, et al., 2013). Only 39% of children in developing countries with diarrhea receive ORT, and there has been little improvement in this rate since 2000 (WHO-UNICEF, 2009). This is driven by a number of factors including the misconception that diarrhea is ‘part of growing up,’ the fact that often both parents work and have limited time to pay attention to their children, weak healthcare systems, and the lack of awareness that diarrhea can be a major risk to a child’s life.

There are many fundamental scientific questions that remain unanswered

Experts noted many key scientific questions, highlighted below, that require further research to help reduce the burden of diarrheal disease and STHs.

- What is the relative importance of various pathways of transmission?
- What is the relationship between gastrointestinal pathogens and malnutrition?
- What is the burden of disease, other than mortality, that is attributable to gastrointestinal pathogens? (For example, the loss of cognitive development associated with both intestinal parasites as well as growth faltering which may be mediated through environmental enteropathy).
- What is the role of the microbiome in increasing or decreasing the susceptibility of the child to exposure to gastrointestinal pathogens? And, what interventions might contribute to a healthier more protective microbiome?
- How clean does the environment need to be for thriving children and thriving communities?
- What is the underlying cause of environmental enteropathy?
- What are the pathways through which environmental contamination and malnutrition contribute to growth faltering?
- How do we scale up successful pilot projects to better protect large vulnerable populations?
- What are easier, lower cost methods for detecting and measuring the concentration and viability of pathogens in the environment?
- What are better dose-response curves to use for modeling exposure (Quantitative Microbial Risk Assessment) that describe the susceptibility of children to different organisms? Most dose-response data are from studies on healthy adults.

In summary, systemic challenges require systemic solutions. The core challenge, breaking the fecal-oral pathway, is dealt with in developed countries through large government investments in public infrastructure including sewer systems, wastewater treatment plants, water purification facilitates, and ubiquitous piping into households—all of which require constant service and maintenance. This is almost certainly not practical in most of the poorest regions of the world.
SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

There have been several successes in reducing diarrheal disease at a small to mid-level scale, usually in the range of thousands of households. Very few interventions, however, have been proven at a scale comparable to the problem itself—in the range of hundreds of thousands to millions of households. Amidst the successes are an abundance of failed interventions—broken water filters or toilets that were installed but never used or that quickly broke, again highlighting the fact that diarrheal disease is not a challenge that can be solved just by technology, by building infrastructure or by influencing behavior or habits, but rather successful interventions must be holistic and consider the whole system and include business or public financing models to ensure sustainability.

Resource recovery systems for fecal waste

Sanitation systems undergo constant use, requiring ongoing maintenance and cleaning, and often have high upfront costs. This requires either significant public financing or a business model to generate revenue to cover startup and operating costs. One emerging model to support this involves collecting fecal waste for conversion into energy (biogas, biofuel, electricity), or higher value compounds (compost, fertilizer, plastic), or harvesting nutrients which can then be sold to defray costs, or ideally, provide a return on investment.

There are multiple approaches to resource recovery. The most focused on approach thus far has been the production of biofuels (often liquid biofuels), which can be very high value. This, however, has been hindered by the fact that only a fairly small quantity of biofuel can be produced from human fecal sludge and that human waste biofuel is often inconsistent with the embedded fuel infrastructures in developing (and developed) countries. Nitrogen and phosphorus, which are essential for agriculture, can also be harvested from fecal sludge, either through composting or more advanced nutrient harvesting, such as struvite precipitation and ammonia stripping from source-separated urine. Fecal sludge can also be dried, processed (e.g., into fuel pellets), and then sold as a carbon neutral fuel. The ideal recovery solution would be able to extract energy and nutrients while disinfecting and minimizing the volume of any remaining waste.

Technologies that facilitate the conversion of fecal sludge to fertilizer or biofuel exist, but face two major problems. The most immediate is that these technologies generally remain too costly to reach significant market penetration. The broader, and potentially more significant challenge is that it is unclear how much economic value can be actually extracted from fecal waste. The ideal technology would be able to convert fecal waste to a sufficient quantity of energy or another substance to cover the operating costs of the sanitation system, and even generate returns on the investment. However, many experts believe that this level of value extraction is unlikely, and that it is more likely that any technology will only be able to offset costs. If this is the case, it calls into question the viability of resource recovery systems as an at-scale solution to sanitation challenges.

The market readiness of these technologies varies by the type of technology. Technologies that can extract biofuel and nitrogen exist currently, although costs for many technologies remain high. Phosphorus recovery from fecal sludge and nitrogen recovery from urine are likely closer to 4-6 years out, while some of the more novel technologies such as microbial fuel cells are 10-15+ years away from being market ready.

There are many challenges in the distribution of sanitation systems that extract high-value content from fecal waste. In particular, no resource recovery driven sanitation system models have been proven at scale in developing countries yet. Sanitation systems also tend to have fairly high up-front costs,
require skilled labor to install and maintain, and distribution channels are poorly defined. In addition, significant public investment is likely to be still required.

The projected time to market readiness varies by technology ranging from market ready to 15+ years. Given the lack of proven models and the scale of the urban sanitation problem, the level of difficulty for deployment is EXTREMELY CHALLENGING.

### Breakthrough 1 – Difficulty of deployment

**Extremely Challenging**

- Policies
- Infrastructure
- Human capital
- Access to user finance
- Behavior change
- Existing demand
- Market fragmentation/Distribution channels
- Business model innovation

**Challenging**

- Low role of policy / regulation
- Moderate need to train a limited number of people
- Moderate behavior change required with evidence of behavior change being viable
- Moderate demand
- No identified deployment model, major hurdles identified

**Complex**

- Requires some improvements to existing infrastructure
- Significant financing required, limited mechanisms available
- Highly fragmented, challenging to reach customers
Next generation toilets or homes with in-home toilets for the urban poor

Most existing housing for the urban poor does not have an in-home toilet, which is a major barrier towards the use of a proper sanitation system. Development of appropriate toilets for urban houses or inclusion of an in-home toilet as part of the broader opportunity to provide low cost housing to the urban poor could overcome this first barrier of low toilet usage. This will also help address critical problems such as the safety risks women and children face when using shared toilets. An effective model to dispose of fecal waste will still be required to remove waste from houses.

The challenges of an in-home toilet vary depending on whether there is piped water supply and sewerage, which is uncommon in most urban slums. Those living in urban slums also often do not have legal land tenure. When water and sewage infrastructure is expanded into these areas, the cost and value of land increases dramatically, forcing out the most vulnerable populations. Increased land cost indirectly also increases the cost of owning a toilet, which is a low priority for most since it takes up precious space in households that are often extremely small. In considering options to provide sanitation to the very poor, it should be assumed that there will not be adequate piped water or sewerage infrastructure.

Where there is no piped water or sewerage, an in-home toilet must be low-cost, have an effective way to control odor, a system for managing waste, and require minimal space. Ideally, appropriate in-home toilets will be included in the actual construction of each low cost home, leveraging the significant efforts underway to provide better housing for the urban poor. While many organizations are focusing on developing new housing options for the urban poor, most have struggled to develop houses that provide necessary amenities at a reasonable cost to each household. Sanitation facilities, more often than not, end up as a shared resource. Opportunities exist in the development of new, low-cost, robust materials that have the look and feel of current housing materials. Market deployment in urban areas would depend heavily on market models. Ideally new housing models could be pioneered by development companies or governments, which could reach significant scale in urban areas. See the chapter on Healthcare Delivery for a more detailed discussion of opportunities in improved housing. The projected time to market readiness is 6-8 years, and the difficulty of deployment is CHALLENGING.
Additives to facilitate the breakdown and/or disinfection of fecal sludge in pit latrines

One of the major problems with pit latrines is that they often fill up before fecal sludge is fully digested, creating the need to empty pit latrines or build new ones. Pit latrines are often emptied in a way that contaminates nearby land or water sources (from emptying services that don’t remove the sludge appropriately), and the need to build additional pit latrines increases the cost of sanitation for families. Additives can facilitate the breakdown of fecal sludge, reducing the need to empty latrines, which can result in contamination. Several options are currently being developed and tested including addition of higher organisms, microorganisms, and hydrolytic enzymes. In the longer term, opportunities could include use of fermenting organisms, development of new enzymes, or facilitation of the current microorganisms involved in digestion.

Distribution of additives at a meaningful scale is highly challenging, as a high percentage of individuals in a community would need to purchase additives to have a meaningful impact on health. This level of market penetration would require a large and consistent supply chain for biological compounds, which is challenging, particularly in rural areas. Additionally, perceived value to households is often low. There is little existing demand for additives.

The time to market readiness varies by type of additive. Some, such as the addition of higher organisms, are market ready. Others, like new enzymes, are conceptual and 7-10 years away from being market ready. The difficulty of deployment is CHALLENGING.
Water pumps that automatically disinfect with chlorine

Chlorine is considered by many to be an ideal form of water purification as it is simple and provides residual disinfectant properties for treated water (a critical characteristic, given water is often re-contaminated in the household). However, chlorine must be dosed appropriately – if the dose is too low then it will not disinfect the water, and if it is too strong it creates a significant bad taste and can be toxic.

One solution to this has been providing chlorine dispensers at water pumps in communities, which has had some success, but the need for family members to treat the water on an ongoing basis has reduced penetration and adherence. An ideal solution would remove the need for human action or creation of new habits.

A high-impact possibility is to develop water pumps, which automatically dose water as it is pumped, effectively treating water, providing residual protection, and removing the need for behavior change on the part of the user. The key technological challenge is a mechanism that provides appropriate doses of chlorine to water that is flowing dynamically. The mechanism would also need to be robust and low cost.

Challenges to at scale deployment include the lack of effective distribution channels, lack of demand from customers and the lack of clear business or distribution models that can ensure ongoing maintenance. Rather, many pumps are installed by governments or NGOs and rarely receive adequate ongoing attention. Chlorine also presents a specific challenge in having a relatively short half-life, which requires the creation of a reliable chlorine supply chain, although methods to manufacture chlorine at a local level do exist.

No low cost automatic chlorine-dispensing pump has yet been developed, although a handful are under development. The expected time to market readiness is 2-4 years and the difficulty of deployment is COMPLEX.

Breakthrough 4 – Difficulty of deployment

- Extremely Challenging:
  - Policies
  - Infrastructure
  - Human capital
  - Access to user finance
  - Behavior change
  - Existing demand
  - Market fragmentation/Distribution channels
  - Business model innovation

- Challenging:
  - Low role of policy / regulation
  - Low-moderate need for human capital development
  - Minimal behavior change required
  - Moderate financing needed, viable mechanisms identified
  - Moderate fragmentation of customers, under-developed channels
  - Low demand, needs to be built
  - Deployment model(s) being tested

- Complex:
  - Depend on existing infrastructure

- Feasible:
  - Simple
**Extremely simple point-of-use water treatment systems**

Multiple studies have shown that household water treatment is effective at reducing microbial contamination of drinking water, as well as reducing diarrheal disease. Both NGOs and major corporations have marketed these products with some success, although adherence and continued usage have been disappointing. Point-of-use water treatment systems tend to be complex and time consuming to use, which has led to low adoption, particularly in sub-Saharan Africa.

Importantly, families that are at the highest risk for diarrheal disease are the least likely to practice adequate household water treatment. In a *meta analysis*, Rosa and Clasen found that among families in the poorest quintile of surveyed African countries, only 5.5% of households practiced adequate household treatment, in contrast to a regional average of 10.6%, which is already low (Rosa & Clasen, 2010). They also found that rural populations were less likely to practice adequate household water treatment, despite having less access on average to improved water sources (Rosa & Clasen, 2010).

While there are a plethora of household water purification systems, there are none that sufficiently meet the needs of the poor. An adequate household water purification system, in addition to effectively removing all types of pathogens must be extremely simple to use (both in terms of process complexity and time required) as well as inexpensive. An ideal system would eliminate the need for human intervention. Such a system would face some difficulty in wide scale deployment, particularly due to low demand from users who may not see the value in purifying their water, especially if it is time consuming. That said, purification systems have been and continue to be marketed, so distribution channels are somewhat developed, and business models (direct to consumer marketing) are similarly somewhat developed. This provides a starting point for deployment, which could be leveraged by a water purification system that overcomes existing shortcomings for the user. Based on the above analysis, the time to market readiness is 2-4 years, and the difficulty of deployment is COMPLEX.

**Breakthrough 5 – Difficulty of deployment**

- **Extremely Challenging**
  - Policies
  - Human capital
  - Access to user finance
  - Behavior change
  - Existing demand
  - Market fragmentation/Distribution channels
  - Business model innovation
- **Challenging**
  - Infrastructure
  - Minimal role of policy/regulation
  - Moderate behavior change required with evidence of behavior change being viable
  - Low demand, needs to be built
  - Moderate fragmentation of customers, under-developed channels
- **Feasible**
  - Business model innovation
  - Moderate financing needed, viable mechanisms identified
  - Deployment models in process of scaling
- **Simple**
  - Business model innovation
  - Low-moderate need for human capital development
  - Dependent on existing infrastructure
As many developing countries experience economic growth, increasing urbanization, and declining disease burden from infectious disease, non-communicable diseases (NCDs) have become an increasingly important health concern. While the rise of NCDs has been most pronounced in wealthier developing countries, such as those in Latin America, these diseases are becoming increasingly important in South Asia and sub-Saharan Africa as well.

The leading cause of mortality amongst NCDs is cardiovascular disease (CVD), which represents 41% and 35% of NCD mortalities in South Asia and sub-Saharan Africa respectively. Contributing to this figure, and driven by many of the same risk factors, is diabetes, which is often considered a parallel epidemic. Diabetes is a key risk factor for CVD; half of all diabetic deaths are caused by CVD. Other key risk factors for CVD include hypertension, smoking, raised cholesterol and being overweight. Of these, hypertension is considered the most crucial. In sub-Saharan Africa, 46% of adults have raised blood pressure—more than in any other region of the world.

Key drivers of CVD mortality and risk factors include demographic trends such as increasing life expectancy, increased urbanization and inactivity, poor diets, and high rates of smoking, along with genetic risk factors like predisposition to diabetes and hypertension. In addition to these are challenges in the delivery of care. Medical systems in most developing countries were designed to treat infectious diseases rather than NCDs. Consequently, there is a broad lack of awareness about CVD and diabetes, and NCDs as a category are not a healthcare priority for most countries yet.

While technology can help reduce the overall disease burden of CVD and diabetes, there are no major technological breakthroughs in the next 10-15 years. Although incremental improvements like further reducing the costs of blood pressure or glucose monitors can be made, these devices are already inexpensive (either can be purchased for $10-$50). The most significant issues are systemic; unhealthy diets, lack of awareness about the diseases, and availability of care. Technology is not a key hurdle in addressing CVD or diabetes.
Non-communicable diseases (NCDs) are becoming increasingly prevalent in developing countries, primarily in middle income regions. Over the past few decades, life expectancy and incomes in developing countries have increased substantially, allowing for more prosperous and older populations. At the same time, the burden of NCDs has increased to the point that today more people in lower-middle income countries die from NCDs than from infectious diseases.

CORE FACTS AND ANALYSIS

NCDs in 2010 accounted for 54% of total DALYs worldwide, 45% of DALYs in South Asia and 24% of DALYs in sub-Saharan Africa (IHME, 2012). NCD mortality attribution is shown in Exhibit 1.

Exhibit 1: As countries become wealthier, NCDs contribute increasingly to overall deaths (WHO, 2013).

The bulk of NCD-driven mortality and morbidity in the developing world is in relatively higher income developing countries (in Latin America & the Caribbean, Middle East & North Africa, East Asia Pacific, and Eastern Europe & Central Asia), while the disease burden in lower income developing countries, particularly in sub-Saharan Africa, is still largely from infectious diseases. However, as life expectancies and incomes increase in South Asia and sub-Saharan Africa, so too will the relative importance of NCDs in public health (Exhibit 2 and 3). As in the case with the rest of this study, this chapter also focuses primarily on sub-Saharan Africa and South Asia.
Exhibit 2: As life expectancy increases, the attributable share of mortality due to NCDs rises. Sub-Saharan Africa and South Asia’s low life expectancies and young populations explain in part why NCDs are not as significant a source of mortality in these regions as in the rest of the world. As the populations in these regions age, NCDs are expected to occupy a greater share of causes of mortality (WHO, 2013) (UNDP, 2013).

Exhibit 3: As incomes rise, the attributable share of mortality due to NCDs rises. Higher incomes accompany urbanization, richer diets, and sedentary lifestyles. More significantly, higher incomes enable governments to provide more resources to controlling communicable diseases, feeding into the longer life expectancies seen in Exhibit 1 (WHO, 2013) (UNDP, 2013).

SSA - sub-Saharan Africa  SA - South Asia  MENA - Middle East & North Africa  EAP - East Asia Pacific  EE/CA - Eastern Europe & Central Asia  LAC - Latin American & the Caribbean
Cardiovascular disease: the leading cause of death

Among NCDs, cardiovascular disease (CVD) is the single largest cause of death (Exhibit 4). CVD causes nearly one-third of all NCD deaths in South Asia and sub-Saharan Africa and is over twice as prevalent as cancers—the next largest NCD category in these regions.

While CVD prevalence rates in developing regions are low due to young populations, age-standardized mortality rates are among the highest in the world. Higher age-standardized prevalence and lack of treatment options in low-income countries indicate that the combination of younger populations and higher communicable disease burdens are masking a CVD problem that will manifest itself more acutely as countries successfully address other public health burdens.

Exhibit 4: In most regions, CVD represents between a third and half of all deaths from NCDs (WHO, 2013).

CVD encompasses a range of conditions afflicting the heart and circulatory system. Notably, 2 conditions in this category account for 80% of all NCD mortality.

Ischemic heart disease
Also known as coronary heart disease, ischemic heart disease is characterized by the reduction of blood flow to the heart, usually due to atherosclerotic build-up in arteries. This disease is the leading cause of acute myocardial infarctions (AMI) or more generally, ‘heart attacks.’ An AMI can rapidly cause permanent heart damage or death. Ischemic heart disease accounts for 42% of CVD fatalities worldwide, 52% of CVD fatalities in South Asia and 30% of CVD fatalities in sub-Saharan Africa (IHME, 2012). Ischemic heart disease is the leading cause of death in South Asia.
Cerebrovascular disease
More commonly known as a ‘stroke,’ cerebrovascular disease results from a disturbance in blood flow to the brain, usually either through lack of blood flow or a blockage. Approximately one-third of CVD victims are killed by strokes, and another third are permanently disabled. Strokes account for 17% of all CVD fatalities in South Asia and 45% of all CVD fatalities in sub-Saharan Africa. Cerebrovascular disease is the most significant NCD cause of death and the fifth highest overall cause of death in sub-Saharan Africa (IHME, 2012).

Diabetes: a parallel epidemic
While diabetes is a separate disease, it shares many risk factors with CVD, particularly poor diets and low exercise. Diabetes is also one of the leading risk factors for CVD, the latter being a leading cause of death for diabetics. Half of diabetic deaths are caused by CVD. This is due both to the co-occurring risk factors with CVD as well as additional risk factors unique to diabetes such as high fasting blood sugar. Given the close relationship between the two, including common risk factors, we consider these diseases in tandem.

Diabetes mellitus, known simply as diabetes, refers to a group of diseases in which the body is unable to metabolize sugar. In Type 1 diabetes, also known as juvenile diabetes because it disproportionately affects children, the pancreas does not produce adequate insulin to break down the sugar. In Type 2 diabetes, also known as adult-onset diabetes because it occurs later in life, the body still produces insulin, but cells lose their ability to use the insulin to metabolize sugar. The third type of the disease, gestational diabetes, occurs when pregnant women suffer from very high glucose levels because their insulin receptors are disrupted. Of the 3 types of diabetes, the overwhelming share of the disease burden in developing countries (90%) is due to Type 2 (IDF, 2013), which is the focus of this section. Type 2 diabetes doubles the risk of CVD and can cause retinopathy and blindness, reduced blood circulation to limbs (which can lead to severe complications such as gangrene), long-term nerve damage, and kidney failure.

Diabetes has grown rapidly in the past 2 decades. The number of people with Type 2 diabetes globally has more than doubled between 1980 and 2008, from 150 million to 350 million. Current estimates place the number of people with diabetes globally at 382 million, which is expected to increase to 592 million in 2035 (IDF, 2013). In developing countries, 70% of this increase can be attributed to population growth and aging, while the remaining 30% is considered to be due to increasing prevalence (Danaei, et al., 2011). Prevalence of Type 2 diabetes in sub-Saharan Africa between 1960 and 1980 was lower than 1% but now stands at 4.8% and is expected to grow to 5.3% by 2035 (Mbanya, et al., 2010) (IDF, 2013). Prevalence in South Asia is predicted to increase from 8.2% currently to 10.1% by 2035 (IDF, 2013).

Metabolic syndrome and key risk factors
Growth of both CVD and diabetes has been linked to growth in metabolic syndrome and the risk factors associated with it. Metabolic syndrome is a cluster of 5 risk factors for CVD: central (abdominal) obesity, raised triglycerides, reduced HDL cholesterol, raised blood pressure, and raised fasting plasma glucose. Individuals are considered to have metabolic syndrome when they have central obesity and at least 2 of the remaining 4 risk factors. People with metabolic syndrome are twice as likely to die from CVD, and 3 times as likely to have a heart attack or stroke, as people without the syndrome. They are also 5 times
more likely to develop Type 2 diabetes (IDF, 2006). It is estimated that 20-25% of the world’s adult population has metabolic syndrome. While each of these factors independently increases the risk of CVD, the clustering that indicates metabolic syndrome appears to confer an additional cardiovascular risk beyond the sum of the individual risk factors (IDF, 2006).

The underlying causes of metabolic syndrome are still not fully understood, but insulin resistance and central obesity are believed to play key roles, in addition to genetics, physical inactivity, aging, a pro-inflammatory state, and hormonal changes (IDF, 2006).

Cardiovascular disease has several additional risk factors beyond metabolic syndrome and its contributing risk factors. The INTERHEART and INTERSTROKE studies focused on CVD specifically and identified 9 major risk factors, which are believed to drive 90% of the cerebrovascular and AMI burden. These risk factors and the odds an individual will have CVD relative to those without the risk factors are shown in Exhibit 4 (O’Donnell, et al., 2010) (Yusuf, et al., 2004).

Addressing CVD involves addressing the risk factors that drive it (Table 1). The most important and broad reaching risk factor is hypertension, which contributes to 45% of ischemic heart disease deaths and 51% of cerebrovascular disease deaths worldwide (WHO, 2013). The age-standardized adult prevalence rate of hypertension in Africa is 46% — the highest in the world (WHO, 2013). Hypertension is primarily driven by age, genetics, and certain behavioral factors like poor diet, lack of exercise, obesity, alcohol abuse, and psychosocial stress.

Odds ratios1 of various risk factors and AMI or Stroke (Odds Ratio > 1 indicates positive association)

<table>
<thead>
<tr>
<th>Risk Factors</th>
<th>AMI</th>
<th>Stroke</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypertension</td>
<td>1.9</td>
<td>2.6</td>
</tr>
<tr>
<td>Smoking</td>
<td>2.8</td>
<td>2.1</td>
</tr>
<tr>
<td>High cholesterol</td>
<td>3.3</td>
<td>1.9</td>
</tr>
<tr>
<td>Diabetes</td>
<td>2.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Overweight</td>
<td>1.1</td>
<td>1.7</td>
</tr>
<tr>
<td>Diet*</td>
<td>0.7 (healthy diet)</td>
<td>1.4 (unhealthy diet)</td>
</tr>
<tr>
<td>Exercise*</td>
<td>0.9</td>
<td>0.7</td>
</tr>
<tr>
<td>Moderate alcohol*</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Psychosocial stress</td>
<td>2.7</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Table 1: Various risk factors increase the likelihood of a serious CVD incident. These risk factors are responsible for 90% of the CVD burden worldwide (O’Donnell, et al., 2010) (Yusuf, et al., 2004).

*These are protective factors, which protect against CVD. Diet was defined as ‘healthy diet’ for the INTERHEART study and ‘unhealthy diet’ in the INTERSTROKE study.

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1 The likelihood that someone with a particular risk factor (e.g. hypertension) will have a particular outcome (e.g. AMI) relative to the likelihood that someone without that risk factor will have the same outcome.
KEY CHALLENGES

Reducing mortality from NCDs requires focusing on CVD as the end cause of death. In South Asia and sub-Saharan Africa, the drivers of mortality can broadly be classified under, (1) demographic, behavioral and genetic risk factors, and (2) challenges in delivery of medical care (WHO, 2013).

Demographic, behavioral and genetic risk factors

People are living longer
As mentioned earlier, life expectancy in developing countries has increased substantially over the past several decades through a combination of economic development, successes in combating infectious diseases, and improved access to basic healthcare and nutrition. These gains in life expectancy have resulted in the populations of these countries getting older. By 2025, the number of Africans over the age of 60 years is expected to double (Mbewu, 2009). Older populations are more vulnerable to NCDs like CVD and Type 2 diabetes, as shown in Exhibit 5.

Age distribution of mortality and disease burden in sub-Saharan Africa and South Asia

Exhibit 5: As life expectancy increases in developing countries, the population becomes susceptible to a different class of diseases such as CVD and diabetes, which disproportionately affect older people (IHME, 2012).
Urbanization and inactivity

There has also been an increase in the rate of urbanization in developing countries, which is linked to an increase in NCDs due to reduced physical activity and less healthy diets. As Exhibit 6 shows, urban populations tend to have higher rates of diabetes than their rural counterparts. The lower levels of physical activity are also contributing to higher rates of systolic blood pressure, a significant risk factor for CVDs in African countries. The bulk of the increase in CVD in India occurred in urban settings (Gupta, et al., 2008) and obesity has nearly doubled in urban areas of India between 1991 and 2006 (Cecchini, et al. 2010). In Africa, the highest rates of diabetes are in urban and peri-urban communities in South Africa (Mbanya, et al., 2010).

Prevalence of diabetes amongst adults in urban and rural settings

Exhibit 6: Urban populations suffer substantially higher rates of diabetes, likely due to factors such as lower levels of physical activity and higher consumption of processed foods (IDF, 2013).

Poor diets, high in processed foods

Dietary patterns in developing countries have also been changing (Pingali, 2004). Diets in low income countries often fail to meet the criteria for healthy eating (classified by the Alternative Healthy Eating Index). In some countries (e.g., in India), traditional foods have always been high in refined carbohydrates (e.g., white rice), sugar, salt, and tropical oils (Gupta, et al., 2011) (Hu, 2011) and have been a major contributor to diabetes. Unhealthy diets also contribute to hypertension (Institute of Medicine, 2010) (Hu, 2011).

High rates of smoking

Tobacco use is a significant risk factor for heart disease and diabetes. It is associated with a three-fold increase in the risk of non-fatal AMI (Teo, et al., 2006) and a 45% increased risk of diabetes (Hu, 2011). It is estimated that 82% of the world’s tobacco smokers live in developing countries (Teo, et al., 2006).
High blood pressure
Hypertension is caused by the previously mentioned risk factors as well as genetics and a high intake of salt. Globally, it is estimated than 40% of adults have raised blood pressure. In Africa, 46% of adults have raised blood pressure, higher than any other region in the world (WHO, 2013), which is particularly high considering that the demographic risk factors that generally influence hypertension are less pronounced in sub-Saharan Africa relative to other regions (i.e. sub-Saharan Africa has a small middle class, is still largely rural, has lower rates of obesity).

Hypertension is diagnosed easily either through an electronic blood pressure cuff or through an inflatable pressure cuff and a stethoscope. Hypertension is treated with two inexpensive and generic drugs—captopril and nifedipine—which are generally available, although they must be taken on a daily basis.

Diabetes
As mentioned earlier, while diabetes is a condition on its own, it is also a critical risk factor for CVD, with half of all deaths of diabetic individuals being caused by CVD. Diabetes is diagnosed using a glucometer—a blood glucose measurement device—which costs $10 - $20, although it requires single-use enzymatic strips. These strips are inexpensive to manufacture but are proprietary, which means specific strips work with a specific glucometer. This limits the availability of low cost strips in developing countries with small existing markets. Treatment of diabetes is challenging relative to high blood pressure. Early stage Type 2 diabetes can often be managed using only oral medication. Once the disease becomes more advanced, however, injectable insulin is required, which is more expensive, challenging to administer, requires a constant supply, and has some sensitivity to temperature. Moreover, patients being treated for both early stage and late stage diabetes need access to a glucometer to monitor their blood glucose on a daily basis.

Challenges in delivery of care
In addition to these trends and risk factors, there are 2 major challenges in reducing mortality from CVD and diabetes.

Broad lack of awareness of (and indifference towards) the risk factors, symptoms, or consequences
For decades, CVD and diabetes have been lower priority medical conditions relative to major diseases like TB, Malaria and HIV. Many individuals are unfamiliar with NCDs, the risk factors, and the options or need for care. The risk factors for diabetes and CVD are often considered a ‘normal’ part of life or can be mistaken for other conditions. In the absence of a reliable healthcare delivery system and a culture of regular medical tests, patients in low income settings can go many years without knowing about their condition (IDF, 2013) (Mbanya, et al. 2010). About 80% of diabetics in sub-Saharan Africa and 50% of diabetics in South Asia remain undiagnosed (IDF, 2013).

Medical systems were developed to treat infectious diseases and are poorly set up to manage chronic diseases
Healthcare systems in developing countries were built to primarily treat infectious diseases, where treatment occurs over a fixed period of time or care is focused on certain, distinct life events like birth, early childhood, or pregnancy. Chronic diseases like CVD and diabetes require different approaches to care, particularly mechanisms for broad screening and systems that facilitate disease management and patient compliance with treatment over the course of years, rather than weeks or months. The lack of appropriate delivery systems is compounded by patients’ approach to medicine in developing countries, where the concept of lifelong medication is extremely unfamiliar. Even in the United States, it is estimated that only about a third of individuals with hypertension are managing it effectively.
SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

CVD and diabetes are major public health challenges that require systemic interventions such as policy and healthcare system strengthening. While technology can support this, lack of technology is not the key bottleneck preventing a reduction in CVD mortality. The decrease in CVD mortality in developed countries can be linked with 3 pivotal aspects: increased awareness of CVD and its risk factors, timely diagnosis, and access to treatment. Reducing risk factors requires nutritional awareness and access to healthy foods, environments that enable physical activity, and actively discouraging the use of harmful substances like tobacco. Such national level behavior change interventions largely rely on government policy and implicitly demand economic development. Developing the medical system to provide more appropriate diagnosis and care for patients is also critical.

Implementing these changes in developing countries will require national level awareness campaigns about the risk factors and signs of CVD and diabetes, inclusion of blood pressure and glucose level screening in routine medical care, and increased distribution of medication to treat hypertension. Additional interventions could include increased distribution of oral medication for those with early stage diabetes and development of simple tracking systems to ensure compliance with treatment. In the longer term, insulin should be available to all diabetics who require it, although the logistical and cost challenges around daily use of insulin make this unlikely to be a wide scale possibility in the near future.

While existing technologies can be improved upon, the technological gaps when it comes to tackling NCDs are marginal as opposed to fundamental. Blood pressure and glucose monitors are already fairly inexpensive. Even as the price could be dropped further, their lack of usage is driven by factors other than cost and energy requirements. In the case of glucose monitors, improvements can be made in reducing the cost of proprietary enzymatic strips, although this is likely a market coordination or competition issue rather than a technological one. More fundamental improvements could be made in provision of insulin to late stage diabetics by making it thermostable, less expensive, and easier to use (oral not injectable). However, the reduction in disease burden from making insulin more widely available is still small relative to broader interventions such as regular health screening and influencing dietary and lifestyle habits.

A few technologies can help with behavior change in areas such as exercise and diet, and with the treatment of diabetes-related complications such as foot ulcers and eye disease. Treatment for foot ulcers leading to amputation is an area that appears to have some opportunity for technological innovation, particularly in devices that can help treat peripheral vascular disease.
Malnutrition is linked to 45% of all childhood deaths, and 165 million children across the world are stunted. Factors influencing nutrition, especially for children and women, are often complex, rooted in systemic and social issues, and extend well beyond simply satisfying caloric needs.

There are two primary lenses through which nutrition is viewed. The first is physical growth in early life, specifically in the first 1,000 days, stretching from conception to a child’s 2nd birthday. Growth during this crucial period is a strong predictor of adult height, as well as learning and earning potential. Children who are undernourished (and become stunted), are significantly more likely to experience disease. Linear growth requires a diverse diet including sufficient caloric intake, proteins, fats and micronutrients, absence of infectious disease (particularly from diarrheal pathogens) and appropriate feeding and care. The second lens for viewing nutrition is deficiency of key micronutrients, particularly iron, vitamin A, zinc and iodine. These critical micronutrients are linked closely to cognitive development, anemia, and the ability of a child to fight off infections. Micronutrients also play an important role in overall health throughout life.

While there are many technological breakthroughs that can support improved nutrition, there are a few game-changing opportunities in the first 1,000 day period. We identify 8 promising breakthroughs, focusing on the preservation of food and enhancing (and assessing) the nutritional content of food, that can vastly improve nutritional outcomes for both children and adults.

- Refrigeration and cold chain technologies for horticulture, meats, and milk
- Improved processing technologies to preserve food life and reduce degradation of nutritional content
- Improved storage technologies for grains and pulses to reduce development of mycotoxins
- Diagnostics to determine nutritional content and bioavailability of nutrients in foods
- Affordable, nutrient-dense complementary foods for infants
- Improvement of staple crops through breeding and genetic modification
- Ultra low cost packaging for food preservation
- Diagnostics and biomarkers to rapidly determine malnutrition, especially iron-deficiency anemia, in women and girls
Nutritional deficiencies due to suboptimal intake of carbohydrates, fats, proteins, and micronutrients like iron, zinc, folic acid, vitamin A and iodine, are among the most significant risk factors for death and disability in children in developing countries. Beyond supporting just health, good nutrition is vital for cognitive development and correlates with educational performance. Nutritional deficiencies underlie 45% of all child deaths, resulting in 3.1 million deaths annually (Black, et al., 2013).

**CORE FACTS AND ANALYSIS**

Nutrition is a broad area but is generally considered from the perspective of anthropometry or physical growth in early life, focusing on the nutritional needs to support normal and healthy growth in children. Growth is measured using physical metrics including weight for age, height for age, and weight for height at birth and throughout early childhood. In the past, the global burden of undernutrition was principally measured by tracking the prevalence of underweight, which refers to children with a weight-for-age 2 standard deviations below a population median. More recently, with the rapid emergence of overweight and obesity as global health concerns, the nutrition community has begun tracking prevalence of stunting—low height for age—as a superior indicator of nutrition and health. Whereas weight for age can be optimized through the provision of energy alone, through carbohydrates and fats, linear growth requires a high quality diet with protein and growth promoting nutrients, as well as absence of inflammation, infection and disease. In addition to supporting growth, nutrition influences susceptibility to infection in children; 33% of the disease burden from LRIs and 50% of the disease burden from diarrheal disease are attributable to malnutrition. Other infections where malnutrition is a major underlying factor include measles and typhoid (IHME, 2012).

**Nutrition and growth in early life**

Growth in early childhood, including height attained by the age of 24-36 months, is a strong predictor of adult height as well as future learning and earning potential. This has led to a focus on the first ‘1,000 days’ stretching from conception to a child’s 2nd birthday. Children who are stunted at the age of 2 often remain stunted throughout life.

Globally, 165 million children suffer from stunting, 101 million are underweight, and 52 million suffer from wasting. Wasting is an acute condition that requires medical intervention and is a challenge particularly in areas affected by drought, disaster and conflict. Preventing stunting in the first 1,000 days of life is considered critical for a child’s health and survival.

**Maternal health and nutrition during and before pregnancy**

The first factor driving a child’s development is the health of the mother entering, and during, pregnancy. The mother’s nutrition is important for assuring healthy fetal growth, a term delivery, and for providing adequate nutrition during the even more nutritionally demanding process of lactation. Mothers who are undernourished are more likely to give birth to low birthweight and small for gestational age infants.
Maternal health and nutrition during breastfeeding

The quality and energy density of breast milk is directly linked to a mother’s diet during the breastfeeding period. When a mother’s milk is low in fat (energy), the newborn must suckle more to receive sufficient nutrients to support optimal growth. This can be physically difficult for low birthweight babies, further contributing to faltering growth.

Childhood nutrition and health during breastfeeding and weaning

Exclusive breastfeeding is recommended for infants for the first 6 months of life. After the age of 6 months, babies should be given a combination of breast milk and complementary foods. The caloric and nutrient density and diversity of these foods are major factors contributing to adequate early growth. Having sufficient energy is important to maintain basal metabolic function as well as to support healthy growth, but energy (calories) alone is not sufficient to ensure that bone and muscles develop and grow properly. Healthy growth, in height and lean body mass, requires a diverse and nutritious diet and absence of disease. Any infection or inflammation either diverts nutrients away from growth to mount an immune response, or wastes them due to poor absorption and inefficient utilization. Hygiene and sanitation are important for preventing diarrhea and subclinical inflammatory processes. There is also evidence that other environmental conditions, including stress, can interfere with nutrient use and healthy growth.

The second lens for characterizing nutrition is ‘Hidden Hunger’ or micronutrient deficiencies. In this context, 4 micronutrients are particularly critical.

Iron-deficiency anemia

Anemia is a condition when the body does not have sufficient red blood cells. While it can be caused by many conditions, such as blood loss or hereditary conditions, the primary driver in developing countries is iron deficiency. Iron is required to produce hemoglobin, the protein that carries oxygen in red blood cells. When there is insufficient intake of iron, usually found in red meat and leafy green vegetables, the body cannot produce enough red blood cells. Globally, anemia affects 1.6 billion people and iron deficiency is the leading cause. In sub-Saharan Africa, anemia affects 68% of preschool age children, 47% of non-pregnant women and 57% of pregnant women. The most common symptom of anemia is chronic fatigue, although it can also cause symptoms such as dizziness, irregular heartbeat, and cognitive problems. Anemia can also increase the likelihood of post-partum hemorrhage in pregnant women (Kavle, et al., 2008). Iron deficiency affects a mother’s ability to supply oxygen and iron to the fetus, and increases the
risk of low birthweight in the infant. A recent review found that iron supplementation in pregnant women reduced at-term anemia by 70%, and the rate of low birthweight babies by 19% (Peña-Rosas, et al., 2012).

**Vitamin A and zinc**

Found in a mix of meats, fruits and vegetables, vitamin A and zinc serve a range of critical needs like fighting infections, healing wounds, and tissue repair. Without an adequate intake of these nutrients, children are more susceptible to infectious diseases. Around the world, 33% of preschool age children—190 million—and 15% of all pregnant or lactating women suffer from vitamin A deficiency (Klemm, et al., 2010). One study found that Vitamin A supplementation in infants caused a 14% reduction in mortality within the first 6 months of life (Haider & Bhutta, 2011). A similar analysis showed that zinc supplementation reduced incidence of diarrhea by 13% and reduced pneumonia morbidity by 19% (Yakoob, et al., 2011).

**Iodine deficiency**

Almost 2 billion individuals around the world suffer from insufficient iodine intake. This leads to cretinism and other forms of cognitive developmental delays. Iodine deficiency is considered the single largest preventable cause of mental retardation (UNICEF, 2008).

The Global Burden of Disease models that protein-energy malnutrition or underweight, as it is more commonly known, and iron-deficiency anemia account for 96% of the direct disease burden from nutritional deficiencies, as well as 99% of fatalities (Exhibit 1) (IHME, 2012). Childhood malnutrition, across the developing world, is more prevalent in rural areas than in cities (Smith, et al., 2004). Exhibit 2 shows statistics for stunting and wasting in rural vs. urban areas in South Asia, sub-Saharan Africa, and Latin America & the Caribbean.

Over the past 20 years, the disease burden from underweight has decreased significantly, but the same is not true for anemia (Exhibit 3). The global prevalence of stunting, as an indicator of underweight, has decreased by 31% since 1990. Although the DALYs rate of anemia has decreased by 25%, the increase in population has kept overall DALYs essentially constant (IHME, 2012).

In addition to the effects of nutritional deficiencies, the risk of over-nutrition, which leads to obesity and related non-communicable diseases (NCDs) has garnered increasing attention in the last few years. Unhealthy diets comprising an excess of sugar or fat, and too few fruits and vegetables, combined with inactive lifestyles are leading to a dramatic increase in diabetes, cardiovascular disease and obesity. These NCDs currently account for 28 million deaths in low and middle income countries (NCD Alliance, 2013), and this figure is expected to grow. We address nutrition-related NCDs in a separate chapter on cardiovascular disease and diabetes, rather than this one on core nutritional deficiencies.

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1 Many experts preferred to use data sources beyond the Global Burden of Disease which utilizes complex modeling. We use IHME data here for its availability over the past two decades.
Conditions that drive disease burden and deaths due to nutritional deficiencies

Exhibit 1: Two nutritional conditions—iron-deficiency anemia and underweight—account for the vast majority of DALYs and deaths caused by nutritional deficiency. While the direct disease burden of other major nutritional conditions is low (e.g., deficiency of Vitamin A, folic acid, zinc), they have a high indirect impact (e.g., through decreased immunity to infectious diseases) (IHME, 2012).

Prevalence of stunting and wasting in developing countries

Exhibit 2: Childhood malnutrition is somewhat more prevalent in rural areas of developing countries (Smith, et al., 2004).

Disease burden from various nutritional deficiencies

Exhibit 3: The disease burden of underweight has decreased significantly in recent decades, but iron-deficiency anemia and other nutritional conditions have not (IHME, 2012).
KEY CHALLENGES

There are 4 broad challenges in addressing nutritional deficiencies, 3 of which relate directly to early childhood growth while one pertains specifically to the problem of iron-deficiency anemia. These challenges extend well beyond simple dietary intake (although diet is a crucial challenge), to also include the health and care of young children.

Lack of rich, diverse diets, early in life

Newborns often receive poor diets beginning with suboptimal breastfeeding and continuing through the first 2 years of life.

Breastfeeding
The WHO recommends, “immediate breastfeeding within the first hour of life, exclusive breastfeeding up to 6 months of age, with continued breastfeeding along with appropriate complementary foods up to two years of age or beyond.” Breast milk provides key nutrients for infants, as well as antibodies that protect against infections like diarrhea and pneumonia (Fleming & de Silva, 2009). On the other hand, substitutes like infant formula and other foods do not contain the antibodies found in breast milk, are expensive, and can lead to diarrheal disease when such food is prepared with unsafe water or in unsterilized feeding bottles. Still, due to cultural factors, lack of knowledge and support, and other impediments, less than 40% of infants under the age of 6 months are exclusively breastfed (WHO, 2013). Furthermore, the nutritional quality of breast milk is linked to the nutritional intake of the mother, and mothers who are undernourished or are not eating a diverse and nutritious diet produce lower nutritional quality breast milk for their babies.

Weaning
The nutritional content of complementary foods is critical as the infant weans off breast milk. Due to an infant’s small stomach, it is important that complementary foods be high in nutritional value to support growth. However, in many countries infants are given thin cereal-based porridges that lack nutritional diversity.

Childhood and beyond
Nutritional deficiencies continue as a health concern well past the first 1,000 days. There are several additional diet-related challenges that affect children, adolescents and adults of all ages in developing countries.

- Lack of access to fruits and vegetables, which provide critical nutrients that are not found in sufficient quantities in cereals. Fruits and vegetables are often more challenging to grow than cereals and available easily only during harvest times; they are more sensitive to stresses and water availability, and once harvested have a limited shelf life in the absence of appropriate cooling or refrigeration. These foods are also more expensive than cereals, thus reducing access for low income families.
- Inadequate access to or a tradition of not feeding young children animal source foods like meat, poultry, eggs, and dairy that are rich in easily-absorbed iron, is a major driver of iron deficiency.
- Lack of awareness about the importance of dietary diversity—and what it entails—leads to infants and young children primarily being fed grain-based foods.
- The absence of agricultural cold chains and in-home refrigeration limits access to horticulture products and the ability to store perishables.
- Increasing abundance of low priced, highly processed foods that are high in fat and sugar particularly in urban settings.
Increasing abundance, and in turn consumption, of low priced, highly processed foods (high in fat and sugar) in place of healthier alternatives, particularly in urban areas, can lead to conditions like obesity.

Unclean water, poor sanitation and hygiene conditions inhibit absorption of nutrients

Diarrheal disease and intestinal nematode infections lead to reduced nutrient absorption and can cause long-term intestinal damage, inhibiting nutrient absorption long after the infection has cleared (Brown, et al., 2011). Diarrheal disease significantly increases the risk of stunting, especially before the age of 24 months (Checkler, et al., 2008). Fecal pathogens also cause environmental enteropathy, which can lead to long-term reduction in nutrient absorption even in the absence of frequent diarrheal episodes (Brown, et al., 2013). Young children are extremely vulnerable to diarrheal disease and gut enteropathy. Other infections and inflammation can also affect nutrition by diverting nutrients away from growth for immune response. These concerns have been discussed in greater detail in the chapter on water quality, sanitation and diarrheal disease.

Improper care of the infant

Core to the health of a child is the care he or she receives from the mother. Key behaviors related to nutrition include feeding practices and care seeking practices. The former entails knowledge of what comprises a rich and diverse diet and how to prepare and store complementary foods while the latter entails recognizing signs of sickness and seeking care when necessary. Often, cultural practices can be at odds with what is best for the child. For instance, taboos exist in some cultures against bringing an infant out of the house and this limits access to care if the infant is sick. Proper care of the infant is increasingly being linked to a mother’s education, her own self-efficacy, self-confidence, and control over the family’s resources. Many of these issues are believed to be more severe in urban settings where support networks are often weaker.

Intestinal nematode infections, and to a lesser extent, malaria infections (for anemia specifically)

Chronic blood loss resulting from parasitic infections, primarily hookworm, trematodes and whipworm are a major cause of anemia in children. Although anemia caused by blood loss is not iron-deficiency anemia explicitly, it exacerbates the effects of iron deficiency. Both conditions, nematode infection and iron-deficiency anemia, are very common and tend to occur together. Smaller-scale studies have found that, particularly in areas with a high hookworm burden, deworming can lead to reduced anemia (Smith & Brooker, 2010). However, the effectiveness of large-scale deworming programs is a controversial topic and the subject of significant debate. Malaria too can contribute to iron-deficiency anemia (Verhoef & West, 2003).
As the above discussion suggests, nutritional deficiency is driven by systemic issues tied to broader food production and food infrastructure, economic development, education, gender dynamics, and the extent to which women have control over a family’s resources and food. Programs like deworming, free school lunches for low income students, and conditional cash transfers can serve as effective safety nets for vulnerable populations, but these are likely not a sustainable substitute for deeper systemic change.

**Refrigeration and cold chain technologies for horticulture, meats and milk**

Refrigeration prolongs the life of and can preserve the nutritional content of many food items including fruits, vegetables and animal proteins. Requirements for refrigeration technologies vary along the cold chain, including farm-level storage, transport, central storage and household level storage, but in general the key parameters are cost and energy requirements.

There are a handful of primary refrigeration technologies, the most common being vapor compression. This is a powerful cooling technology but has a minimum efficient scale, which makes it challenging to produce small-scale compression refrigerators. Absorption refrigerators run on fuel, usually kerosene, making them an easy off-grid option, but they are complex systems that utilize toxic chemicals, and the cost of kerosene is high. Thermoelectric refrigeration can be scaled down to very small sizes, and thus be used to make small, cheap refrigerators, but these refrigerators are less efficient than compression technologies, have less cooling power, and therefore are less suitable for dense, warm products like milk. Simpler cold chain possibilities, like cold water bathing and cool chambers, do not provide the same level of preservation, are limited in scope, and appropriate only at the farm and or household level. Most rural and many urban areas do not have access to reliable power. A suitable refrigeration technology will need to be able to function with intermittent power supply. There are numerous approaches to solving this challenge, often involving cooling water during periods when electricity is available to maintain cold temperatures in the absence of electricity.

Deployment issues vary by customer segment such as farm use vs. home use, or household consumers vs. businesses. In general, consumer surveys and small experimental refrigeration products have affirmed that there is a strong demand for refrigeration both at the household level and at commercial levels. The projected time to market readiness for appropriate refrigeration and cold chain products is 1-3 years, and the difficulty of deployment is FEASIBLE.
Improved processing and storage technologies to preserve food life and reduce degradation of nutritional content

Due to the seasonal nature of agriculture, farmers experience major swings in the availability of different foods. This is often most acute with fruits and vegetables, which spoil fairly rapidly after harvesting, leading to limited availability. Drying and processing preserves the life of food and often its nutritional content, thereby reducing the seasonal nature of hunger.

Specific technological needs vary depending on the food items (e.g. grains vs. vegetables). In general, however, drying, processing and storage technologies need to be less capital intensive and should preserve as much of the nutritional content of the crop as possible. This is an area of emerging research. Milling rice, for example, often strips away nutritional content in the germ, although it also removes phytates, which bind nutrients and can prevent their absorption. The full impact of processing on nutrition requires continued research for improved understanding.

In most cases there is no fundamental technological issue to overcome. Rather, these are technologies that have received minimal attention. While there are some technologies capable of, for example, hermetic or air tight storage, none are at a cost that would enable scale. When it comes to drying and processing technologies, the primary constraint is developing a technology with a low enough cost to enable a sustainable deployment model.

The projected time to market readiness varies widely. Some new products may enter the market within 1-2 years, while other products have received such little attention that they will likely not be introduced for 7-10 years. The difficulty of deployment is similarly varied, but due to low margins and the need to target remote, rural areas, the expected difficulty of deployment is CHALLENGING.
Improved storage technologies for grains and pulses to reduce development of mycotoxins

Mycotoxins are poisonous compounds that are created primarily by fungi that accumulate during harvest and post-harvest storage and processing. The FAO has estimated that as much as a quarter of the world’s crops could be contaminated with mycotoxins. The problem is believed to be most acute and least understood in sub-Saharan Africa followed by South Asia. In particular, aflatoxins are known to build up in maize and groundnuts, when crops are improperly dried and/or stored in cool, damp places in the household. Chronic exposure to mycotoxins has been linked to malnutrition, impaired immunity and various forms of cancer.

There are multiple approaches to preventing contamination from mycotoxins. Storage technologies have focused on prevention of insect infestation, which can cause exposure to fungi spores, and technologies to reduce condensation. Biological strategies include development of fungi or bacteria that can outcompete the mycotoxin producing fungi. Chemical strategies have generally focused either on compounds that prevent insect infestation or those that prevent the growth of fungi.

Different approaches are at various stages of development. Several compounds are being tested and some are nearly market ready. However, any successful technology will face major deployment challenges. Mycotoxin poisoning is poorly understood by most smallholder farmers. Moreover, there are few distribution channels that address smallholder farmers, where most contamination occurs.

While market readiness varies by technology, some technologies could be ready within 2-4 years. The difficulty of deployment for any technology is EXTREMELY CHALLENGING.
**Breakthrough 3 – Difficulty of deployment**

<table>
<thead>
<tr>
<th>Simple</th>
<th>Feasible</th>
<th>Complex</th>
<th>Challenging</th>
<th>Extremely Challenging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Policies</td>
<td>Infrastructure</td>
<td>Human capital</td>
<td>Access to user finance</td>
<td>Behavior change</td>
</tr>
<tr>
<td>Low role of policy / regulation</td>
<td>Moderate need to train a limited number of people</td>
<td>Moderate behavior change required with evidence of behavior change being viable</td>
<td>Extremely low demand or not a perceived need</td>
<td>No identified deployment model, major hurdles identified</td>
</tr>
<tr>
<td>Dependent on existing infrastructure</td>
<td>Moderate financing needed, viable mechanisms identified</td>
<td>Fragmented market, weak distribution channels</td>
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**Diagnostics to determine nutritional content and bioavailability of nutrients in foods**

Many nutrition interventions rely on provision of fortified foods to address nutrient gaps. While there are multiple processes to fortify staple foods, creating quality assurance, and safety controls is challenging due to the difficulty of assessing nutritional content in food. Assessments are usually done in laboratories, which are rarely sufficiently resourced to either accurately assess nutritional content of food or handle the sheer number of samples that need testing. Due to this lack of quality assurance, a major nutrition agency has estimated that as much as half of ‘fortified’ food staples do not actually contain enough supplemental nutrients to create desired health benefits. In order to address this issue, better diagnostics are needed that can assess the nutritional content and bioavailability of nutrients in food. The ideal device would produce rapid results and be usable in a field rather than lab setting.

There is little applied research being done in this area. Only a small number of universities or companies are developing rapid micronutrient testing devices, with at least one nearing market release. Further work related to precision, validation and local reagent production need continued research. Detecting Vitamin B9, iodine and zinc deficiencies, in particular, require rapid diagnostic technologies.

The current market for such devices is concentrated. Only a small number of entities have an existing need for such a device. These institutions could benefit greatly from such a diagnostic and may be somewhat price insensitive, although cost is still expected to be a major barrier. A dearth of commercial demand for diagnostics and a lack of willingness within local governments to enforce micronutrient testing in food remain significant hurdles. The projected time to market readiness is about 1-3 years, and the difficulty of deployment is COMPLEX.
Affordable, nutrient-dense complementary foods for infants

Complementary foods are critical for the health of infants who consume a relatively small volume of food, yet have high nutrition needs. In most countries across sub-Saharan Africa and South Asia, infants are given thin grain-based porridges that deliver limited nutritional value. Nutrient-dense complementary food supplements have been developed and distributed successfully on a small scale, but these food supplements are expensive and lack a sustainable deployment model. A sizable portion of the end cost comes from the price of milk powder, packaging and distribution. In most areas there is weak demand for these products as customers do not see such supplements as an essential commodity. Customers are also cost sensitive given that infants need complementary foods for 18 months. While technological advances are required to bring down costs, a viable deployment model is the critical bottleneck.

The projected time to market readiness is about 3-5 years, and the level of difficulty for deployment is EXTREMELY CHALLENGING.
**Breakthrough 5 – Difficulty of deployment**

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<tr>
<th>Breakthrough 6</th>
<th>Difficulty of deployment</th>
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</thead>
<tbody>
<tr>
<td>Policies</td>
<td>Simple</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>Complex</td>
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<tr>
<td>Human capital</td>
<td>Challenging</td>
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<tr>
<td>Access to user finance</td>
<td>Extremely Challenging</td>
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<tr>
<td>Behavior change</td>
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<tr>
<td>Existing demand</td>
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<tr>
<td>Market fragmentation/Distribution channels</td>
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<tr>
<td>Business model innovation</td>
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<tr>
<th>Breakthrough 5</th>
<th>Improvement of staple crops through breeding and genetic modification</th>
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Major investments have been made in development of crops, which are biofortified with key micronutrients, either through traditional breeding or genetic modification. A prime example of genetically modified grains is Golden Rice, engineered to contain beta-carotene, a biochemical precursor to vitamin A. Additional efforts have been made to breed crops with greater protein, iron, zinc and provitamin A.

The broader question of genetic modification has been highly controversial. Among the problems cited by critics are untested long-term environmental externalities and the possibility of corporate monopoly over seeds, although proponents note that many nutritious transgenic biofortified seeds have been developed in the public domain. This has led to significant public discord that has, barring a few exceptions, prevented genetically modified organisms (GMO) from being adopted at scale in sub-Saharan Africa. Certain GMO crops are banned entirely in many African countries. While this genetic biofortification could yield significant health benefits, careful consideration of risks and appropriate regulatory changes are necessary to allow GMOs intended to treat malnutrition to reach meaningful scale. Nutrition content of crops can and has been improved through more conventional breeding techniques, although the potential of non-genetic modification is more limited.

The projected time to market readiness varies by crop and nutrient, with some crops being market ready while many more are in development. Deployment faces a number of barriers, including heavy regulation in many markets, the lack of seed distribution networks to reach rural farmers, the lack of readily visible benefits and volatility in rain-fed African agriculture, which suppress investment. Based on these challenges the expected difficulty of deployment is EXTREMELY CHALLENGING.
Diagnostics and biomarkers for rapidly detecting malnutrition in women and girls

There are limited tools to ‘diagnose’ malnutrition. Stunting is measured by comparing a child’s height to average heights for children of the same age. While this is an adequate overall measure, there are opportunities to diagnose various nutritional deficiencies more precisely. There is no effective way, for example, to determine whether an infant is receiving the nutrients essential for healthy growth. Diagnostics for anemia exist and are improving, but none of the non-invasive anemia diagnostics have reached scale yet. At a higher level, the lack of good diagnostic data has impeded the creation of policy-making resources such as maps about the prevalence of nutritional deficiencies.

The technologies underlying these diagnostics vary based on what is being measured, but in many cases the technology base is minimal or nonexistent. Non-invasive and non-laboratory dependent methods need to be developed and appropriate biomarkers identified.

Distribution challenges vary by model. Diagnostics intended for aid agencies that want to gather data on malnutrition should be fairly easy to distribute given the ready market. Wider-scale interventions, however, such as getting simple anemia diagnostics into schools to help diagnose the large number of anemic adolescent girls will be challenging.

The projected time to market readiness varies by technology, but is likely 4-10 years depending on the diagnostic goal. The level of difficulty for deployment for the more difficult of these technologies is CHALLENGING.
Breakthrough 7 – Difficulty of deployment

- **Extremely Challenging**
  - Policies: Requires high level of training for large numbers of people
  - Infrastructure: Requires high level of training for large numbers of people
  - Human capital: Regulated market with supportive policies
  - Access to user finance: Regulated market with supportive policies
  - Behavior change: Requires high level of training for large numbers of people
  - Existing demand: Requires high level of training for large numbers of people
  - Market fragmentation/Distribution channels: Requires high level of training for large numbers of people
  - Business model innovation: Requires high level of training for large numbers of people

- **Challenging**
  - Policies: Requires high level of training for large numbers of people
  - Infrastructure: Requires high level of training for large numbers of people
  - Human capital: Requires high level of training for large numbers of people
  - Access to user finance: Requires high level of training for large numbers of people
  - Behavior change: Requires high level of training for large numbers of people
  - Existing demand: Requires high level of training for large numbers of people
  - Market fragmentation/Distribution channels: Requires high level of training for large numbers of people
  - Business model innovation: Requires high level of training for large numbers of people

- **Complex**
  - Policies: Requires high level of training for large numbers of people
  - Infrastructure: Requires high level of training for large numbers of people
  - Human capital: Requires high level of training for large numbers of people
  - Access to user finance: Requires high level of training for large numbers of people
  - Behavior change: Requires high level of training for large numbers of people
  - Existing demand: Requires high level of training for large numbers of people
  - Market fragmentation/Distribution channels: Requires high level of training for large numbers of people
  - Business model innovation: Requires high level of training for large numbers of people

- **Feasible**
  - Policies: Requires high level of training for large numbers of people
  - Infrastructure: Requires high level of training for large numbers of people
  - Human capital: Requires high level of training for large numbers of people
  - Access to user finance: Requires high level of training for large numbers of people
  - Behavior change: Requires high level of training for large numbers of people
  - Existing demand: Requires high level of training for large numbers of people
  - Market fragmentation/Distribution channels: Requires high level of training for large numbers of people
  - Business model innovation: Requires high level of training for large numbers of people

- **Simple**
  - Policies: Requires high level of training for large numbers of people
  - Infrastructure: Requires high level of training for large numbers of people
  - Human capital: Requires high level of training for large numbers of people
  - Access to user finance: Requires high level of training for large numbers of people
  - Behavior change: Requires high level of training for large numbers of people
  - Existing demand: Requires high level of training for large numbers of people
  - Market fragmentation/Distribution channels: Requires high level of training for large numbers of people
  - Business model innovation: Requires high level of training for large numbers of people
Accurate and timely diagnosis increases the likelihood of successful treatment. Diagnostics play a particularly vital role in clinical scenarios where patients present with non-specific symptoms that are common to multiple diseases, or in situations where the specific strain of the disease must be identified to determine the correct treatment regimen. Since many infectious diseases are asymptomatic, diagnostics are necessary for screening asymptomatic patients. This helps prevent long term complications from untreated infections and decreases the rate of disease transmission within communities. Diagnostics are also essential for monitoring treatment effectiveness for chronic diseases like diabetes. Indeed, diagnostics inform and influence 60-70% of healthcare decisions.

Unfortunately, the diagnostics currently on the global market have a number of serious shortcomings for use in resource-poor settings. Most reliable diagnostics require clinical infrastructure, and need to be administered by highly trained healthcare workers; as such, they are not suitable for point-of-care use. Most of the simpler diagnostics that have been deployed on a large scale are proving to be inadequate due to low sensitivity or specificity, and the inability to determine the drug susceptibility of the infecting pathogen. Today, 60% of people in developing countries have access to only poorly equipped, peripheral health clinics. This means that their diagnoses are often unreliable, or they have to incur high out-of-pocket expenses at distant facilities with better equipment and more trained staff.

To meet the needs of these patients, a new generation of innovative diagnostics need to be developed. These tests must be portable and lightweight, capable of operating without grid electricity, be tolerant to high ambient temperature and humidity, be able to withstand physical shock while being transported, and be simple enough to be used by minimally trained healthcare workers at the point-of-care. There are 4 technological breakthroughs which can make that possible.

- Automated and multiplex immunoassays that can test for a wide range of diseases, and are compatible with easily collected sample types
- A point-of-care nucleic acid test (NAT) that is simple, robust and compatible with easily collected sample types
- Fully integrated bench-top diagnostic platforms that eliminate the need for individual platforms for separate disease conditions
- Discovery of new biomarkers, especially those available through easily accessible and easily processed sample types
Around the world, clinical assessment is core to the diagnosis of disease. Diagnostic testing confirms or disproves clinical suspicion, enables early detection of disease, and allows clinicians to provide patients with the right treatment quickly, including triage to a higher level of care. Importantly, diagnostics inform and influence as much as 60-70% of healthcare decision-making (The Lewin Group, 2005), but must be used in conjunction with appropriate treatments and other interventions to have real impact on health outcomes.

CORE FACTS AND ANALYSIS

Diagnostic tests play a particularly crucial role when the patient’s symptoms are non-specific (common to multiple diseases requiring different treatments), or when the treatment is sufficiently expensive that it is given only to those with confirmed cases of infection (Mabey, et al., 2004). In such clinical scenarios, diagnostics increase the chances of successful therapy and decrease the chances of mis-treatment or over-treatment. This is critical for diseases such as malaria where drug resistance threatens the long term viability of existing treatments, or diseases where different treatment protocols exist for different pathogen strains, as is the case with TB. Even after treatment selection, diagnostics play an important role in monitoring treatment effectiveness for diseases like HIV, where treatment is chronic and efficacy of treatment regimens must be closely tracked. Since many infectious diseases are asymptomatic, diagnostics also play a critical role in screening asymptomatic patients; this helps prevent long term complications from untreated infections and decreases the rate of disease transmission within communities.

In this chapter, we focus on diagnostic challenges and needs in peripheral health centers and clinics (‘Level 1’ health facilities), in developing countries. Currently, for 60% of people in the developing world, point-of-care facilities are peripheral health clinics, which are typically poorly resourced with little in the way of reliable electricity, clean running water, laboratories, laboratory equipment (e.g., centrifuges, refrigerators), or well-trained clinicians (Nantulya, 2006) (Girosi, et al., 2006). Patients seeking care in such settings often do not have access to reliable diagnostics. The problem is particularly acute for diseases like TB, where existing diagnostic methods most commonly employed in such settings have proven lacking due to low sensitivity and specificity, and the inability to determine the drug susceptibility of the pathogen. Diagnostic uncertainty today exacts an enormous toll in morbidity and mortality in the developing world by implicitly restricting the control of non-communicable diseases and the most fatal infectious diseases, particularly where HIV is prevalent (Perkins & Small, 2006).

Innovative diagnostic tools need to be developed and deployed in low resource settings, especially in developing countries.

There are 4 main categories of analytes (indicators) of disease

Our focus is on in vitro diagnostics, the predominant method for testing for various diseases. In vitro diagnostics utilize a fluid or tissue sample from a patient to identify the presence, absence or changed quantity of specific ‘analytes’, or molecular indicators of disease, through a biological or chemical analysis.

1 Convergence of infectious diseases such as TB and HIV exacerbates the negative impact of weak diagnostic tools. HIV in TB-endemic settings increases incidence and the population of symptomatic individuals, while co-infection decreases the sensitivity of microscopy for accurately diagnosing TB.
The 4 main categories of analytes measured by in vitro diagnostic technologies are explained below.

Cells
Cell-based diagnostics are a mainstay of modern medicine and rely on the evaluation of whole cells to detect the presence of certain diseases and for hematological analysis. Information on full blood cell counts is required to diagnose and monitor conditions such as HIV/AIDS, for which CD4+ T-lymphocyte counting (CD4 count) forms the basis of monitoring disease progression. Most cell-based diagnostics, in their current form, are not practical for use in low resource settings because they generally require sophisticated laboratory facilities, stable electricity, and highly skilled personnel. Moreover, the success rate of these diagnostics is dependent on the skill level of the technician running the assay.

Proteins
Proteins found in patient samples such as whole blood, serum/plasma, saliva, urine, and other samples are important for diagnosing a variety of diseases. At the point-of-care, protein detection is done using both immunoassays and enzymatic assays. Tests are available for viral infections (anti-HIV antibodies, antibodies against influenza A/B virus, rotavirus antigens), bacterial infections (antibodies against Streptococcus A and B, Chlamydia trachomatis, Treponema pallidum), parasitic infections (histidine-rich protein 2 for P. falciparum, trichomonas antigens), and non-communicable diseases (PSA for prostate cancer, C-reactive protein for inflammation, HbA1c for plasma glucose concentration) (Chin, et al., 2013).

Nucleic acids
Nucleic acid detection is used in prenatal diagnosis of inherited disorders, diagnosis of genetic disease, identification of infection, disease staging, and to measure drug resistance. Nucleic acid testing (NAT) detects the presence of a pathogen either by directly detecting the presence of the pathogen’s genetic material (DNA or RNA) in the host, or by first amplifying the pathogen DNA or RNA, and then using probes that are specific to the pathogen of interest. Advantages of NAT include high sensitivity due to amplification, and specificity, given that it targets unique sequences associated with the pathogen of interest. NAT can detect low-level infections when either the amount of the infecting agent is very low or when the immune system hasn’t had time to form antibodies against it. This reduces the time between infection and diagnostic detectability of the disease (Chin, et al., 2013). This method can be used to accurately quantify the level of infection, for typing of strains, and for determining drug resistance profiles, which are significant issues in diagnosing and treating diseases like TB and HIV.

Small molecules
Small molecules from a variety of bodily fluids can be used to measure health parameters. Examples include testing of iron levels to indicate anemia in pregnancy, blood glucose for diabetes monitoring, and lipid levels for cholesterol monitoring. Such tests analyze a range of electrolytes like potassium ion and chloride, physiologically important molecules like urea, lactate, albumin and creatinine, and blood gases. These tests are based on electrochemical detection such as potentiometry, amperometry and conductance (Chin, et al., 2013).
Over the years, a number of point-of-care diagnostic tests and devices have been developed.

In order to benefit the majority of developing world patients, diagnostic tests must be portable and lightweight, capable of operating without clean water or electricity and of withstanding heat, humidity, and transport, and simple enough to be used by minimally trained health care workers at the point-of-care. For none of the analytes above have diagnostic tests been fully optimized for use in low resource settings. Nevertheless, there are a number of relevant point-of-care diagnostic applications, profiled below.

Cell-based assays
Point-of-care cell-based diagnostics are becoming increasingly important in hematology, particularly for the quantification of white blood cells for diagnosing, monitoring, and clinical staging of diseases like HIV/AIDS. Such tests aim to replace resource-intensive laboratory technologies, like flow cytometry, which are typically not viable in low resource settings (Chin, et al., 2013). Most technologies being developed now are self-contained, portable, handheld, do not require extensive sample processing, and have the potential to meet the pressing need for a point-of-care CD4 count quantification method for the management of HIV/AIDS (Chin, et al., 2013).

Immunoassays
These assays utilize the binding of an antibody (naturally produced by the immune system to neutralize pathogens) to an antigen, to diagnose a disease. Immunoassays make use of the binding interactions between antigens and antibodies to detect protein markers from either the pathogen or the host immune response. Immunoassays generally rely on either a visual read-out for the healthcare worker administering the test, to show whether the antigen or antibody of interest is present, or on a fluorescent dye that can be quantified using a plate reader, microscope, or other detection methods. Immunoassays are considered the gold standard laboratory assays for diagnosing a variety of diseases that involve natural host immune responses, including infectious diseases like HIV/AIDS and a wide variety of autoimmune diseases such as multiple sclerosis. In the developing country context, immunoassays have led to simple, low cost rapid diagnostic tests (RDTs), based on simplified ELISA (Enzyme-linked immunosorbent assay) testing techniques, for a small number of important conditions: malaria, HIV/AIDS, syphilis, hepatitis B (RDTInfo, 2013), as well as proteinuria and pregnancy. These tests have yielded significant improvement in health outcomes across the developing world, and have overcome the challenges of traditional immunoassays (namely personnel training and equipment), by including all of the reagents as part of the test and producing a visual readout that is easy to interpret. Critically, these tests are based on patient samples like nasal swabs, urine, saliva, or whole blood that can be collected using minimally invasive techniques, by healthcare personnel with limited training. Currently, most RDTs are ‘strip tests’ or ‘dipsticks’ and rely on low cost immunochromatography (ICS) technology to detect antigens or antibodies.

Nucleic-acid testing
Nucleic acid tests are high cost, complex, and require trained laboratory technicians. They are therefore mainly used in hospitals and centralized laboratories (LaBarre, et al., 2011). The difficulty of developing a self-contained, simple, robust and cost-effective NAT system for use at the point-of-care has a lot to do with the technical difficulties of integrating the steps of sample preparation, nucleic acid amplification, and detection, which will be explored in more detail later in this chapter. Despite these difficulties, there is increasing emphasis on bringing NAT to the point-of-care. One commercial example is Cepheid’s
GeneXpert® test platform for TB, which is currently available in many developing countries. However, this system requires uninterrupted and stable electrical power supply and annual validation of the system to ensure test accuracy (Chin, et al., 2013), limiting its use in low resource healthcare settings. GeneXpert® utilizes a realtime fluorescence-based technique for polymerase chain reaction (PCR) detection. Other detection approaches being explored for NAT at the point of care include electrochemical methods, lateral flow devices for end-point detection, and magnetic resonance (Chin, et al., 2013).

**Clinical chemistry assays**
These assays measure a variety of blood parameters including gases, electrolytes, hemoglobin, pH, enzymes, metabolites, lipids, hormones, vitamins and trace factors, inflammatory markers and cytokines, coagulation proteins, therapeutic drugs, and drugs of abuse (Chin, et al., 2013). Point-of-care testing of these clinical chemistry markers is preferable as test accuracy can reduce when samples are transported to central laboratories for testing. Very few peripheral healthcare facilities in the developing world today carry out clinical chemistry testing. Some instruments that use an electrochemical detection method for measurement of electrolytes, general chemistries, blood gases and hematocrit, are not widely available yet at the point-of-care. Others are still exploring optical detection methods that have the potential to reduce the cost of clinical chemistry assays at the point-of-care (Chin, et al., 2013).

**Hematology**
At the point-of-care, hematology tests are widely used for measurement of hemoglobin and hematocrit to test for anemia, and to measure blood coagulation. Several companies have developed point-of-care technologies to measure such parameters, including Sphere Medical, Abbott Diagnostics, Roche Diagnostics, and Alere (Chin, et al., 2013).

### Current diagnostic technologies for major diseases have a number of shortcomings

To be accessible to low income patients seeking care peripheral healthcare facilities, diagnostic tests need to be inexpensive, portable, robust, capable of operating without heavy reliance on clean water or electricity, able to withstand ambient heat and humidity, and simple enough to be used by minimally trained healthcare workers. Based on their ability to meet such requirements, diagnostic methods currently being used have a number of shortcomings, as summarized for four major disease conditions, in Table 1.

### The state of diagnostic technologies for 4 major diseases: HIV/AIDS, TB, Malaria and Lower Respiratory Infections

<table>
<thead>
<tr>
<th>Diagnostic needs</th>
<th>HIV/AIDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Identification of infection/disease screening</td>
<td></td>
</tr>
<tr>
<td>2. Disease staging to determine treatment initiation (CD4 count)</td>
<td></td>
</tr>
<tr>
<td>3. Monitor treatment efficacy/failure (viral load and drug resistance)</td>
<td></td>
</tr>
</tbody>
</table>

1 Decreases in the CD4+ T lymphocyte cell population are indicative of progression of HIV to AIDS. As many HIV drugs result in toxicities from long-term use, the WHO uses CD4+ cell counts in parallel with clinical staging to determine when antiretroviral (ARV) therapy should be initiated.
| Methods used in developed countries | 1. Screening: ELISA-based immunoassay and rapid diagnostic tests  
2. Disease staging: Flow cytometry (cell-based)  
3. Viral load and drug resistance: Nucleic acid-based tests in central labs
| Methods used in developing countries | 1. Screening: Rapid immunoassays that do not require lab facilities  
Confirmatory tests can be done with a minimum of 2-3 different rapid assays in high prevalence areas  
2. Disease staging: Flow cytometry in central labs; new handheld devices are beginning to be available  
3. Viral load and drug resistance: Nucleic acid-based tests in central labs
| Challenges with current mechanisms in developing countries | 1. Rapid immunoassays can be of poor quality, and cannot store data to link patients to care following a positive test result  
2. CD4 monitoring requires expensive lab equipment and trained personnel. Simplified bench-top devices cost >$20,000, require regular electricity, and are costly to repair and maintain, largely limiting their utility to centralized laboratory facilities in the developing world  
3. Nucleic-acid tests require expensive lab equipment and trained personnel, making their widespread implementation in low resource settings very difficult. There are currently no point-of-care viral load tests
| Promising technologies | 1. Hand-held CD4 counters  
2. Nucleic-acid based POC diagnostic for viral load testing
| Hurdles to broad penetration | 1. Regulatory harmonization  
2. Quality control/assurance  
3. Training and appropriate use of RDTs by healthcare providers  
4. Data management and link to care  
5. Affordability

### Pulmonary Tuberculosis

| Diagnostic needs | 1. Identification of active TB disease  
2. Determination of drug susceptibility
| Methods used in developed countries | 1. Bacterial culture from sputum / sputum smear or chest radiograph  
2. Drug susceptibility testing (DST) via line probe assay (LPA)
| Methods used in developing countries | 1. Sputum Smear Microscopy (SSM) based on laboratory diagnosis of TB through microscopic examination of specially stained sputum for the presence of acid-fast bacilli (AFB)  
2. Smear-negative and MDR-TB diagnosis: bacterial culture (or liquid culture)
| Challenges with current mechanisms in developing countries | 1. SSM is insufficient:  
- Requires extensive training for those administering the test, and delivers low-throughput results  
- Not highly sensitive, no better than 60% under the best circumstances; <50% in patients with HIV co-infection  
- Does not identify smear negative TB (common among HIV positive patients)  
- Cannot detect drug-resistant TB

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1. The majority of tests today monitor viral load by using nucleic acid amplification techniques to detect the presence of viral nucleic acid. Treatment failure occurs when viral load does not drop, or repeatedly rises after have dropped previously, in what is called virologic failure.

2. More than 25 commercially available rapid tests for HIV screening have been independently evaluated by the WHO and many have demonstrated acceptable sensitivity, specificity, and suitability for use in resource poor settings.
### Challenges with current mechanisms in developing countries

- Cannot detect extra-pulmonary TB
- Only a fraction of drug-resistant patients are accurately diagnosed:
  - DST if available, is only performed after treatment failure
  - Most existing culture and DST laboratories in resource-limited settings do not meet minimum standards for laboratory biosafety or technical proficiency

### Promising technologies

- Point-of-care NATs

### Hurdles to broad penetration

- Affordability
- Lack of laboratory infrastructure and capacity has limited the penetration of tests for drug-resistant TB

### Malaria

<table>
<thead>
<tr>
<th>Diagnostic needs</th>
<th>Identification of infection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methods used in developed countries</td>
<td>N/A</td>
</tr>
<tr>
<td>Methods used in developing countries</td>
<td>Rapid immunoassays that do not require access to lab facilities</td>
</tr>
<tr>
<td>Challenges with current mechanisms in developing countries</td>
<td>Rapid immunoassays can be of poor quality, and cannot store data to link patients to care following a positive test result. Further, they do not enable differential diagnosis between malaria and other causes of febrile illness</td>
</tr>
<tr>
<td>Promising technologies</td>
<td>‘Fever panel’ for differential diagnosis</td>
</tr>
</tbody>
</table>
| Hurdles to broad penetration | 1. Regulatory harmonization  
2. Training and appropriate use of RDTs by healthcare providers  
3. Data management and link to care  
4. Lack of patient confidence in negative test results  
5. Proving cost-effectiveness of fever panel |

### Lower Respiratory Infections

| Diagnostic needs | 1. Identification of pneumococcal infection and etiology  
• *Streptococcus pneumoniae*  
• *H. influenzae*  
• RSV  
• Influenza  
• Other pathogens |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Methods used in developed countries</td>
<td>Chest x-ray and/or bacterial culture from sputum or blood</td>
</tr>
</tbody>
</table>

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1. Very few patients are tested for malaria in the developed world, as the disease has been eliminated in these regions.
Methods used in developing countries

| Sympotmic management or use of diagnostic surrogates (e.g., arm circumference, chest auscultation) |

Challenges with current mechanisms in developing countries

| Diagnostic approach to disease management is lacking due to: |
| • Difficulty of sample acquisition (particularly sputum from children) |
| • Lack of pathogen identification, which relies on bacterial culture with long lead-times |
| • Poor link to appropriate therapy |
| • Lack of radiography |

Promising technologies

| 1. Rapid tests for differential diagnosis of viral vs. bacterial infection |
| 2. Multiplex tests |

Hurdles to broad penetration

| 1. Selection of targets for multiplex tests |
| 2. Proving cost-effectiveness and clinical value of multiplex tests |
| 3. Training and appropriate use of by healthcare providers |

Table 1: There are several gaps in the current state of diagnostics available to low income populations and their healthcare providers for the four major infectious diseases—HIV/AIDS, TB, Malaria and lower respiratory infections. These gaps are different for each disease.6

Diagnostics for patients in developing countries need to consider several other factors

In addition to meeting operational requirements of low resource settings, several additional technical parameters must be considered in the design of appropriate diagnostics for the developing world. Ideal diagnostic solutions will account for broader health trends, and the needs of national public health systems. Three significant dimensions are listed below.

Drug resistance

A number of infectious diseases are developing drug-resistant strains, in turn complicating the already difficult task of diagnosis and treatment. For such diseases, it is critical to go beyond simple detection, and recognize whether or not the strain is drug-resistant, and to what particular treatment will the infecting pathogen be sensitive to. With TB, in particular, the emergence of multiple drug-resistant strains is making it important to identify the specific drugs to which the pathogen or bacterium is resistant to. This means that the diagnosis needs to go beyond a ‘yes or no’ detection of drug-resistant TB. In cases of co-infections (such as HIV-TB co-infection) such detection becomes even more critical as combining two separate treatments may reduce the efficacy of one or more drugs being administered to a patient.

Storing and transmitting data

For public health systems to plan broader disease control strategies, it is very helpful to track cases as well as epidemiological and health statistics obtained during diagnoses. Additionally, there is strong need to store and transmit patient data from point-of-care to higher-level health facilities and national-level databases. This data may be used to prevent patient dropout due to lack of followup, enable ongoing clinical management of patients that need protracted treatment, and to enable efficient inventory

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4 Diarrheal disease, caused by bacterial, viral, or parasitic agents, is primarily diagnosed by clinical symptoms and has been excluded from this table. Immunoassay-based, nucleic acid amplification-based, and culture-based diagnostic techniques are available for multiple specific causes of diarrhea. However, all of these diagnostics require access to sophisticated laboratory facilities. As diarrheal disease is managed by supportive rehydration therapy and non-specific medications, specific diagnosis is generally not considered essential.
management, quality assurance and need-based training for healthcare providers. The proliferation of mobile information and telecommunications platforms makes such a capability possible (Reid, 2012).

**Multiplexing capabilities**

Often, poor patients are more likely to suffer from low immunity due to malnutrition, inadequate hygiene and other risk factors, and thus face a higher possibility of infection from multiple diseases or pathogens. Additionally, different diseases can present with similar symptoms, such as fever. In such cases, a single device or platform capable of simultaneously diagnosing multiple diseases that present with similar symptoms will be extremely valuable. Specific examples of clinical scenarios in which multiplex testing would be desirable, and examples of specific diagnostic panels are provided later in this chapter. The importance of multiplex testing must be carefully balanced against affordability; adding additional pathogen tests to a diagnostic device adds to overall costs. The selection of multiplex tests should be determined based on the clinical actions that will be informed through this differential diagnosis, and the improved health outcomes that can be achieved by doing this.
KEY CHALLENGES

With the above criteria in mind, current diagnostic products and technology applications fall well short of what is required for affordable and effective diagnosis for a number of important diseases and medical conditions. Several technical challenges play a role when it comes to developing point-of-care diagnostics for low resource settings.

Available immunoassay rapid diagnostic tests (RDTs) have significant limitations

Immunoassays have several limitations that restrict their suitability in low resource settings. First, high ambient temperatures and humidity, common to many developing countries, and the lack of refrigerated storage can cause degradation of patient samples and diagnostic reagents, which limits assay sensitivity and shelf life. Second, antibodies can persist beyond the clearance of an infection. Immunoassays that rely on detecting antibodies in a patient can measure only the one-time existence of an infection, and not whether the infection is active or has cleared (BVGH, 2012). Such tests can also result in a false negative result when there is either a low level of antigenemia, or when the antigens have short life cycles (LaBarre, et al., 2011). Third, due to inadequate regulations, there is a proliferation of poor quality or counterfeit products (Mehta & Cook, 2010). Finally, immunoassays cannot generally be used for identifying specific strains of pathogens or test for drug resistance. Thus, while lateral flow RDTs have represented an important advancement over diagnosis based entirely on clinical symptoms for a number of diseases, consistently high performance tests that allow for external quality control are essential.

NATs have proven difficult to develop for point-of-care use

NATs require the use of unstable or sensitive reagents, specific infrastructure or equipment, and highly trained staff. Integrating these essentials into portable, user friendly, and affordable tools, appropriate for use by minimally trained staff in low resource settings is extremely difficult. NAT is time-consuming and typically involves three steps: sample preparation (consisting of sample collection and processing), signal amplification, and detection. Several challenges within each of these steps makes the current implementation of NAT at the point-of-care prohibitively complex (Chin, et al., 2013).

Sample preparation
An intrinsically complicated process, sample preparation involves cell or virus capture and isolation, lysis (breaking down of the cell wall or viral coat), and nucleic acid extraction and purification. This generally requires laboratory equipment such as a centrifuge or vacuum manifold. Optimal sample preparation is critical to the outcome of the NAT assay. Post extraction, the nucleic acids are prone to degradation, which can lead to misinterpretation of results. Subsequent sequence amplification steps are highly sensitive to contaminants that result from incomplete purification. Further, the risk of cross-contamination between separate samples also poses a significant obstacle to the reproducibility and reliability of NAT assays. Overall, the time-consuming nature of sample collection and processing, and the training and infrastructure requirements associated with sample preparation limit the applicability of NAT at point-of-care in low resource settings.
The ability to develop improved diagnostic tests is limited by the availability of biomarkers of disease

In the context of diagnostics, biomarkers are measurable indicators of organisms or diseases in human tissue or bodily fluids. Known disease biomarkers are necessary to develop diagnostic tests. Ideally these samples should be easily obtainable. Depending on the availability of biomarkers for specific diseases, multiple diagnostic technologies may be needed to analyze multiple types of samples. An expert panel organized by the American Society of Microbiology singled out the identification of novel biomarkers as “having the most potential” to contribute to the development of new point-of-care tests (Reid, 2012).

There are a range of challenges related to biomarkers for diseases prevalent in developing countries. For some diseases, relevant biomarkers have not been identified yet, while there are a number of diseases for which known biomarkers require sample types that are difficult to obtain. For example, meningitis\(^7\) can only be diagnosed by analyzing cerebral spinal fluid, which must be obtained through an invasive lumbar puncture; TB, on the other hand, generally relies on sputum, which can be a difficult sample to obtain (from children) and process (for patients of all ages). Some biomarkers represent only a subset of the organisms that are responsible for a single disease, and other biomarkers depend on a host response that can be variable and can lack sensitivity. There is a need for new biomarker discovery, but this is an unpredictable scientific challenge. Current incentives do not support biomarker discovery; long timelines, high costs, and low returns are unattractive to industry, and it does not offer the promise of rapid publication sought by academics (Mehta & Cook, 2010).

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\(^7\) Except for cryptococcal meningitis.
Multiplex diagnostic test panels to support clinical needs are yet to be defined

As mentioned earlier, there is increasing recognition of the value of multiplex diagnostic platforms that can diagnose multiple conditions within a single patient visit. To perform a true differential diagnosis, a broad test menu must be available at the point-of-care. The Bill & Melinda Gates Foundation has been defining such panels of tests for a number of important conditions and clinical scenarios. These represent complete panels required for treatment decisions, and a departure from the historical focus on disease specific tests; except for the neglected infectious diseases category (Gates Foundation, 2013).

Potential multiplex diagnostic platforms for point-of-care use

Exhibit 1: A number of diagnostic panels are required for thorough treatment decisions. This is a departure from the historical focus on disease specific tests (Gates Foundation, 2013).

Other tests with a potential to greatly impact healthcare and health outcomes in the developing world include (Reid, 2012):

Bacterial vs. viral infection

Syndromes such as fever or upper respiratory infections can be caused by many different pathogens like viruses, bacterium, fungus or parasites. No simple test that can determine the cause of such seemingly commonplace illnesses, exists yet. Such a test should ideally be able to determine the resistance profile of the causative agent; but even a simple differentiation among causative agents will go a long way towards enabling appropriate treatment (e.g., antibiotics vs. antimalarials). Such tests could be customized further to reflect and address specific needs of a region. For example, a ‘fever panel’ in a malaria endemic area could capture various causes of fever including bacterial infection, viral infection, and different malaria strains.
STD panel
Sexually transmitted diseases (STDs) affect patients and their partners, and can also be transmitted to fetuses by pregnant mothers. It would be useful to have a single test to differentiate between syphilis, herpes simplex, trichomonas, chlamydia, and HPV. A rapid test for HPV can also be used as a screening test for determining the risk of contracting other STDs.

Central nervous system infections
Meningitis (with the exception of cryptococcal meningitis) can only be diagnosed by examining cerebral spinal fluid that is obtained through lumbar puncture. This is an invasive procedure and requires highly trained caregivers. A simpler test that can also differentiate bacterial and viral meningitis, and the pathogens responsible for encephalitis and meningitis, would be extremely useful for enabling appropriate treatment. This depends on the discovery of new biomarkers.

‘State of health’ panel
There are opportunities to develop panels of tests outside of infectious diseases, which might measure health indicators related to chronic or non-communicable diseases (NCD) such as diabetes, or heart disease. NCDs represent 43% of the global burden of disease and are expected to be responsible for 60% of the disease burden and 73% of all deaths by 2020 (WHO, 2013). A rapid test that can provide information such as white cell count, lipid profile, and other indicators can also be of great value in enabling effective clinical case management.
Diagnostic tests that are robust, inexpensive, and simple to use have the potential to greatly improve quality of healthcare in the developing world. Today, approximately 60% of the target patient population in developing countries lacks access to advanced diagnostics tools (Nantulya, 2006). This is a result of poor infrastructure (unreliable access to power, lack of indoor climate control, poor cold chain storage conditions, and lack of trained technologists), limited menu of available diagnostic tools, and cost barriers including both capital investment in equipment and per-test costs.

To improve diagnosis at the point-of-care in resource-poor developing world settings, there is a clear need for simpler and smaller instruments. Test development should focus, in the short term, on single tests for critical disease-specific unmet diagnostic needs such as point-of-care tests for HIV viral load monitoring or TB drug susceptibility. In the medium term, platform technologies that offer broad menus of tests in a variety of sample types, that previously required multiple detection technologies, could be the answer. Finally, the ultimate breakthrough will be an integrated and comprehensive ‘semi-open source’ diagnostic system that processes samples, performs assays, and automatically reports results for a range of conditions, using components made by different manufacturers.

Automated and multiplex immunoassays that can test for a wide range of diseases, and are compatible with easily collected sample types

The development of point-of-care immunoassays that can use different types of samples (e.g., blood, urine, sputum), and test for multiple biomarkers from a single patient sample represents a major breakthrough applicable to a wide range of disease conditions. Next generation immunoassays will be multi-well, micro-scale, will integrate and automate steps from sample preparation through detection, and be appropriate for use in low resource healthcare settings.

Several different types of point-of-care immunoassay platforms have been attempted, including antibody microarrays, immunosensors, microwell arrays, and microfluidic chips, or combinations of these. Microfluidics represents an important technology for point-of-care immunoassays, given that microfluidics offer increased surface-to-volume ratios, which can be exploited by immunoassays that capture analytes’ surfaces (Chin, et al., 2013).

However, challenges of developing such immunoassays, including the high sensitivity of detection required for measuring analytes in small sample volumes, the robustness and reproducibility in performing micro-scale assays, and miniaturized component manufacturing, have not yet been fully overcome.

Overall, several hurdles limit the development, deployment and adoption of new diagnostic technologies. Development is being hindered by the relatively small investments currently being made in developing diagnostics relative to developing new drugs and vaccines. Deployment finally rests on regulatory processes, WHO endorsement, and the enormous capital expenditure required of countries that may look towards adopting new diagnostics on a large scale. Regardless of how pressing a need a new diagnostic may be, two other factors impact end adoption of new diagnostics: the costs and resources required to adequately train healthcare workers to use new tests, and patients’ willingness to pay for these new tests.

Based on the above assessment, the projected time to market readiness is 4-6 years, and the difficulty of deployment is EXTREMELY CHALLENGING.
A key breakthrough in disease detection is the development of point-of-care NATs applicable to a wide range of disease conditions. These tests should be compatible with simple sample types (such as whole blood), portable, rapid, robust despite high heat and humidity, non-reliant on refrigeration, running water, and stable electricity, user friendly and capable of being used by minimally trained technicians. In addition, the technology should have a low price-point to make it appropriate for use in peripheral healthcare facilities. Developing such a test poses significant technical challenges; it requires modular, instrument-free technologies for each of the NAT steps: sample processing, signal amplification, and detection (LaBarre, et al., 2011).

Sample preparation technologies
The manual, time-consuming and infrastructure-intensive sample collection, processing, and purification associated with preparing an optimal sample for NAT must be integrated and automated so that minimally trained healthcare workers can perform testing. Non-invasive sampling technologies, simplified extraction techniques, sample concentration technologies, and purification-free chemistries can help advance this goal.

Signal amplification technologies
The thermocycler, electricity, and temperature control required for PCR make NAT unsuitable for point-of-care adoption in low resource settings. New technologies that are less sensitive to sample
contaminants, have simpler thermal profile mechanisms that reduce sample processing requirements, and are not dependent on grid electricity, appear to be the way forward. Also critical is reduced reliance on cold chains and refrigeration. This will come from improvements in packaging, the ability to monitor temperature history, and the use of more stable substitutes in place of heat-sensitive reagents. Additionally, NATs that do not have to rely on stable grid power may depend on improved battery technology, solar chargers or generators, or any other new technology breakthroughs that provide instrument-free heat sources.

Detection technologies

Optical detection poses a challenge because of its potential dependence on extensive equipment. There are new detection technologies that do not rely on optical detection, including measurements of mass, magnetic properties, diffraction, or electrical potential that may enable development of more robust detection systems (Mehta & Cook, 2010).

Developing a point-of-care NAT will further depend on advancements in micro-fabrication and the ability to miniaturize test components that allow for multiplexing, reductions in sample size, and reduced reagent costs (Reid, 2012). Microfluidic platforms may yield a possible path forward for NATs as well, as demonstrated by the GeneXpert test for TB (Chin, et al., 2013). Deployment challenges for simplified NATs are similar to those listed in Breakthrough 1.

Based on the above assessment, the projected time to market readiness is 4-6 years, and the level of difficulty is EXTREMELY CHALLENGING.

**Breakthrough 2 – Difficulty of deployment**

<table>
<thead>
<tr>
<th>Extreme Challenging</th>
<th>Challenging</th>
<th>Complex</th>
<th>Feasible</th>
<th>Simple</th>
</tr>
</thead>
<tbody>
<tr>
<td>Policies</td>
<td>Infrastructure</td>
<td>Human capital</td>
<td>Access to user finance</td>
<td>Behavior change</td>
</tr>
<tr>
<td>Dependent on existing infrastructure</td>
<td>Requires high level of training for large numbers of people</td>
<td>Moderate behavior change required with evidence of behavior change being viable</td>
<td>Low demand, needs to be built</td>
<td>Highly fragmented, challenging to reach customers.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Policies</th>
<th>Infrastructure</th>
<th>Human capital</th>
<th>Access to user finance</th>
<th>Behavior change</th>
<th>Existing demand</th>
<th>Market fragmentation/Distribution channels</th>
<th>Business model innovation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highly regulated market with policy changes required</td>
<td>Requires high level of training for large numbers of people</td>
<td>Moderate behavior change required with evidence of behavior change being viable</td>
<td>Low demand, needs to be built</td>
<td>Highly fragmented, challenging to reach customers.</td>
<td>No identified deployment model, major hurdles identified</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fully integrated single diagnostic platforms, that eliminate the need for individual platforms for separate disease conditions

In the long term, the ultimate diagnostic breakthrough would be the development of a bench-top diagnostic platform that could integrate a wide variety of individual platforms like an optical reader for HIV screening, a bench-top chemistry analyzer, an analyzer for CD4 counting, NAT for TB diagnosis and viral load testing. Such a platform would be able to perform all diagnostic test menus required at the point-of-care in peripheral health clinics. The ideal technology would be portable, rapid, non-reliant on refrigeration, running water, and grid electricity, function effectively in high heat and humidity, and be capable of being used by minimally trained technicians. In addition, the technology would have a low price-point (less than $5,000).

Moving towards a single platform may help limit the capital expenditure which would be required of countries attempting to adopt a wide variety of diagnostic platforms. Additionally, aligning around a single platform pares down the effort of training healthcare workers to use a wide variety of tests, reduces the need to service and maintain multiple platforms, and optimizes the use of limited bench-top space available in peripheral health clinics.

There remains significant uncertainty around both the technical feasibility of integrating multiple technologies onto a single device, as well as private industry willingness to participate in an ‘open-source’ or ‘semi open-source’ model. Once developed, aligning around a single diagnostic platform will require buy-in from a wide array of stakeholders, including donors, implementers, healthcare practitioners, and national governments. Even if a wide range of diagnostic platform technologies can be integrated, developing the broad menu of tests required will take significant time, and in many cases is dependent on biomarker discovery. Based on the above assessment, the projected time to market readiness is 10+ years, and the difficulty of deployment is EXTREMELY CHALLENGING.

Breakthrough 3 – Difficulty of deployment
The discovery and validation of novel biomarkers in readily available sample types that specifically address developing world diseases is a critical unmet need. The expert panel of the American Society of Microbiology identified several areas that are ripe for biomarker discovery in the developing world context, including: antibiotic resistance, immune status, inflammation, virulence factors, disease stage, disease progression, and response to treatment (Reid, 2012).

There has been swift expansion in the potential range of biomarkers, from specific gene sequences and surface markers, to ratios of expressed genes, to quantitative measures of antibody or pathogen levels, to detection of specific metabolites, proteins, and lipids. New biomarkers, especially those available through easily accessible sample types, can support the development of new tests that can then run on the next generation of point-of-care diagnostic platforms. However, discovery of novel biomarkers is scientifically unpredictable and requires significant additional investment. As biomarkers become available in accessible sample types, diagnostic test developers can easily incorporate them into new tests for the developing world. Still, there will be challenges in getting clinicians to uniformly learn and adopt the new practices.

Based on the above assessment, the projected time to market readiness is 10+ years, and the level of difficulty is COMPLEX.
DIAGNOSTICS GLOSSARY

- **Assay** A term used to describe the procedure used for conducting a diagnostic test.
- **Analyte** Entity or target that is being analyzed (can be an ion, a protein, a cell, a molecule, etc.).
- **Enzyme-linked immunosorbent assay (ELISA)** A biochemical technique used mainly in immunology to detect the presence of an antibody or an antigen in a sample. In ELISA an unknown amount of antigen is affixed to a surface so that it can bind to the antigen. This antibody is linked to an enzyme, and in the final step a substance is added that the enzyme can convert to some detectable signal.
- **Flow cytometry** The analysis of characteristics of a particle or cell as it flows in a fluid through a beam of light.
- **Fluorescence** The emission of radiation (usually visible light) by a substance that has been exposed to light or other electromagnetic radiation.
- **Immunoassay** A biochemical test that measures the concentration of a substance in a biological liquid, typically serum or urine, using the reaction of an antibody or antibodies to its antigen.
- **In vitro diagnostics (IVD)** Medical device products including instrument and reagents that utilize a variety of methods and formats to perform tests on human samples in order to assess disease risk, diagnose a condition, or monitor a patient’s health.
- **Lateral flow test** A simple device intended to detect the presence (or absence) of a target analyte in sample. Lateral flow tests are a form of immunoassay in which the test sample flows along a solid substrate via capillary action, and are often produced in a dipstick format.
- **Microfluidics** Deals with the behavior, precise control, and manipulation of fluids that are geometrically constrained to a small, typically sub-millimeter, scale.
- **Multiplexing** Simultaneous measurement of multiple analytes in single reaction vessel.
- **Nucleic acid** Macromolecule composed of chains of monomeric nucleotides. These molecules carry genetic information or form structures within cells. The most common nucleic acids are deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). Nucleic acids are universal in living things, as they are found in all cells and viruses.
- **Polymerase chain reaction (PCR)** A technique to amplify a single or few copies of a piece of DNA across several orders of magnitude, generating thousands to millions of copies of a particular DNA sequence.
- **Thermal cycling** A temperature modulation process developed to improve the performance, strength, and longevity of a variety of materials.
Delivery of quality, affordable healthcare for low income communities in developing countries remains one of the most challenging and elusive goals in global health. The problem is systemic. There are very few functioning peripheral clinics; not enough qualified clinicians practice in low income areas; existing medical devices are too expensive; and there is far too little funding in most developing countries to build the health system from the bottom-up. External aid, which has historically focused on major infectious diseases, has proven neither sufficient nor sustainable for structural change. Evidently, sustainable solutions will have to be systemic. Clinicians have to be trained and certified, policies have to be reformed in order to ensure governance, people have to be convinced to invest in preventative care, and financing mechanisms like affordable health insurance have to become widely available. In addition, the absence of affordable medical devices, and the lack of access to electricity and clean water pose significant barriers to building functional low cost peripheral clinics. To augment gains made through wider systemic changes, living conditions for the poor have to be improved, so that they are less exposed to pathogens and toxins in the environment. There are 4 breakthroughs that can contribute to delivery of healthcare.

- A thermo-stabilizing mechanism for vaccines and other temperature sensitive pharmaceuticals
- Solar-powered, portable, refrigeration for vaccines (and other temperature sensitive pharmaceuticals), for remote, off-grid areas
- An easy to install, easy to operate, affordable (in the $10,000-$15,000 range), integrated, and solar-powered suite of medical devices specifically for maternal, child and primary care in low resource settings
- A new kind of a home—made with strong lightweight material—especially for the urban poor, with a private toilet, solar-powered lighting and ventilation
Major investments in global health since the announcement of the Millennium Development Goals (MDGs)—from initiatives and organizations like PEPFAR, GAVI, and the Global Fund to Fight AIDS, TB and Malaria—have led to significant progress and improvements in a number of health conditions. However, these initiatives have largely been vertical programs aimed at combating specific communicable diseases, with limited investment in system-strengthening (Travis, et al., 2004). Consequently, there is now a recognition of the value of ‘diagonal’ approaches in which effective disease-specific programs also build elements of sustainable delivery systems (Kim, et al., 2013).

**CORE FACTS AND ANALYSIS**

The historical lack of investment in development of healthcare infrastructure and delivery systems remains a fundamental hurdle to improving overall national health outcomes. One important contextual factor to consider, however, is that some of the basic constraints of the past few decades may no longer be as difficult to overcome today. Proliferation of technologies like solar-power, mobile networks and low cost ICT devices like smartphones and tablets, have made efficient and effective healthcare delivery a much more viable prospect now. In the words of one expert (Interview, 2013), delivery can evolve from a ‘hub-and-outreach’ model to a ‘hub-and-spoke’ model in which brick-and-mortar clinics can be constructed in tandem with larger, better-equipped facilities. The emergence of telemedicine for remote consultation can also help the growth of such ‘hub-and-spoke’ facilities.

While the previous chapters discussed the context and challenges associated with various health conditions that disproportionately affect low income populations, this chapter focuses on the actual delivery of care. Delivering healthcare requires 6 structural elements:

1. **Funds and financing mechanisms at multiple levels:** Funding for public health systems; business financing for entrepreneurs interested in building clinics and providing care; and financial services like health insurance, for low income populations so that patients can afford services.

2. **Infrastructure:** Networks of easily accessible clinics for routine care, with adequate facilities for escalation in the event of emergencies and special needs.

3. **Human capital:** Adequate numbers of trained and licensed physicians, nurses, midwives and health workers, with minimal reliance on untrained or unlicensed health practitioners.

4. **Pharmaceuticals:** A reliable supply of effective and affordable medications for prevention and treatment of conditions common to the population.

5. **Equipment and medical devices:** To ensure the clinics are well provisioned and functioning regularly; to preserve vaccines and other sensitive materials like blood; to conduct lab tests; and to help clinicians perform routine as well as emergency operations.
Information and governance: Data on patient history, population-level trends, and performance of clinics, clinicians, and the health system as a whole, which can be utilized to develop standards, and monitor compliance to those standards.

All available data about health systems in low income countries (WHO, 2013) show that there are significant gaps along each of the above structural elements. The most important of these gaps are discussed further in this chapter.
KEY CHALLENGES

The hurdles to healthcare delivery, especially in rural areas, are structural and multi-faceted. The absence of a robust tax base leads to a lack of public funding, which then leads to a lack of investment in infrastructure, human capital and oversight.

There is very limited public funding of healthcare, with even more limited financing mechanisms

Per capita annual health expenditure in sub-Saharan Africa and South Asia, respectively, are $95 and $53; this is 1-2% of the expenditure in high income OECD countries ($5,457), and 10% or less of the global average of $952. Even as a percent of total government expenditure (which is already low in developing countries), South Asia and sub-Saharan Africa spend, respectively, 41% and 65% of what high income OECD countries do, on healthcare. In sub-Saharan Africa and South Asia, the bulk of health expenditure is on private systems; a reflection of both the poor quality of public health systems as well as the higher cost of private systems. In addition, the lack of affordable and appropriate insurance schemes or other financing mechanisms results in much higher out-of-pocket health expenditures in sub-Saharan Africa and South Asia; 30% of health spend in sub-Saharan Africa and 60% in South Asia is out-of-pocket, compared with less that 14% in high income OECD countries and 18% globally (Exhibit 1).

Distribution of healthcare expenditure

Exhibit 1: Healthcare spend in sub-Saharan Africa and South Asia lags significantly behind global averages and high income OECD countries. As a result of lower public investment in health, citizens of countries in these regions incur much higher out-of-pocket expenditure, and tend to rely more heavily on private healthcare providers.
One measure of the availability of healthcare infrastructure is the number of healthcare beds—across urban hospitals, rural clinics and remote outposts—available to the population. In sub-Saharan Africa and South Asia, there are approximately 0.6 healthcare beds for every 1,000 people,¹ compared with 4.2 in high income OECD countries and 3.7 around the world. Beyond these quantitative measures, several studies (Gawande, 2003) (WHO, 2006) (Dastur, 2008) have shown that even available clinical facilities tend of be of very low quality; few clinics have reliable electricity, lighting, running water, clean sanitation facilities, and general hygiene. As a result, patients are often treated at facilities that are not equipped to address many conditions, and clinicians have limited scope of escalating care to better-equipped facilities (Exhibit 2).

### Healthcare infrastructure

<table>
<thead>
<tr>
<th></th>
<th>sub-Saharan Africa</th>
<th>South Asia</th>
<th>High income OECD countries</th>
<th>World average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of healthcare beds</td>
<td>0.6</td>
<td>0.6</td>
<td>4.2</td>
<td>3.7</td>
</tr>
<tr>
<td>Per 1,000 people</td>
<td></td>
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</tbody>
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Exhibit 2: One of the most significant challenges to delivering adequate healthcare in sub-Saharan Africa and South Asia is the lack of hospitals and clinics, which is often measured in terms of the number of beds per 1,000 people.

¹ Data on the number of healthcare beds is very sparse, and these estimates represent averages from a small number of countries.
Density of clinics and health workers

There is a significant shortage of human capital, in the form of physicians, nurses, and other trained care providers.

In addition to the severe dearth of optimally functioning clinics, there is also a significant shortage of trained clinicians in developing countries (Exhibit 3). In sub-Saharan Africa, for example, there are only 0.2 physicians and 0.8 nurses/midwives per 1,000 people. In South Asia, there are only 0.6 physicians and 0.9 nurses/midwives per 1,000 people. In comparison, high income OECD countries have 2.8 physicians and 7.4 nurses/midwives for every 1,000 people, while the global average is 1.4 physicians and 2.9 nurses/midwives for every 1,000 people. This shortage has serious consequences for those in need of care. The majority of births in sub-Saharan Africa and South Asia take place at home and are administered by untrained health workers. Hence, most patients at all stages of life often end up relying on unlicensed, untrained ‘quacks’ (Economist, 2008) (Monitor, 2013), who frequently misdiagnose conditions and prescribe wrong medications.

Exhibit 3: There is a major shortage of trained clinicians (physicians, nurses or midwives) to administer healthcare in developing countries. One consequence is that the majority of births are administered by untrained health workers.

The supply of affordable pharmaceuticals is extremely limited

The problem of inappropriate prescription only exacerbates the more widespread problem of inadequate access to affordable medicines. There is very little systematically collected data on the availability and affordability of medications. A survey (WHO, 2006) in a small number of African countries found that drugs considered essential according to the national essential medicines list in each country are often unavailable in both public and private facilities (Exhibit 4). When drugs are available, even the lowest cost generics tend to be highly unaffordable. Drugs sold in East Africa tend to cost 290-360% of benchmark international prices; hence, a month’s worth of generic reference medications for a household costs between 5 and 7 days’ worth of wages for the lowest wage rung of government employees in those countries.
Many clinics, especially those in rural areas, lack basic amenities such as electricity, lighting, running water, and sanitation. Urban clinics, on the other hand, tend to have access to some of these core amenities. However, sophisticated equipment like radiology machines, centrifuges, autoclaves, medical refrigerators for vaccines and other sensitive pharmaceuticals, and diagnostic devices (beyond RDTs and basic microscopes), tend to be available only in a fraction of the medical facilities. For example, across sub-Saharan Africa, there are only 0.1 MRI scanners, 0.4 CT scanners and 3.6 mammography scanners for every 1 million people, whereas OECD countries have 20.2 MRI scanners, 36.1 CT scanners and 123.3 mammography scanners per 1 million people (WHO, 2010). According to a recent study in several countries in sub-Saharan Africa and South Asia (Gates Foundation, 2013), as many as 85% of primary health centers, responsible for national vaccine delivery do not have any vaccine refrigerators. In those that do have a refrigerator, as many as 45% are non-functioning (Exhibit 5). As a result of the lack of functioning vaccine refrigerators, a large number of children remain inadequately immunized, and more than a million children under 5 die each year from vaccine-preventable diseases (CDC, 2006).

Exhibit 4: Availability and affordability of essential drugs is low in much of sub-Saharan Africa, as shown in this WHO study of 3 East African countries.

Most essential medical devices on the market are far too expensive for low income populations, and those made for developing country settings are not robust or functional enough.
Exhibit 5: Clinics in sub-Saharan Africa and South Asia generally lack basic equipment such as refrigerators and radiology machines. The lack of vaccine refrigeration leads to large gaps in immunization.

There is inadequate information collected on patients or populations, leading to a lack of transparency

Most healthcare record-keeping in developing countries is done on paper, if at all. This lends itself to significant problems with governance, which in turn, impacts quality of care. There are leakages in budget and resource management; jobs are ‘purchased’; there is limited meritocratic performance management of individuals, facilities, or systems; and there is significant bribery and corruption (Lewis & Pettersson, 2009) (Exhibit 6). Fortunately, the recent emergence of mHealth technologies has shown tremendous promise in remote data collection, monitoring, communication and procedural support, diagnosis and telemedicine, and training of health workers (UN Foundation and Vodafone Foundation, 2009).

Poor living conditions increase exposure to diseases

Low income populations through much of the developing world do not have access to adequate sanitation infrastructure. As a result, they have to defecate in the open or in other spaces not conducive to safe, hygienic living. Their homes have little in the way of ventilation, which increases their exposure to airborne pathogens and to pollutants from cookstoves. Access to safe drinking water is an additional concern. These problems are much worse in urban slums, and the high rate of urbanization promises to exacerbate the health consequences.
Governance challenges in health systems in sub-Saharan Africa

Budget leakages in sampled programs

<table>
<thead>
<tr>
<th>Country</th>
<th>Public officials</th>
<th>Percent of budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ghana (Discretionary Non-wage funds, 2000)</td>
<td>24%</td>
<td>80%</td>
</tr>
<tr>
<td>Uganda (Drugs and supplies, 2000)</td>
<td>19%</td>
<td>70%</td>
</tr>
<tr>
<td>Tanzania (Non-wage funds, 2000)</td>
<td>22%</td>
<td>41%</td>
</tr>
<tr>
<td>Ghana (Wage funds, 2000)</td>
<td>20%</td>
<td>20%</td>
</tr>
</tbody>
</table>

Public officials’ reports on the extent to which health personnel decisions are influenced by illegal payments

<table>
<thead>
<tr>
<th>Country</th>
<th>Percent of surveyed officials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benin (2000)</td>
<td>9%</td>
</tr>
<tr>
<td>Guinea (2005)</td>
<td>19%</td>
</tr>
<tr>
<td>Sierra Leone (2002)</td>
<td>22%</td>
</tr>
<tr>
<td>Ghana (2000)</td>
<td>25%</td>
</tr>
<tr>
<td>Zambia (2003)</td>
<td>50%</td>
</tr>
</tbody>
</table>

Share of households and public officials perceiving the health system as corrupt

<table>
<thead>
<tr>
<th>Country</th>
<th>Households</th>
<th>Public officials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zambia (2003)</td>
<td>25%</td>
<td>24%</td>
</tr>
<tr>
<td>Mozambique (2004)</td>
<td>28%</td>
<td>24%</td>
</tr>
<tr>
<td>Ghana (2000)</td>
<td>40%</td>
<td>28%</td>
</tr>
<tr>
<td>Benin (2006)</td>
<td>18%</td>
<td>40%</td>
</tr>
<tr>
<td>Sierra Leone (2002)</td>
<td>57%</td>
<td>50%</td>
</tr>
</tbody>
</table>

Exhibit 6: The lack of well-documented and tracked data on health treatment and transactions in developing countries leads to significant governance problems.
Clearly, the development of sustainable, large-scale health systems and delivery structures requires substantial funding, ideally through a local tax base powered by a robust economy. Still, targeted gains can be achieved in the absence of substantial funding or economic development—an ‘interim’ state until developing countries reach a point where they have high-caliber institutions to train large numbers of clinicians, dense networks of facilities, adequate equipment, a functioning supply chain of medications, and robust information management systems. Importantly, health outcomes are not just a function of the strength of the health system, but also of living conditions. We believe there are 4 technological breakthroughs which can improve delivery of care while also reducing need for care.

**A thermo-stabilizing mechanism for vaccines and other temperature sensitive pharmaceuticals**

Vaccines need to remain refrigerated between 2°C and 8°C essentially from the moment they are manufactured, all the way to the point of consumption. Other life-saving pharmaceuticals like Oxytocin—used to treat post-partum hemorrhage after women give birth—are also equally reliant on refrigeration (although the requisite temperature range can vary for different types of pharmaceuticals). The main reason these pharmaceuticals are temperature sensitive, is the vulnerability of the pathogens in typical live-attenuated vaccines, and the intrinsic instability of protein structures in pharmaceuticals. Therefore, the lack of electricity and refrigeration in remote areas means that many millions of individuals do not have access to critical vaccines and medications. A mechanism (e.g., stabilizing additives), to thermally stabilize these pharmaceuticals can substantially increase their viability and availability.

While a number of efforts are underway to develop stabilizing formulations for vaccines (e.g., nanostructured polymers, viscous liquids like propylene glycol, novel drying sprays), virtually all of them are in early stages, and none have proven applicable to the range of vaccines, especially in field tests. Given the complexity of the R&D required, the need for rigorous clinical trials, and the required approvals by various regulatory agencies, it will be surprising if a proven solution becomes market ready within the next 10 years. Once such a technology becomes viable, the established channels for vaccine procurement and distribution, relatively strong coordination of the market for vaccines (e.g., through the major institutions responsible for global immunization like the WHO, GAVI and UNICEF), and the demand for such a breakthrough from these institutions, will make deployment relatively FEASIBLE.
Breakthrough 1 – Difficulty of deployment

Solar-powered, portable, refrigeration for vaccines (and other temperature sensitive pharmaceuticals), for remote, off-grid areas

As mentioned earlier, vaccines and a number of other pharmaceuticals are highly temperature sensitive. Thermostable mechanisms undoubtedly represent the long-term solution for deploying these life-saving pharmaceuticals to remote parts of the world. In the meantime, refrigeration will continue to play a critical role in preserving and delivering them to those in need. Larger storage and health facilities tend to have access to reliable refrigerators powered by grid electricity or diesel-powered generators. Smaller, rural facilities, however, have neither the necessary funding, nor access to reliable power sources. Until recently, refrigeration for such facilities was made possible primarily through kerosene-powered fridges. Increasingly, solar ‘direct-drive’ fridges, which do not require batteries to store power, are becoming the preferred option. But very few on the market are affordable—or proven reliable—for small, remote clinics. Outreach campaigns have no access to active refrigerators, and have to use ice-lined cooler boxes which often lead to freezing and keep the vaccines cold only as long as the ice does not melt. As such, an affordable, portable, solar-powered refrigerator will be crucial, especially for outreach campaigns to remote areas.

The past 1-2 years have seen the introduction of new refrigeration technologies like smaller-scale vapor compressors and solid-state thermoelectric cooling mechanisms, which are beginning to be used for small refrigerators. While there still is no proven method at the scale needed for outreach campaigns, we believe that the new technologies will lead to viable solutions within the next 2-3 years. Once such a technology becomes available, the standardized structures created by international institutions—such as WHO, UNICEF, GAVI—for regulatory approval, procurement and distribution of vaccine refrigerators will make the difficulty of deployment FEASIBLE.
Breakthrough 2 – Difficulty of deployment

An easy to install, easy to operate, affordable (in the $10,000 - $15,000 range), solar-powered and integrated suite of medical devices specifically for maternal, child and primary care in rural, off-grid settings

Among the many structural challenges in healthcare delivery in developing countries, is the virtual absence of adequately equipped clinics. The majority of clinics, especially in rural areas serving low income populations, lack even the basic amenities, let alone the equipment necessary to provide essential services. To build a clinic with the equipment necessary to provide basic maternal, neonatal and primary healthcare would likely cost in excess of $100,000. This is based on preliminary research on costs of essential medical devices already available on the market including solar panels, lighting, water purifier, ultrasound, IV, suturing, continuous positive air pressure machine, basic infant incubator, sterilizer, medical refrigerator, smart phone, tablet or other computer and imaging device, diagnostics for commonly occurring conditions, and cost of constructing a basic building. In the absence of adequate public funding, this is clearly too expensive for low income populations; by a factor of 10, based on our high-level assessment. In addition, the logistics of procuring the various components and assembling them into a functioning clinic require considerable effort. As such, we believe this type of a suite or a ‘clinic-in-a-box’ can be a significant breakthrough if it:

- Combines the aforementioned devices.
- Costs approximately $10,000 - $15,000, based on our high level assessment of financial feasibility, given published data on how much low-income rural families in sub-Saharan Africa and South Asia spend on healthcare.
- Integrates power management, computation/imaging, data, and communication, so that the various devices can function in an easy-to-install ‘plug-and-play’ mode.

While some of the listed devices are available at the appropriate price point, many are still priced for industrialized markets. Given the number of groups working towards developing individual devices,
Breakthrough 3 – Difficulty of deployment

we believe enough of them will become available (at the right price point), within the next 3-5 years. Within the same time window, it will be possible to develop a platform to integrate the various devices. However, even once such an integrated suite is developed, it will face a large number of deployment challenges. There is not enough public funding to procure a sufficient number of such clinics, the private market is underdeveloped and fragmented, and the regulatory requirements are unclear. Moreover, significant behavior change, encouraged by some form of insurance or financing to allow affordable access, is required for most low income rural communities to seek regular and formal care. Hence, the difficulty of deployment will be EXTREMELY CHALLENGING.

A new kind of a home—made with strong lightweight material—especially for the urban poor, with a private toilet, solar-powered lighting and ventilation

The majority of the poor live in homes made with found material. In urban shantytowns, these homes are densely packed single-story shacks, which are usually off-grid (or have illegal access to grid power), allow very little light or fresh air, have no running water, and no toilet. This heavily contributes to a range of severe health conditions: illnesses from indoor air pollution, the spreading of infectious diseases like pneumonia and TB, as well as diarrheal diseases because the absence of private toilets or clean and convenient public toilets leads to open defecation. Without addressing the problem of decent living conditions, it is unlikely that remedial medical care will lead to significant gains in health in the long run. Currently, the only option for constructing robust homes is brick and cement, which is far too expensive for the poor. Additionally, the absence of clear land rights—and the threat of eviction—makes
such permanent homes a risky investment. A new kind of home, with the characteristics listed below, can contribute to a significant improvement in quality of life:

- Very low cost, so that it is affordable for the poor (recognizing that it will often compete with free, found material).
- Robust, so that it withstands harsh weather, and can potentially support a duplex structure.
- Lighting and ventilation.
- Equipped with basic appliances, e.g., solar-powered LED lighting, and a fan.
- Equipped with a private in-home toilet, which can be used even without a connection to running water or drainage systems (in principal the waste can be extracted from outside the home, for disposal).
- Aesthetically pleasing and culturally appropriate.
- Lightweight, so that it can be relocated if necessary.

Such construction material currently does not exist, and it is not clear if there are any efforts underway to develop such material at the right price point. It is also not clear what such material would be made of. As such, we believe such a technology is at least 10 years from becoming a reality. Even when it does become available, there are significant dependencies on behavior change, user finance, and policy changes (e.g., for land tenure). The difficulty of deployment in this case will be EXTREMELY CHALLENGING.

**Breakthrough 4 – Difficulty of deployment**

<table>
<thead>
<tr>
<th>Difficulty</th>
<th>Policies</th>
<th>Infrastructure</th>
<th>Human capital</th>
<th>Access to user finance</th>
<th>Behavior change</th>
<th>Existing demand</th>
<th>Market fragmentation/Distribution channels</th>
<th>Business model innovation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple</td>
<td></td>
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<tr>
<td>Feasible</td>
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</tr>
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<td></td>
</tr>
<tr>
<td>Challenging</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extremely Challenging</td>
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</tbody>
</table>

- Highly regulated market with policy changes required
- Requires moderate improvements to infrastructure
- Moderate need to train a limited number of people
- Significant behavior change needed on daily basis, changes contrary to cultural norms
- Low demand, needs to be built
- Highly fragmented, challenging to reach customers
- No identified deployment model, major hurdles identified
FOOD SECURITY AND AGRICULTURAL DEVELOPMENT
Food security is one of the most significant problems faced by the global poor, with more than 800 million people—constituting about 13.5% of the population of the developing world—not having enough food to live a healthy life (WFP, 2014). This happens in spite of the fact that most developing countries, especially in sub-Saharan Africa and South Asia have large agrarian populations. Over 60% of the people in sub-Saharan Africa live in rural areas, more than half of whom are below the poverty line; in South Asia too, over 60% of the population is rural, with one-third below the poverty line. About 50% of the total population in these regions is either employed in agriculture, or dependent on local agriculture as the primary source of food (Exhibit 1) (World Bank, 2014).

The typical farmer in these regions is a smallholder, working on plots of land that are about 1 hectare (or smaller) in size. Most smallholder farmers, especially in sub-Saharan Africa, are subsistence farmers—their main source of food is what they grow.

Despite the significance of local agriculture as the primary economic base and source of food, agricultural yields in sub-Saharan Africa, in particular, and South Asia, to a smaller extent, lag well behind those in other parts of the world (Exhibit 2). As a result, most countries in sub-Saharan Africa and South Asia are net importers of food (Exhibit 3). For example, about 30% of cereals consumed in sub-Saharan Africa are imported (FAO, 2014). In both regions, rates of poverty and undernutrition (Exhibit 4) are considerably higher than in rest of the world. These interrelated factors have made agriculture and its role in alleviating poverty, and improving food security and health, a primary focus of international development.

**Portion of global population living in rural areas and employed in agriculture**

<table>
<thead>
<tr>
<th>Region</th>
<th>Living in rural areas</th>
<th>Employed in Agriculture</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America</td>
<td>18%</td>
<td>2%</td>
</tr>
<tr>
<td>Latin America &amp; the Caribbean</td>
<td>21%</td>
<td>5%</td>
</tr>
<tr>
<td>European Union</td>
<td>26%</td>
<td>9%</td>
</tr>
<tr>
<td>Eastern Europe &amp; Central Asia</td>
<td>30%</td>
<td>15%</td>
</tr>
<tr>
<td>Middle East &amp; North Africa</td>
<td>37%</td>
<td>23%</td>
</tr>
<tr>
<td>East/Southeast Asia &amp; Pacific</td>
<td>47%</td>
<td>35%</td>
</tr>
<tr>
<td>sub-Saharan Africa</td>
<td>64%</td>
<td>47%</td>
</tr>
<tr>
<td>South Asia</td>
<td>58%</td>
<td>58%</td>
</tr>
</tbody>
</table>

**Exhibit 1:** Most people in sub-Saharan Africa and South Asia live in rural areas. In addition, the majority of the labor force in these regions works in agriculture and related activities (World Bank, 2014).

1 The term undernutrition refers to vitamin and mineral deficiencies, as well as caloric deficiency (WHO, 2014).
Yields of cereal crops, in different regions of the world

Kilograms per hectare; 2012

Exhibit 2: Cereal crop yield in sub-Saharan Africa is less than half of South Asia, and a fraction of that in other parts of the world. Yields for other agricultural commodities—cash crops, horticulture, livestock—also lag significantly behind (FAO, 2014) (World Bank, 2014).

Number of countries that are net importers vs. net exporters of food in each region

Exhibit 3: The majority of countries in sub-Saharan Africa and South Asia are net importers of food (World Bank, 2014) (FAO, 2014). While this is also true of all other regions, agriculture is neither the mainstay of their economies, nor the primary generator of employment.
Rates of undernourishment, in different regions of the world

Exhibit 4: Based on daily caloric intake, 25% of the population in sub-Saharan Africa and 17% in South Asia are undernourished. This is a clear indicator of food insecurity in these regions (World Bank, 2014) (FAO, 2014).

The Green Revolution has led to a dramatic increase in food production in South Asia, while sub-Saharan Africa has lagged behind

The Green Revolution that started in the 1960s and 1970s is widely considered one of the most successful large-scale programs to help alleviate poverty and improve food security, in the history of international development (Spielman & Pandya-Lorch, 2009) (Hazell, 2009). By combining improved seed varieties with intensive use of irrigation and fertilizers, strengthening local institutions, and a range of major policy reforms, several Asian countries were able to make substantial and lasting gains in food production. Norman Borlaug, the biologist who developed the high-yield seed varieties which launched the Green Revolution, was awarded the Nobel Peace Prize in 1970. South Asian countries, in aggregate, have tripled their agricultural yields since 1960 (Exhibit 5). During the same period, sub-Saharan Africa—which was not a part of those Green Revolution efforts—did not achieve much in the way of increased agricultural productivity. Another telling measure of the Green Revolution’s impact is the role agricultural intensification has played on the amount of land used for food production. As Exhibit 6 shows, the yield of cereals in South Asia increased by 165% between 1961 and 2009, with only a small increase in cultivated land area. During the same time, there was only a 60% increase in per hectare cereal yield in sub-Saharan Africa, and farmers have had to increase the amount of land for cultivation by 140% (Virtual Fertilizer Research Center, 2012).
Change in cereal yield per hectare, since 1960

Exhibit 5: The Green Revolution led to dramatic increases in agricultural productivity in South Asia, to the extent that South Asia is approaching agricultural self-sufficiency. On the other hand, sub-Saharan Africa continues to lag far behind the world average.

Cereal production, yield and land usage in South Asia and sub-Saharan Africa, 1961 - 2009

Exhibit 6: South Asian countries have increased agricultural yield dramatically over the past few decades using intensified agricultural practices. Compared with 1961, per hectare cereal yield in South Asia has increased by 165%, leading to a total output increase of 210%, with only a small increase in cultivated land. During the same period, sub-Saharan Africa saw a 140% increase in cultivated land and only a 60% increase in per hectare yield, for a total increase in output of 259% (Virtual Fertilizer Research Center, 2012).
Prevalent forms of agriculture have a significant environmental footprint

Virtually all forms of agriculture practiced currently—in both industrialized and developing countries—cause significant environmental damage. The intensified agricultural practices that arose from the Green Revolution have had at least two negative environmental effects: water overuse and fertilizer runoff. About 80% of the water in South Asia today is used for agriculture. Overuse, together with population growth, has led to a 65% reduction in the supply of renewable water since the early 1960s, on a per capita basis (FAO, 2014); as a consequence, much of South Asia is now facing severe water scarcity. Meanwhile, runoffs of excess fertilizer have caused many waterways to become ‘dead zones’. Fertilizer stimulates the growth of algae (which, in turn, depletes oxygen in the water) and cyanobacteria (which produce toxic compounds) (Conijn, et al., 2013). Currently, there are over 400 marine ‘dead zones’ worldwide, caused by nutrient runoff; these have doubled every decade since the introduction of synthetic fertilizers in 1960s (Diaz & Rosenberg, 2008). As other sections in this study discuss, South Asia is one of the regions with the largest concentration of such dead zones. Livestock farming too has a significant environmental footprint, primarily from greenhouse gas emissions, deforestation and desertification (McMichael, et al. 2007). Not surprisingly, industrialized agricultural systems have a greater impact on the environment than those in developing countries.

A sizable amount of food is lost or wasted because smallholder farmers do not have appropriate storage facilities or access to markets

Most African smallholder farmers lack access to ready markets for their produce. As a result of this and other factors, a large number of grain producers store their grains themselves, as food for their families until the next harvest. The storage facilities they use—typically made with material easily available locally, like mud and straw—do not offer adequate protection from moisture, excess heat, rodents or pests, and a substantial portion of the grains are spoiled (Exhibit 7). Another equally pressing problem is the lack of adequate refrigeration, because of which perishable products like fruits, vegetables, dairy, and meat, cannot be preserved for long.

Agricultural losses in sub-Saharan Africa across the value chain, for different types of crops

Exhibit 7: Smallholder farmers in sub-Saharan Africa lose a substantial portion of their produce, even before the food is ready to be consumed. The primary reason for the losses is the lack of appropriate technologies for handling, storage and transportation (FAO, 2011).
A dearth of local food processing facilities to convert raw produce to consumable foods (e.g., cocoa beans to chocolate, milk to packaged cream or cheese, or raw cashew nuts to consumable cashews), means that the bulk of high value produce is processed outside the region. While this is especially true for export commodities (e.g., cocoa), there are also many food products imported into the region (e.g., fruit juices, chocolate, cheese) made from raw produce that is locally available. Exhibit 8 is an illustrative example of the gap between overall production and available processing facilities for cashew nuts. The lack of processing facilities deprives the local economy of agribusiness jobs, and smallholder farmers of higher prices for what they produce (African Cashew Alliance, 2010). This also drives up the costs of food and agricultural products, making them unaffordable for low income populations.

**Percent of overall cashew production that is locally processed, in select countries**

<table>
<thead>
<tr>
<th>Country</th>
<th>Percent of production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mozambique</td>
<td>50%</td>
</tr>
<tr>
<td>Cote d’Ivoire</td>
<td>2.5%</td>
</tr>
<tr>
<td>Ghana</td>
<td>2%</td>
</tr>
<tr>
<td>Burkina Faso</td>
<td>10%</td>
</tr>
<tr>
<td>Benin</td>
<td>5%</td>
</tr>
</tbody>
</table>

A significant portion of agricultural labor is performed by women

Agriculture constitutes the single most significant type of economic activity performed by women in South Asia and sub-Saharan Africa, accounting for about 40% of their effort (Exhibit 9). Women perform between 30% and 70% (depending on the country) of the agricultural labor in these regions (FAO, 2011). Still, as the section on Gender Equity discusses, most farm implements are not engineered for use by women—taking into account their size, weight, strength, traditional clothing and other constraints.
Exhibit 9: In South Asia and sub-Saharan Africa, agriculture constitutes the single largest type of economic activity performed by women.

Share of agricultural work performed by women across 10 low and middle income countries

Exhibit 10: Women contribute to a substantial portion of total agricultural labor, ranging from 32% in India, to almost 70% in Cameroon.
RECENT TRENDS IN AGRICULTURAL DEVELOPMENT

As we examine the role of various interventions in improving food security, the following recent trends in agricultural development are important to consider.

There is now a significant emphasis on sustainable agriculture
There has always been an ongoing tension between economic development and environmental sustainability, in both industrialized and developing countries. Until recently, most developing countries (including emerging middle income countries like China) had taken the posture that climate change (and other forms of environmental damage) are problems caused primarily by industrialized countries. However, there has been a marked turnaround in attitudes in recent years, and developing countries are beginning to recognize the steps they can take to reduce the environmental impact of their actions (Parliament of India, 2013) (Mattoo & Subramanian, 2012). Sustainable agronomy is now a core component of the agricultural development agenda, even in sub-Saharan Africa where the environmental impact of food production is relatively low (African Green Revolution Forum, 2014) (USAID, 2014).

The central role of women in agriculture has been acknowledged, although it is not clear yet whether concrete results are being achieved
There is finally acknowledgment of the central role women play in agricultural development. This recognition has manifested itself through broad efforts to make ‘mainstream’ agriculture programs like extension, strengthening of farmer organizations, technology development etc., more gender inclusive. However, while there is clearly more activity toward greater equity, it is not yet clear whether there has been much impact in achieving true gender parity in agricultural development.

With increasing globalization, agricultural value chains are becoming disintermediated
Tropical countries grow more agricultural commodities than countries in colder climates. Some of these commodities, such as cocoa and coffee, have become increasingly valuable for export to industrialized markets, with both consumption and prices steadily growing over the past 2-3 decades (International Coffee Organization, 2014). As a result, large food companies are beginning to pay more attention to the quality of raw produce, and working much more closely with farmer groups on training and quality control.

Currently, the primary focus of agricultural development is sub-Saharan Africa
The Green Revolution of the 1960s and ‘70s led to tremendous improvements in agricultural productivity in Asia and Latin America. Combined with other forms of economic development, many of these countries have reached middle income status, and most are now self-sufficient with respect to food. While there is still a significant concentration of poverty and food insecurity in South Asia (especially in areas like India’s lower gangetic plain, which were not integral to the Green Revolution), a number of influential funders of agricultural development programs are dedicating much more resources to sub-Saharan Africa than to South Asia (Gates Foundation, 2014).
New methods to produce fertilizers to replace current processes, which are extremely capital intensive and have significant environmental footprints.

Production of synthetic fertilizers—a mainstay of agricultural yields for many decades—depends on processes that are very capital intensive (manufacturing plants and mines costing hundreds of millions to billions of dollars), and in the case of nitrogen, extremely dependent on natural gas (nitrogen fixation factories must be located close to natural gas sources). As a result there are no fertilizer manufacturing plants in sub-Saharan Africa, and this creates a cost burden for African farmers who must buy fertilizer from international sources. From a more global perspective, current production processes have a large ecological footprint, create dependence on fossil fuels for food, and introduce volatility in fertilizer and food prices tied to volatility in fossil fuel prices. New research is required to explore options like simulating natural nitrogen fixing mechanisms (found in crops such as legumes), foliar nutrient uptake (instead of roots, to reduce fertilizer runoffs from farms), etc. In addition, it will be important to improve the safety and effectiveness of existing sustainable methods like composting biological waste.

Affordable off-grid refrigeration for smallholder farmers and small agribusinesses.

The absence of affordable refrigeration and electricity severely limits the ability of smallholder farmers to produce, preserve and sell high-value perishable commodities like vegetables, fruits, meat and dairy. A new kind of refrigerator that costs less than $50 and can run on solar power will help smallholder farmers take such high-value commodities to market, thereby increasing their incomes.

Low cost refrigerated vehicles, sturdy enough for unpaved roads in rural areas.

The ability to transport food to markets while preserving its freshness will help farmers increase their incomes from higher-value produce like vegetables, fruit, meat, and dairy products. Currently, the absence of refrigerated transportation is one of the factors contributing to the lack of a market for such commodities. Refrigerated trucks available on the market today are unaffordable for small agribusiness entrepreneurs, and are generally built for paved roads. In order to be useful in sub-Saharan Africa, refrigerated transportation vehicles must be built for unpaved, rough terrain, and cost less than $5,000.

Low cost systems for precision application of fertilizers and water.

Overuse of fertilizers and water contributes to significant environmental damage. In South Asia, since the Green Revolution, groundwater has been severely depleted, and fertilizer runoffs are causing ‘dead zones’ in waterways around the world. Overuse can also be a tremendous economic waste for smallholder farmers. Precision application systems for irrigation and fertilizers, calibrated to crop type and soil conditions, can be a very cost effective way to increase agricultural yields, while also reducing negative impacts on the environment.

A low cost drilling system for shallow (rain-fed) groundwater wells, combined with portable sensors for measuring groundwater depth. Such systems should reduce the cost of drilling wells to under $100 per farmer in Africa.

Most smallholder farmers in sub-Saharan Africa do not have access to irrigation. Wells are expensive to dig, drilling equipment is expensive to hire (and typically needs to be transported by truck), and it
is hard to precisely locate groundwater. A new type of lightweight drill for shallow groundwater (e.g., one that can be transported by motorcycle instead of truck) can decrease capital costs. In addition, equipment for detecting groundwater can change the hit-or-miss nature of digging for water. It will be important to ensure that non-renewable groundwater is not overused.

6 **Low cost (under $50) solar-powered irrigation pumps.**
Currently available manual irrigation pumps are expensive and strenuous to use, especially for women farmers. Motorized pumps available on the market are even more expensive, and the cost hurdle is compounded by the recurring cost of fuel. A solar powered pump that is under $50 can dramatically increase access to irrigation. As with other irrigation solutions, it will be important to ensure that non-renewable groundwater is not overused.

7 **Affordable herbicides or other mechanisms to control weeds, ideally ones that are more environmentally friendly than herbicides currently on the market.**
Weeds are among the biggest causes of on-field losses for smallholder farmers. General herbicides—not specifically targeting particular types of weeds—can damage the food crops they are intended to protect. An herbicide specifically targeting the biological vulnerabilities of the most destructive weeds can dramatically reduce crop waste. Ideally, such herbicides will be more environmentally friendly than herbicides currently available in most markets.

8 **A low cost (under $50) tilling machine.**
Weeds are responsible for significant on-field losses for smallholder farmers. A commonly used method of eliminating weeds is to till the soil before planting. Mechanized tillers currently on the market cost 4-5 times more than what a typical smallholder farmer can afford. Animal-drawn tilling has not proven entirely effective, and manual tilling is simply too cumbersome and too slow. A mechanized tiller that costs under $50 can greatly improve weed control and lead to major improvements in agricultural yields.

9 **A low cost alternative to liquid nitrogen for preserving animal semen.**
Artificial insemination (AI) is an effective mechanism for breeding cattle and other animals, leading to significant improvements in livestock health and productivity. Preservation and transport of animal semen requires extremely low (sub -100°C) temperatures, currently achieved with liquid nitrogen. Production of liquid nitrogen at a large scale is expensive (although it appears more feasible at a small scale). A mechanism to preserve and transport animal semen without the need for a substance as cold as liquid nitrogen, thereby avoiding the capital costs associated with producing liquid nitrogen, can lead to a greater adoption of AI in Africa. This, in turn, can lead to major improvements in livestock health and farmer incomes.

10 **High-nutrient and low cost, sustainable animal fodder.**
Currently, most livestock farmers in sub-Saharan Africa practice extensive forms of livestock production, which involves animals grazing over large tracts of land but with limited access to nutrient-dense food. This grazing also contributes to deforestation and desertification. Affordable, nutrient-rich animal fodder made with sustainable and locally available ingredients can make a significant contribution to productivity (i.e., more and better quality of milk and meat), while also reducing environmental damage.
A portable toolkit for agricultural extension workers and livestock veterinarians.
Extension agents can provide valuable training for farmers, helping them optimize yield and improve produce quality. However, most extension agents do not have the tools to perform many of the services farmers need. An ideal extension worker toolkit should help them test soil quality, install and repair irrigation and other on-farm equipment, test the quality of produce (e.g., through chemical probes), and show videos or other instructional material to farmers. A similar toolkit for veterinarians and livestock extension agents, including point-of-care diagnostics for major diseases, a vaccine cooler, and other tools to provide on-farm care for animals can significantly improve the health and productivity of livestock.

Spatial repellent for on-farm pests.
Insects and other pests reduce potential yield by up to 15% for smallholder farmers in Africa. While crop damage is caused by several pests, a small number—borers, mealybugs, mites—cause a disproportionate share of these losses. A low cost spatial repellent that irritates pests (e.g., based on particular sound frequencies) could be an effective and sustainable mechanism to protect crops. It can also reduce the need for chemical pesticides, which can be harmful to health and the environment.

New seed varieties that are tolerant to drought, heat, and other emerging environmental stresses.
Climate change and water shortages are putting heavy stresses on crops and agricultural output. These stresses will continue to increase in the coming years. Just as new seed varieties were critical to the Green Revolution in Asia and Latin America, new varieties of seeds for essential cereals (e.g., maize, rice) that are tolerant to drought, heat, and other emerging environmental stresses will be necessary for agricultural development and food security in the near future.

A new method for desalination: scalable, low cost, and using renewable energy.
Water scarcity is one of the most critical problems the world is facing today, and this problem is likely to get significantly worse in the coming years. An increasing amount of the world’s freshwater is becoming brackish, and more is being dissipated into oceans and other bodies of unusable water. Reclaiming this seawater and inland brackish water through desalination will need to be a significant part of the larger solution to meet the needs of the growing global population. Current forms of desalination (e.g., reverse osmosis) are prohibitively expensive and energy-intensive.
This section focuses on the key factors that can improve food production and smallholder farmer incomes: increasing yield, preserving food, improving market access, reducing workload (especially for women), and making agriculture more sustainable. These issues are discussed in the following dedicated chapters:

- Irrigation
- Fertilizers and plant nutrients
- Biotic stresses
- Post-harvest handling and storage
- Extension services
- Livestock
- Sustainable agriculture

Note: As mentioned earlier, most of South Asia has a much more advanced agricultural ecosystem than sub-Saharan Africa, largely due to the Green Revolution. As such, some of the chapters (e.g., irrigation and fertilizer) focus more on sub-Saharan Africa. Beyond those specific issues, most of the following analysis is applicable to both regions.
The lack of proper irrigation is a critical constraint to increasing agricultural productivity for smallholder farmers in sub-Saharan Africa. With proper irrigation, not only can farmers improve their crop yields, but diversify their crop portfolio toward higher income crops and increase the total number of harvests in a given year. However, smallholder agriculture in sub-Saharan Africa is largely rain-fed, which results in a limited window for farmers to irrigate their fields.

There are a number of reasons why African farmers do not have access to irrigation systems: there is limited awareness of the value of irrigation; diesel pumps are currently too expensive, and diesel supply is both sparse and expensive; even most manual pumps are too expensive, in addition to being very strenuous to use (especially for women); lastly, digging wells is also a prohibitively expensive proposition.

Current data suggests that there is an adequate supply of shallow groundwater (rechargeable by rain) across much of sub-Saharan Africa. However, the experience from intensified agriculture in South Asia demonstrates that groundwater can easily be depleted if not sustainably used. Our analysis concludes that 5 technological breakthroughs can lead to significant improvements in the overall agricultural productivity of smallholder farmers in sub-Saharan Africa.

- Low cost drilling technologies for shallow groundwater, which reduce the cost to under $100 per farmer
- Low cost, easy-to-construct rainwater storage repositories where harvested rainwater can be stored for several months without contamination
- Affordable (under $50), lightweight, fuel efficient solar-powered irrigation pumps
- A low cost precision irrigation application system, ideally combining fertilizers with irrigation
- Portable sensors for estimating depth of shallow groundwater
Soil moisture, usually enabled by irrigation, is one of the key drivers of agricultural productivity. Studies have found that irrigation can lead to substantial increases in productivity from 50% (IFPRI, 2010) to over 100% (Molden, 2007).

CORE FACTS AND ANALYSIS

Irrigation offers several critical benefits for smallholder farmers including increased crop yields, the possibility of cultivation even during dry seasons and droughts, and the opportunity to grow high value, high nutrition crops. Since the Green Revolution, even as intensified agricultural practices in other parts of the developing world have led to greater adoption of irrigation, sub-Saharan Africa has lagged far behind. Most smallholder farmers in Africa have historically relied on rainfall as the sole source of water and still do. Irrigation technologies remain largely out of their economic means. Currently, only about 6% of farmland in the region is irrigated (Exhibit 1). As a result, cereal production closely follows the amount of rainfall in any given year (Exhibit 2) (McIntyre, Herren, Wakhungu, & Watson, 2009) (Molden, 2007).

It is important to note that South Asia and sub-Saharan Africa face different challenges with regard to irrigation: much of South Asia¹ is struggling with major long-term water scarcity due to overuse and population pressures, while sub-Saharan Africa is facing the problem of inadequate access to seemingly available water.

![Share of rain-fed vs. irrigated arable land in developing countries](image-url)

Exhibit 1: Most of the agricultural land in most developing countries is rain-fed. This is especially true for sub-Saharan Africa.

¹ With the exception of Bangladesh and Indian states like Orissa, which were not deeply involved in the Green Revolution.
Exhibit 2: Cereal production in Africa is closely linked to rainfall, as shown in this study from Burkina Faso (Molden, 2007).

There appears to be abundant shallow groundwater in sub-Saharan Africa; however most farmers cannot access it because they cannot afford pumps.

Exhibit 3 shows a hydrological map of Africa, according to which there appears to be abundant shallow groundwater (at a depth of 7 meters or above) through much of sub-Saharan Africa. It is important to note that water is a highly localized resource; availability at a certain depth in one area does not necessarily imply availability at the same depth in an adjacent area. As things stand, the only available data is in the form of large-scale surveys and maps, which is an imprecise method of estimating local water availability. Still, several studies have found that there is groundwater at shallow depths across most of sub-Saharan Africa. In Ethiopia, for example, it is estimated that roughly 1.9 million hectares of arable land can be irrigated using household-level irrigation systems. This is 5 times the total area currently irrigated (Ethiopia ATA, 2014).

Despite the availability of groundwater, most African smallholder farmers do not have the economic wherewithal to access the water because pumps and other irrigation equipment are too expensive. As such, sub-Saharan Africa is considered to be a region of ‘economic water scarcity’ (FAO, 2012) (Exhibit 4).
Hydrological map of groundwater in Africa

Exhibit 3: Current data suggests that there is substantial unutilized groundwater through much of sub-Saharan Africa (British Geological Survey, 2014).

Water scarcity around the world

Exhibit 4: Most of sub-Saharan Africa is considered to be facing ‘economic water scarcity’ because the majority of the population cannot afford the pumps and other equipment to access available water. By contrast, parts of the world that do not have adequate water present, are considered to be facing ‘physical water scarcity’ (IWMI, 2007).
Irrigation involves several steps, all of which are currently under-developed for smallholder farmers in sub-Saharan Africa.

There are 5 separate steps involved in the process of getting the water from the source, all the way to crops on the farm, as outlined below.

- **Capturing** the water in an artificial central reservoir at the community level. This can take the form of small hand-dug wells, to borehole wells, all the way to dams. A small number of farmers live near natural bodies of surface freshwater, and do not need artificial reservoirs.
- **Lifting** the water from the central reservoir to a local (e.g., on farm) reservoir or tank. This can range from carrying buckets manually, to manual pumps and motorized pumps. As discussed later in this section, manual pumps have severe limitations on the depth from which they can lift water, while motorized pumps are very expensive.
- **Storage** at a local (e.g., on-farm) reservoir or tank. This can range from small drums, to overhead tanks, ponds, and large tanks equipped with their own pumps.
- **Distribution** from the local reservoir to the plant. This can range from furrows in the field (which are flooded by the farmer), to hoses/pipes, and elaborate canals. Most smallholder farmers depend on rainfall, and even those who use irrigation systems do not have access to anything beyond the most rudimentary hoses.
- **Application** of the water to the crops. In the case of simple methods like furrows, there is no additional application mechanism. For piped systems, application systems range from regular hoses, to drip hoses, small sprinklers, and large-scale systems like mobile sprinklers and pivots which can cover considerable acreage. Not surprisingly, smallholder farmers typically do not use anything beyond basic hoses for application.

Table 1 illustrates the irrigation ‘technology staircase’, showing the various levels of sophistication for each of the above five steps, along with the approximate cost of technologies and installations at each level of sophistication (Interview, 2014).
### The irrigation technology staircase

<table>
<thead>
<tr>
<th>Steps</th>
<th>Basic</th>
<th>Limited</th>
<th>Medium-scale</th>
<th>Large-scale, sophisticated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capture</td>
<td>Small hand-dug well ($50-$200)</td>
<td>Borehole ($300-$1,000)</td>
<td>Deep borehole or small dam ($1,000-$3,000)</td>
<td>Community dam (&gt; $0.5 million)</td>
</tr>
<tr>
<td>Lift</td>
<td>Hand-carried by bucket ($50)</td>
<td>Treadle pump, hand pump or rope pump ($50-$100)</td>
<td>Small motorized pump, or animal drawn pump ($100-$150)</td>
<td>Large motorized pump (&gt; $1,000)</td>
</tr>
<tr>
<td>Storage</td>
<td>Drum or small pond ($50-$200)</td>
<td>Artificial pond ($300-$1,000)</td>
<td>Small reservoir or groundwater recharge ($1,000-$3,000)</td>
<td>Large reservoir or community dam (&gt; $0.5 million). Note: this can be the same as the reservoir used for capture.</td>
</tr>
<tr>
<td>Distribution</td>
<td>Furrow ($0)</td>
<td>Ditch, small canal, or basic hose ($10)</td>
<td>Small network of pipes or canals ($500-$2,000)</td>
<td>Extensive network of pipes or canals (&gt; $2,500)</td>
</tr>
<tr>
<td>Application</td>
<td>Pour/furrow ($0)</td>
<td>Hose, or drip/trickle kit ($10-$25)</td>
<td>Automated drip, single sprinkler, or sprinkler system ($500-$2,000)</td>
<td>Pivots or large mobile sprinklers (&gt; $2,500)</td>
</tr>
</tbody>
</table>

**Table 1**: The irrigation ‘technology staircase’, shows the various levels of sophistication for each of the 5 steps involved in irrigation. Most smallholder farmers in sub-Saharan Africa have access only to the ‘basic’ level of equipment and tools.
KEY CHALLENGES

In developed agricultural ecosystems, water is captured either by a dam or deep boreholes. Lift is achieved with large electric or diesel pumps, and water is then stored in large reservoirs, and/or distributed directly to the points of usage via extensive canal networks. Finally, it is applied to the crops via large pivot sprinklers for broad application on large farms, or intricate drip systems for more targeted application. Such irrigation infrastructure and technologies are neither available, nor affordable for smallholder African farmers. The following are some of the major hurdles.

There is a lack of demand for irrigation among African smallholder farmers

Irrigation is a relatively new practice in much of sub-Saharan Africa, and few farmers have witnessed the tangible economic benefits they can derive from irrigation. Most farmers in the region are subsistence farmers, and are understandably wary of investing their already scarce resources into expensive, and seemingly unproven, irrigation systems. As a result, they have been unwilling to change traditional practices and still depend on rainfall as the primary source water for their crops. While irrigation system costs could theoretically be shared among farmers within a community, such models have not shown the ability to scale yet.

Drilling wells is expensive, and unaffordable for subsistence farmers

The cost of drilling is driven by capital equipment, fuel and labor. High competition in emerging economies like India has historically pushed down the overall costs of drilling a bore. Such competition does not exist in Africa, and hence the cost of equipment is generally higher. The difficulty and cost of digging wells is a direct function of the depth of the water table.

▶ When water is available at fewer than 4 meters of depth, manual digging is adequate. Hand-dug wells are inexpensive, with the primary cost being the farmer’s time.

▶ When water is between 4 and 7 meters deep, a drill is usually required. This can be a human-powered drill, especially for soft soils. In Kenya, drilling a 7 meter well in soft soils costs about $300-$400 (Kickstart, 2013).

▶ For water tables of 7-20 meters, more sophisticated equipment like a motorized percussion drill is required. These wells are much more expensive to dig, and the risk of hitting rock increases as the bore goes deeper. Twenty meters is roughly the upper limit for which manually operated pumps are practical. Tube wells for that depth cost roughly $1,000 in Kenya.

▶ Deep boreholes greater than 20 meters are very expensive, often costing more than $10,000. A case study in Ethiopia analyzed a 150 meters borehole (Rural Water Supply Network, 2006) worth $18,000 (Exhibit 5), and found that the cost per meter is roughly $130, with about 75% of this cost being expense for capital equipment, fuel, and labor.
There is no easy way to detect groundwater and its depth

There generally appears to be abundant shallow groundwater through much of sub-Saharan Africa. However, availability and depth of groundwater can vary dramatically over relatively short distances. While water may be just 5 meters below the surface in one location, it may be 20 meters below the surface just a few yards away. Currently, there is no practical mechanism to identify shallow groundwater depth at specific points in order to choose an optimum digging location. Soil composition and depth are major determinants of drilling costs. While soft soil can be dug with simple, manual drills, rock requires motorized equipment that is more expensive. Igneous rock, prevalent across much of Africa, is particularly challenging to dig through. The risk of not finding water at the chosen location or hitting rock once the digging starts further increases the expected cost of drilling for smallholder farmers.

Pumps available on the market today are too expensive for smallholder farmers

Once a well is dug, the type of pump required to lift water similarly varies in cost and functionality, depending on water depth. Treadle suction pumps that cost between $30 and $150 can draw water from up to a depth of 7 meters and can irrigate 0.25 hectares per 4 hours of labor (Kickstart, 2013) (ATA, 2013). These pumps are easy to service as the entire pumping mechanism is above the surface. In recent years treadle pumps have achieved some adoption in a few regions, which indicates this core technology is feasible. IDE has sold 1.4 million treadle pumps in South Asia since 1985, and Kickstart sells about 25,000 pumps each year in East Africa. A portion of the Kickstart pumps are bought by NGOs, who then handle distribution to farmers (Kickstart, 2013) (ATA, 2013). Despite some success, treadle pumps are still relatively expensive for smallholder farmers and labor-intensive, especially for women.
Manual rope pulleys that cost around $100, can draw water from up to 18 meters below surface and can irrigate roughly 0.1 hectare per 4 hours of labor (ATA, 2013) (Kickstart, 2013). These are low cost, and easy to service. Hand pumps on the other hand cost upwards of $500 (McKenzie & Ray, 2009). Like treadle pumps, hand pumps are manual but require much more physical effort to operate since they do not use the entire body weight of the person operating it.

The cost of motorized pumps ranges from $100-$3,000 and depends on the mechanism they use: suction (drawing water from 7 meters or shallower depths), displacement, or pressure (drawing water from 12 meters or more). Motorized pumps can irrigate 3 hectares per hour on average (Kickstart, 2013) (ATA, 2013). While some types of motorized pumps are now becoming available in markets such as Kenya for as little as $150-$200, they have been prone to damage after 2-3 years of use. Moreover, the cost of diesel—roughly $120 per hectare per year in East Africa—necessary to run these pumps, increases the overall operating cost for farmers.

There are few methods for storing rainwater for long periods

There are almost no highly efficient structures for holding rainwater in large volumes. Typical storage ponds used to capture and store rainwater tend to have high losses due to evaporation and seepage. These are also costly to construct. As a result, there is little storage of water for anything more than a few weeks. So far, structures that can store water efficiently and can be built at a low cost, do not exist.

There are few private sector suppliers and after-sale-service operators in sub-Saharan Africa

A major challenge with any irrigation system is maintenance. Pumps, in particular, are prone to breakdown. The low demand for irrigation systems has made it unattractive for the private sector to enter markets with suppliers and after-sale-service providers. This further weakens the broader ecosystem for irrigation equipment. Without sufficient industry competition, equipment prices in sub-Saharan Africa are higher than in countries like India.
SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

Making irrigation affordable, desirable and sustainable will require a combination of technologies, along with innovative business models for sales, distribution and maintenance. A core assumption about the irrigation context in sub-Saharan Africa—which may be disproven as more data becomes available—is that there is an abundant supply of shallow groundwater, which can be sustainably tapped without endangering long-term water security. Under this assumption, there are 5 potential breakthrough technologies that can drive the adoption of irrigation across sub-Saharan Africa.

1. Low cost drilling technologies for shallow groundwater, which reduce the cost to under $100 per farmer

An affordable method to reach shallow (e.g., <10 meters) groundwater will allow farmers to utilize the seemingly large renewable water sources across sub-Saharan Africa. While shallow groundwater resources are rechargeable by rain, and hence sustainable under moderate use, there is a risk of overuse. Any low cost solution will have to be accompanied by some form of community-level metering and monitoring to ensure sustainability of the available water resource.

Wells are currently drilled using a standard mechanism, which requires heavy equipment and power (usually diesel) to operate. It is not clear what types of mechanical improvements will make the physical process for burrowing significantly less cumbersome or less expensive (or whether such an improvement is even physically possible). However, in principle, it should be possible to have a drill actuated by the engine of a motorcycle, which is very common form of transport across much of Africa. Hence, we believe such a technology is about 5 years from becoming a reality.

Currently, there is extremely low demand among African smallholder farmers for irrigation. Depending on the cost of the technology that is developed, farmers may require financing to pay for construction and usage of wells (even for community-level wells). Such a technology will also have to overcome many of the typical challenges faced by products and services in this market: fragmentation, and the lack of an ecosystem of suppliers and after-sale-service providers. However, based on the agricultural development experience in South Asia, and what can be seen in areas of Africa that have access to irrigation services, there is reason to believe that appreciation of the benefits of irrigation can become apparent within a short period of time. Overall, we believe deployment will be CHALLENGING.
Breakthrough 1 – Difficulty of deployment

Low cost, easy-to-construct rainwater storage repositories where harvested rainwater can be stored for several months without contamination

A feasible mechanism to capture and store rainwater for several months at a time, can prevent runoff-related losses, and create shallow groundwater reserves. There is considerable research on the artificial recharging of groundwater (Government of India, 2007), but most techniques (e.g., percolation tanks) require intensive construction and technical expertise. Some type of material or structure, which can easily be laid or constructed underground to store several months’ worth of water, can serve as an easily accessible, low maintenance, and environmentally sustainable source for irrigation.

Different types of materials are currently used for capturing rainwater in developed markets, as well as in some emerging markets like India. However, the lack of infrastructure in Africa makes it difficult to transport any type of material to rural areas. Technically, it is feasible to adapt these materials (e.g., making them lighter) for the rural African context. We believe it will take 3-5 years for such a technology to become a reality, at least at a small scale.

However, it is not clear that the market will prefer such a system over simply digging for groundwater. Even with innovative and low cost technologies, capturing a meaningful volume of rainwater, which can be used by a large number of local farmers, will require constructing what will essentially be a series of shallow wells. Building this infrastructure will need a large number of trained workers. Moreover, it will require some form of financial commitment from farmers and their communities, and a large number of trained workers to build these repositories. Overall, the deployment of such a technology in Africa will be EXTREMELY CHALLENGING.

Note that in South Asia, where water scarcity is reaching critical levels, the demand for a technology like this is likely to be higher. That prospect, combined with the market density and strength of the private sector, likely means that it will be significantly more feasible in countries like India.
Affordable (under $50), lightweight, fuel efficient solar-powered irrigation pumps

Irrigation is one of the most significant levers for increasing on-farm yield. The manual (e.g., treadle) pumps currently available are quite labor intensive, and often not suited for the needs of women farmers. Motorized pumps currently on the market require diesel, the cumulative costs of which are high (even though incremental costs might be low). In remote areas, the paucity of distribution networks for diesel is an additional constraint. Affordable, solar-powered pumps can be an ideal solution to this problem. A number of organizations are developing solar pumps, and a small number of them are already being used in India. The biggest hurdle appears to be throughput: the more the volume of water pumped, the larger and more expensive the solar panel needs to be.

Considering the effort being dedicated to this problem and the pace with which this market is developing, it is likely that market-ready pumps will become available within the next 2-3 years. However, even if solar pumps become available, there are a number of deployment hurdles: the majority of African farmers are still extremely poor, live in remote areas, and are used to rain-fed farming. Considerable effort will need to go into creating demand, providing finance, and training. A critical lesson from the decades of agricultural development in South Asia, is that water can easily be overused, and groundwater easily depleted. As such, it will be important to consider regulating water use, so that it is used sustainably. Enforcing any such regulations will be very challenging. Hence, we believe that deployment will be COMPLEX.
A low cost system for precision application of agricultural inputs, ideally combining water and fertilizers

The lessons from the Green Revolution in Asia, also discussed in other sections of this study, show that a few decades of overuse can devastate groundwater reserves for the long term. The additional stress of climate change and the consequent change in rainfall patterns increases the need for efficient use of water.

As discussed in other sections of this report, fertilizer overuse is a major problem, with overall efficiency of about 50% for nitrogen, less than 10% for phosphorous, and about 40% for potassium (Baligar, Fageria, & He, 2001). The rest of the applied fertilizer is unavailable to the plants and is wasted as runoff. The mismatched timing between availability of nitrogen and crop need for nitrogen is likely the single greatest contributor to excess nitrogen loss in annual cropping systems (Robertson & Vitousek, 2009). Ideally, nutrients should be applied in multiple small doses when plant demand for them is greatest. A low cost, robust, scalable technology is needed to precisely meter and distribute plant water and nutrients, based on soil and plant type.

In principle, variations of existing programmable irrigation systems used in industrialized countries can be downscaled and adapted to the needs of smallholder farmers. Already, small scale drip and sprinkler systems—along with other methods for increasing water usage efficiency—are beginning to emerge in markets like India. Their costs will continue to drop through the use of less expensive material, and manufacturing moving to lower cost geographies. With some attention, such technologies can be developed in 5 years.

However, there is limited evidence to suggest that users—farmers or otherwise—will be interested in spending money on technologies to conserve water, when the resource itself is available free of cost. The potential for saving fertilizer can prove to be a positive incentive, although the current demand for fertilizers is also very low. That, combined with the all the other structural barriers surrounding the
African smallholder farmer market—fragmentation and the absence of an ecosystem for distribution and maintenance—means deployment will be CHALLENGING.

**Breakthrough 4 – Difficulty of deployment**

<table>
<thead>
<tr>
<th>Extremely Challenging</th>
<th>Challenging</th>
<th>Complex</th>
<th>Feasible</th>
<th>Simple</th>
</tr>
</thead>
<tbody>
<tr>
<td>Policies</td>
<td>Infrastructure</td>
<td>Human capital</td>
<td>Access to user finance</td>
<td>Behavior change</td>
</tr>
<tr>
<td>Low role of policy/ regulations</td>
<td>Requires some improvements to existing infrastructure</td>
<td>Moderate need to train a limited number of people</td>
<td>Moderate financing needed, viable mechanisms identified</td>
<td>Major behavior change required, potentially on daily basis</td>
</tr>
<tr>
<td>Business model innovation</td>
<td>Market fragmentation/Distribution channels</td>
<td>Existing demand</td>
<td>Extremely low demand or not a perceived need</td>
<td>Deployment model(s) being tested; major hurdles outstanding</td>
</tr>
</tbody>
</table>

**Breakthrough 5**

Low cost, portable sensors for accurately estimating local shallow groundwater depth (reducing, in conjunction with drilling technologies, the cost of wells to <$100 per farmer)

Knowing exactly where to drill, is a process of trial-and-error: water can be 4 meters under the ground in one place, and 20 meters under just a short distance away. The ability to rapidly and inexpensively identify the optimal location for digging can dramatically increase access to shallow groundwater. While technologies exist for exploring deep water reserves, these are extremely expensive (costs in millions of dollars), and have not been adapted for shallow water. Our research found very few efforts underway to address this problem. We believe it will take at least 6-8 years before a technology like this becomes a reality.

When it does become available, such a technology could help individual farmers and well-diggers reduce cost considerably. This can make irrigation affordable for farmers, and help well-drilling become a profitable and scalable business proposition too. At a more macro level, such a technology can be used to obtain crucial data on groundwater depth, and contribute to the construction of up-to-date water maps, which can help policymakers make more informed decisions on water management at the micro level. Assuming it is affordable, such a technology can have significant demand if it successfully overcomes the structural challenges associated with market fragmentation, distribution and maintenance. Deployment of such a technology will be COMPLEX.
Breakthrough 5 – Difficulty of deployment

- Policies: Minimal role of policy/regulation
- Infrastructure: Minimal need for infrastructure
- Human capital: Moderate need to train a limited number of people
- Access to user finance: Moderate financing needed, viable mechanisms identified
- Behavior change: Moderate behavior change required with evidence of behavior change being viable
- Existing demand: Moderate demand
- Market fragmentation/Distribution channels: Moderate fragmentation of customers, under-developed channels
- Business model innovation: Deployment models being tested
- Demand: Moderate demand
- Distribution channels: Moderate fragmentation of customers, under-developed channels
- Behavior change: Moderate behavior change required with evidence of behavior change being viable
- Access to user finance: Moderate financing needed, viable mechanisms identified
- Human capital: Moderate need to train a limited number of people
- Infrastructure: Minimal need for infrastructure
- Policies: Minimal role of policy/regulation

- Simple
- Feasible
- Complex
- Challenging
- Extremely Challenging
Fertilizer has been among the most significant drivers of increases in food production, over the past few decades. Whereas the pace of ‘natural’ plant growth depends on whatever underlying nutrients the soil has to offer, the growth and harvest cycles in agriculture require that the soil be regularly enriched. The three main nutrients in fertilizers are nitrogen, phosphorus and potassium. Almost all of the fertilizer used today is produced with methods which are extremely capital-intensive, location-sensitive, and environmentally damaging. While phosphorus and potassium are usually mined, nitrogen is extracted from the air using the Haber-Bosch process. Factories to produce fertilizers using this process cost hundreds of millions of dollars and need to be located near sources of natural gas.

Agricultural yields in Africa have historically been too low to ensure food security, and not without reason. Unlike South Asia, there is very low demand for fertilizers among African smallholder farmers. This is compounded by the fact that there are no fertilizer factories in sub-Saharan Africa (outside of South Africa). Fertilizer has to be imported from other countries, and the cost of distribution can exceed the cost of production, driving up end user costs. Beyond overall agricultural yield, in some countries another outcome of low fertilizer use is deforestation. Soil loses nutrient content with every crop cycle, and farmers in Africa have had to continuously ‘extensify’ to more fertile land to maintain their total agricultural output.

There is also a flip side to fertilizer use. Where fertilizer is easily available, overuse causes significant damage to the environment. Excess fertilizer finds its way into waterways through runoffs and leads to excessive growth of algae and cyanobacteria, in turn, creating marine ‘dead zones’ where fish and other animals cannot survive.

Recently, there have been some efforts to convert biological waste (from plants, animals and humans) to fertilizer, but such approaches face a number of problems: nutrient content and release can be highly variable; human waste contains many harmful pathogens, and improper handling can cause major health problems; and, fertilizer made from human waste is unlikely to be easily accepted by the market. We believe 4 technological breakthroughs can address these problems.

- New methods for nitrogen fixation and producing other fertilizer components, instead of the energy-intensive and capital-intensive methods used currently
- A mechanism to improve the viability and effectiveness of biological fertilizers, in particular, those made from human waste
- A low cost, point-of-use kit to evaluate soil nutrient content, and recommend tailored use of fertilizers for specific crops
- A low cost system for precision application of agricultural inputs, ideally combining fertilizers and water

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1 We would like to acknowledge the Virtual Fertilizer Research Center (VFRC) for its contribution to this chapter. Much of the material here is drawn from VFRC’s work.
2 A few plants (e.g., legumes) naturally fix nitrogen in their root systems, but natural nitrogen fixation does not occur in most crops.
Synthetic fertilizers—non-natural fertilizers made in factories using chemical processes—have been one of the most significant contributors to global food production over the last 50 years. By some measures, these fertilizers have helped save the lives of more than 2.4 billion food insecure people (Hager, 2008). Since the invention of the chemical processes in the 1960s, global production of cereals has tripled and so has the global consumption of nitrogen, potassium and phosphorus (the three essential ingredients in fertilizer) (FAO, 2014) (Virtual Fertilizer Research Center, 2012). Conversely, where fertilizers have been available, they have been overused, leading to significant environmental damage. Indeed, the process of producing fertilizer, itself, has a large environmental footprint.

**CORE FACTS AND ANALYSIS**

Plants require numerous essential elements from soil, of which nitrogen (N), phosphorus (P) and potassium (K) are the most critical (Silva & Uchida, 2000). In natural systems, each of these nutrients enters the soil through different processes (Exhibit 1). Nitrogen is present in the air in abundance, but is relatively inert in that form. To be absorbed by plants, it needs to be converted into more usable forms like ammonia (NH₃) or nitrate (NO₃). This conversion—nitrogen fixation—occurs naturally through bacteria (and to a much smaller extent, by lightning). Phosphorus is found in soil through the gradual breakdown of various inorganic (phosphate rocks) and organic compounds (plant residue and animal waste). Potassium is a core part of particular types of soil, especially those with high clay content.
In the natural cycle of plant growth, decay and rebirth, these nutrients are replenished slowly, and that replenishment rate determines the pace of plant growth. Agricultural systems are much more rapid and demanding, and soil nutrients deplete faster than they can be naturally restored. Nitrogen and Potassium are primarily lost through harvesting of crops. Nitrogen can also be leached from the soil during periods of heavy rain or over irrigation. Phosphorus is mainly lost due to soil erosion, and to a lesser extent through harvesting. As discussed in more detail later in this chapter, much of the world’s agricultural output outside of sub-Saharan Africa has been dependent on synthetically produced fertilizer to enrich nutrient-depleted soil.

A small number of plants, such as legumes, are able to fix nitrogen naturally, because they contain symbiotic rhizobium bacteria in their root systems. Such plants have been used for crop rotation—in traditional agronomy, as well as in newer sustainable farming systems in many parts of the world—to organically enrich soil. The essential idea in crop rotation is to alternate between the ‘main’ food crops (e.g., maize or wheat) and nitrogen-fixing crops, so that the need for synthetic fertilizers is diminished. Unfortunately, crop rotation is not widely practiced in sub-Saharan Africa, because of pressures to maximize utilization of farmland to meet minimum food requirements. As a result, farmers have prioritized the immediate need to increase the total output of main food crops, over the long-term health of the soil.
Improving soil nutrient quality through fertilizers will significantly increase overall food production across sub-Saharan Africa

Agricultural yield increases with fertilizer application (Exhibit 2). Studies have shown that yield can increase by more than 50% with low levels of application, and over 80% with sufficient application (Pandey, Maranville, & Admou, 2000). Of course, there are diminishing returns beyond a certain point (Roberts, 2007), but it is estimated that addressing soil nutrient deficiencies with fertilizers can close yield gaps in sub-Saharan Africa to almost 50% of maximum attainable yields (Mueller, Gerber, Johnston, Ray, Ramankutty, & Foley, 2012). Smallholder farmers in sub-Saharan Africa have historically never used much fertilizer, and that trend continues to this day. For example, fertilizer use for maize, the most widely-grown staple crop on the continent, is 40 kg per hectare in sub-Saharan Africa, compared with the world average of 153 kg per hectare, 70 kg per hectare in India, 210 kg per hectare in China, and 270 kg per hectare in the USA (Exhibit 3). Fertilizer use in Africa is even lower for other staple crops like rice. As described later, there are a number of reasons behind this low usage: high cost, limited availability, and a broad lack of awareness of the benefits of fertilizer.

Maize yield with different amounts of fertilizer

Exhibit 2: Fertilizer use directly leads to yield increases, as shown in this study of maize (Pandey, Maranville, & Admou, 2000). However, depending on the type of crop, the condition of the soil and other factors, there is a diminishing return to adding fertilizer after a certain point.
Fertilizer use for some staple crops in sub-Saharan Africa compared with other parts of the world

Kilograms per hectare

Maize

<table>
<thead>
<tr>
<th></th>
<th>sub-Saharan Africa</th>
<th>India</th>
<th>China</th>
<th>USA</th>
</tr>
</thead>
<tbody>
<tr>
<td>World average: 153</td>
<td>40</td>
<td>70</td>
<td>160</td>
<td>250</td>
</tr>
</tbody>
</table>

Rice

<table>
<thead>
<tr>
<th></th>
<th>sub-Saharan Africa</th>
<th>India</th>
<th>China</th>
<th>USA</th>
</tr>
</thead>
<tbody>
<tr>
<td>World average: 155</td>
<td>210</td>
<td>10</td>
<td>210</td>
<td>270</td>
</tr>
</tbody>
</table>

Exhibit 3: Fertilizer use in sub-Saharan Africa is a fraction of that in other parts of the world (FAO, 2009).

The Asian Green Revolution (Spielman & Pandya-Lorch, 2009) (Hazell, 2009) is considered one of the most significant achievements in the history of global development. Building on the work of Nobel laureate Norman Borlaug, the Green Revolution led to the practice of intensified agriculture for smallholder farmers across much of Asia. One of the key elements of intensified agriculture is the use of synthetic fertilizer. A telling measure of the impact of intensified agriculture is a comparison of yields between South Asia and sub-Saharan Africa, from the 1960s (when the Green Revolution was launched), to now. As Exhibit 4 shows, between 1961 and 2009, yield of cereals in South Asia increased by 165% from the same amount of cultivated land. There was no similar intervention in sub-Saharan Africa, as a result of which farmers did not have access to synthetic fertilizers, and soil fertility diminished. Between 1961 and 2009, there was only a 60% increase in per hectare cereal yield in sub-Saharan Africa, and farmers have had to increase the amount of land for cultivation by 140% (Virtual Fertilizer Research Center, 2012).
Cereal production, yield and land usage in sub-Saharan Africa and South Asia, 1961-2009

Exhibit 4: Synthetic fertilizers, a critical component of intensified agriculture, have been a key difference between agricultural development in South Asia and sub-Saharan Africa. Compared to 1961, per-hectare cereal yield in South Asia has increased by 165%, for total output increase of 210%, with only a 20% increase in land used. During the same period, the absence of fertilizers in sub-Saharan Africa—and the consequent loss of soil fertility—has led to a 140% increase in cultivated land and only a 60% increase in per-hectare yield (Virtual Fertilizer Research Center, 2012).

Nutrient mining has caused agricultural soil in Africa to become highly, and continuously, degraded

Decades of cultivation, combined with minimal application of soil nutrients, have degraded agricultural soil across sub-Saharan Africa (Exhibit 5 and Exhibit 6). This process of depleting soil nutrients through crop harvesting, without ongoing replenishment, is known as nutrient mining. Studies of nutrient mining among smallholder farmers in Africa found that 85% of African farmland has nutrient mining rates of more than 30 kg per hectare per year and 40% had rates greater than 60 kg per hectare per year (Henao & Baanante, 2006) (Vitousek, et al., 2009). This compares with a global average of 37 kg per hectare per year, meaning that arable land in Africa is losing nutrients and productivity faster than farms in other parts of the world. Quantifying the impact of nutrient mining is difficult, but a 2005 synthesis of studies in Ethiopia found that land degradation was reducing agricultural productivity by 2-3% per year (Yesuf, Mekonnen, Kassie, & Pender, 2005).
Exhibit 5: Soil nutrient losses in Africa are higher compared with most other parts of the world where much more fertilizer is used to replenish nutrient-depleted soil during crop growth and post-harvest (Vitousek, et al., 2009).
Exhibit 6: The problem of nutrient mining is common across sub-Saharan Africa; 85% of African farmland has nutrient mining rates of more than 30 kg per hectare per year and 40% had rates greater than 60 kg per hectare per year (Henao & Baanante, 2006).

Almost all the fertilizer in the world today is produced using methods that are extremely capital-intensive, with a heavy environmental footprint.

The 3 main nutrients in fertilizers, nitrogen, phosphorus and potassium, all depend on environmentally costly extraction processes. Nitrogen is extracted from the air and is converted to compounds that can be used by plants by chemical combination with hydrogen—mainly in the form of ammonia, urea, or ammonium nitrate. The only industrial scale nitrogen fixation process used today (the Haber-Bosch process\(^3\)) requires fossil fuels both as a hydrogen feedstock and for energy. Currently, natural gas comprises 85-90% of operating costs for ammonia plants, making production feasible only at a large scale and near sources of natural gas (Virtual Fertilizer Research Center, 2012). Furthermore, the chemical plants used to produce such compounds are extremely capital-intensive (costing hundreds of millions of dollars) due to the use of large-scale industrial chemical catalytic processes conducted at high pressures and temperatures. As a result, there is currently no synthetic ammonia production in sub-Saharan Africa.

Phosphorus on the other hand is typically extracted from mines as phosphate rock, which can take over $1 billion in investment and several years to commission. Two-thirds of the world’s phosphate rock is concentrated in China, US, and Morocco, and none is extracted or exported from sub-Saharan Africa. Potassium, typically extracted in the form of potash salts, also comes from mines that can take several billion dollars and several years to commission. There are no major potash mines anywhere in Africa.

\(^3\) The Haber-Bosch process is named for the two German scientists who invented it, Fritz Haber and Carl Bosch, both of whom were awarded the Nobel Prize in Chemistry, for this achievement.
With the steady rise in global demand for fertilizer over the decades, the process has become commoditized, and fertilizer is relatively affordable to farmers in countries where it is produced. However, with less than 0.1% of industry sales spent on R&D, there has been little effort to improve the production processes, or make them less capital-intensive.

These factors, together with the extremely under-developed nature of the smallholder farmer market in Africa, have led to a state in which sub-Saharan Africa (excluding South Africa) accounts for only 0.1% of global fertilizer production (Exhibit 7). As a consequence, whatever little fertilizer is used in sub-Saharan Africa is imported, and the cost of distributing fertilizer exceeds the cost of producing it. By some estimates (World Bank, 2007), it costs the typical farmer in sub-Saharan Africa 50% more than it costs a farmer in the USA (Exhibit 8).

**Exhibit 7: Barely 0.1% of the world’s synthetic fertilizer is produced in sub-Saharan Africa (excluding South Africa). All of Africa accounts for 4% of global production, most of which is from North Africa, with South Africa accounting for most of the remaining.**
End user cost of fertilizer in the USA vs. in sub-Saharan Africa

$ per metric ton, 2003

<table>
<thead>
<tr>
<th>Country</th>
<th>Materials</th>
<th>Shipping (to country), import and port fees</th>
<th>Wholesaler margin</th>
<th>Transportation &amp; storage (within country)</th>
<th>Dealer margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>$135</td>
<td>$16</td>
<td>$16</td>
<td>$18</td>
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<td>$4</td>
</tr>
<tr>
<td>Angola</td>
<td>$226</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Exhibit 8: The high cost of shipping (to the country) and transportation (within the country) for most African countries has led to a significantly higher market price of fertilizer in Africa than markets like the USA. The market price varies somewhat even between different African countries (World Bank, 2007).

Fertilizer overuse is a source of significant environmental pollution

Most farmers who can comfortably afford fertilizer, tend to overuse it. While heavy overuse can cause major damage to the crops, the typical amount of overuse causes environmental damage without necessarily hurting the crops. Nitrogen and phosphorus runoffs from farmland constitute a significant source of water contamination in many parts of the world (Conijn, Ruijter, Schroeder, & Bindraban, 2013). Just as fertilizing agricultural fields can stimulate crop growth, increasing nutrient levels in water bodies can cause excessive growth of algae and other aquatic plants. This causes hypoxia (or depletion of oxygen in the water), which then causes the death of fish and other animals in the water. In addition, the growth of cyanobacteria can also produce toxic compounds hazardous to humans and domesticated animals. Currently, there are over 400 marine ‘dead zones’ worldwide, caused by nutrient runoff; these have doubled every decade since the introduction of synthetic fertilizers in 1960s (Diaz & Rosenberg, 2008). Exhibit 9, a global map of dead zones due to runoff, shows that many of the prolific food producing regions of the world face this problem. Globally, about half the nitrogen is harvested with crops, while the rest is lost through leaching, erosion, and other mechanisms. As the chapter on sustainable agriculture discusses, the areas with the greatest nitrogen overuse have the highest concentrations of marine dead zones.
Exhibit 9: Reactive nitrogen flows in many river systems have increased dramatically in recent decades—primarily due to fertilizer runoff from agricultural lands—especially evident in Europe, Asia and North America. This has led to ‘dead zones’ in waterways.

Biological fertilizers can be an alternative to synthetic fertilizer, but face a number of challenges

Biological fertilizers increase the total organic matter in soil and release nutrients gradually, sometimes over the course of several years, depending on the specific source. This can be beneficial for the soil in the long run, providing not only a rich source of nutrients but also reducing erosion. In addition, since it can be made from household and farm waste, the farmer does not need to purchase more expensive synthetic fertilizers (World Bank, 2007). Recently, there have been promising cases of composting plant and animal waste into potent biological fertilizer. For example, farmers can convert coffee cherry pulp (which is usually discarded otherwise) into organic fertilizer using a variety of decomposition methods (e.g., vermiculture, commercial organic sprays containing enzymes). Other sustainable agronomy techniques such as permaculture, have also produced similar yield improvements as synthetic fertilizers. Unlike in biological variants, nutrients in synthetic fertilizer are released quickly, enabling accelerated crop lifecycles. Because of this rapid release, nutrient flow can be controlled and synchronized with the high nutrition need windows of a plant’s lifecycle, ensuring optimal growth. These high-growth phases when a plant needs maximum nutrition for maximum yield vary from crop to crop. While these recent
biological fertilizer trials mentioned above hold promise, large scale production and distribution of biological fertilizers faces a number of challenges.

First, the nutrient content in biological sources of fertilizer is highly variable, depending on, for example, the nature of the food consumed by the animals whose manure is being used. Nutrient content also tends to be more diverse and is present in smaller volumes. Thus, while certain biological fertilizers have shown tremendous promise with cash crops and fruits and vegetables, their potential with cereals (which require high volumes of macro nutrients) remains to be seen. More importantly, the timing of nutrient release in biological fertilizers is dependent on the rate of decomposition and is difficult to control. This means that, in the short run, optimum amount of nutrients are usually not available to the plant when it needs them most.

Second, as opposed to being abundantly available like air is for nitrogen fixation through the Haber-Bosch process, the supply is less reliable and more susceptible to corruption during the conversion process. Biological fertilizers would likely be produced near the source of raw material, and most successful trials have been at the micro level, for example, a vermicomposting site near a coffee cherry pulping station. Without the benefits of economies of scale, production of more complex forms of biological fertilizer is more labor intensive, which can cause a significant barrier to adoption. Currently, biological fertilizer is most prevalent in the form of waste produced by livestock, and only available in small quantities.

Third, most biological waste in sub-Saharan Africa is already used for other purposes, such as building materials (for rudimentary construction in villages), food for animals, and fuel for cooking and heating. Therefore, while there may not be a cash cost to biological fertilizer, there may be an opportunity cost to the farmer.

Human waste is unlikely to be a major source of fertilizer in developing countries due to lack of sanitation infrastructure; however, it can have a number of benefits

Human waste is one potential source for biological fertilizer, and a number of organizations, such as SOIL in Haiti and Sanergy in Kenya, have launched sanitation programs to collect human waste and compost it into fertilizer. Converting human waste to fertilizer can have the added benefit of providing a financially sustainable model for sanitation.

While some studies in Europe have demonstrated that the average adult human excretes enough waste (5.7 kg of nitrogen, 0.6 kg of phosphorus and 1.2 kg of potassium, from 500 kg of urine and 50 kg of feces each year) to produce the fertilizer required to grow enough cereal for one adult human (250 kg) (Heinonen-Tanski & van Wijk-Sjibesma, 2005), the nutritional content of human waste depends heavily on food intake. Therefore, it is likely to produce less rich fertilizer in Africa, where the quality and quantity of food intake tends to be lower (WHO, 2013).

Our analysis shows that the waste (feces and urine) from 3 Kenyan adults, if appropriately processed, can be used to provide a modest 14% boost for the typical Kenyan 1 hectare maize farm (from 1.6 tons to 1.9 tons) (Exhibit 10). At a larger scale, if the waste from a much larger population in Kenya (including both farming and non-farming populations) were converted to fertilizer, food production could be increased by much more. However, human waste is unlikely to be a major source of fertilizer in a developing country. As Exhibit 11 shows, if 100% of the feces and urine from 100% of the adults in Kenya were converted to fertilizer, assuming some natural losses of nutrients during composting, it could lead to a 40% increase in the production of cereal in the country. Collecting even

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6 As described in the section on Health, the lack of adequate sanitation is a significant driver of diarrheal disease, which is among the leading causes of childhood mortality in developing countries.
4 Waste produced by children is not as helpful for plants, since growing children absorb a much greater portion of the nutrients they ingest.
6 Our analysis assumes that the waste in the typical adult in Kenya has two-thirds the nutrients cited in the European study, based on WHO’s estimates of the typical caloric intake in Sub-Saharan Africa vs. industrialized countries (World Health Organization, 2013). Our analysis also assumes that 50% of the nutrients are lost during the conversion process, and during nutrient uptake by the plants.
1% of the total waste, which in the case of Kenya would be the equivalent of collecting all the waste generated by more than 220,000 adults, is extremely difficult due to the lack of sanitation infrastructure. It is highly unlikely that enough human waste can be collected and processed, to produce large quantities of fertilizer to boost cereal yields significantly. However, it is important to note that converting human waste into fertilizer can:

- Help make sanitation solutions in developing countries financially sustainable (through the sale of the fertilizer).
- Increase food production at a smaller scale, including for high nutrition crops (e.g., vegetables).
- Be a significant part of the solution to replace synthetic fertilizers in industrialized countries, where sanitation infrastructures are much more advanced and centralized.

**Potential yield increase on a 1 hectare maize farm in Kenya from using fertilizer made from human waste**

<table>
<thead>
<tr>
<th>Yield (tons/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Current yield</strong></td>
</tr>
<tr>
<td><strong>Potential yield increase from family waste</strong></td>
</tr>
<tr>
<td><strong>Total</strong></td>
</tr>
</tbody>
</table>

**Exhibit 10:** If appropriately processed, the fertilizer made from the waste (feces and urine) generated by 3 adults in a smallholder farming family can provide a modest boost to total crop yield; it can potentially increase yield on a 1 hectare maize farm in Kenya by 14% (from 1.6 tons to 1.9 tons). Higher and better quality food intake by the adults producing the waste, reduction in nutrient loss during processing, and higher nutrient uptake efficiency of the fertilizer can increase this yield boost.
Potential increase in cereal production vs. percent of adult human waste utilized for fertilizer

*(Percentage of current cereal production in Kenya, 4.5 million tons)*

Exhibit 11: If 100% of the human waste in Kenya is composted and used as fertilizer, it will increase cereal production by about 40%. Given the poor sanitation infrastructure in a country like Kenya, it is unlikely to be a major source of fertilizer there. However, it can be a promising source of fertilizer in industrialized countries where sanitation infrastructure is well developed.

Human waste as feedstock for fertilizer faces a number of challenges

Human waste carries very harmful pathogens (bacteria, viruses, parasites). It must be carefully handled and processed for several weeks, depending on the environmental conditions, to fully eliminate health risks. Without appropriate mechanisms for safe collection and processing, it can increase the spread of disease.

The process of converting human waste to fertilizer is complicated. For example, it requires a carbon-nitrogen ratio (C:N) of 30:1, rather than 5:1 or 10:1 which is the normal C:N ratio in human fecal matter. In addition, high-temperature treatment is required to kill the pathogens (Sustainable Organic Integrated Livelihoods, 2011). Both these steps require additional soil amendments. This means that specific training, and in most cases, a dedicated processing facility are required, for collection, storage, processing, and quality control.

Human waste is unpleasant. Unsurprisingly, there is taboo in many societies against handling human waste, and even more on applying it towards food production.

Slow, unpredictable nutrient release. As with other biological fertilizers, the challenge of slow nutrient release rates, as well as the variable amount of nutrients in the raw material, still remain.
KEY CHALLENGES

The ‘fertilizer problem’ can be thought of as 3 separate problems, based on the state of economic and agricultural development in different parts of the world. Industrialized countries have stable fertilizer markets, and there is limited economic incentive to migrate away from synthetic fertilizers, despite the environmental damage caused by overuse. On the other hand, the robust sanitation infrastructures in these countries, combined with the amount of food waste and systems for collecting the waste, offer an opportunity to develop biological fertilizers at scale in a commercially sustainable manner. Green Revolution countries—like industrialized countries—have access to synthetic fertilizers, and also suffer from overuse. However, they do not have robust infrastructures for sanitation or waste collection, neither do they have economic incentives for investing in alternatives to synthetic fertilizers. Unlike either of the above mentioned scenarios, sub-Saharan Africa has scant access to synthetic fertilizers, and the current economics of the fertilizer industry suggest that local production in the foreseeable future is improbable. The absence of fertilizers is continuing to deplete soil of nutrients, which, in turn, is leading to an increasing amount of land being used for agriculture. At the same time, the poor sanitation infrastructure, combined with the limited amount of food waste (and the lack of mechanisms to collect what food is wasted), make it difficult to develop biological fertilizers at any scale. When it comes to using fertilizers for improving agricultural yields, smallholder farmers in sub-Saharan Africa face 4 specific challenges.

1. Synthetic fertilizer is very expensive for farmers in Africa

The core processes for manufacturing fertilizer, the Haber-Bosch process for nitrogen fixation and mining for phosphorus and potassium, are extremely capital-intensive. These production methods have not evolved or improved much in decades (Virtual Fertilizer Research Center, 2012). Poor transportation infrastructure in Africa increases the cost of distributing imported fertilizer to farmers. For most African countries, shipping (to the port), transport (within the country) and related costs add an extra 40% to the per-ton cost of fertilizer. Landlocked countries have to pay another 20-40% extra (World Bank, 2007).

2. There is limited demand for fertilizer among African smallholder farmers

There is a broad lack of awareness of the benefits of fertilizer among smallholder farmers. Their limited economic means make them highly risk-averse too. Farm-gate prices for cereals in Africa are much more volatile than in other regions; maize prices have historically been twice as volatile in Africa than in Asia. In addition, because most African farming is rain-fed, there can also be heavy weather-related fluctuation in yield. Even when fertilizer is used, the lack of knowledge about appropriate usage has resulted in very low nutrient uptake efficiency (NUE), which is 25-30% among smallholder farmers in Africa compared with 50-60% in developed agricultural systems. Finally, the majority of sub-Saharan African countries consume less than 25,000 tons of fertilizer each year; the volume at which fertilizer can be imported cost effectively (World Bank, 2007) (Gregory & Bumb, 2006). All this has discouraged investment in fertilizers or other yield-enhancing inputs. Consequently, Africa accounts for less than 1% of the global fertilizer market.

3. The private sector ecosystem for fertilizer in Africa is very weak

In addition to the low demand, there are other hurdles to private sector investment in the African fertilizer market. The lack of access to financing discourages local dealers, who typically need to build up large inventories since demand tends to be seasonal; agriculture in Africa is largely rain-fed. Unfavorable
business environments and uncertain political environments have made international firms reluctant to enter African markets. What little private sector activity there is, is limited to small dealer networks concentrated near urban centers, serving peri-urban or larger farmers rather than rural smallholder farmers (World Bank, 2007).

Biological fertilizers are not yet a feasible alternative to synthetic fertilizers

As discussed earlier, animal and plant waste are traditionally used for other purposes (energy and animal food, respectively), and several hurdles currently prevent large-scale conversion of biological waste into fertilizer.
New breakthroughs in plant nutrients will have to explore multiple avenues:
- Production systems which are significantly less capital intensive than current methods, and much more environmentally sustainable.
- Greater efficiencies in application, to prevent losses and runoffs.
- Significantly higher uptake efficiencies, so that the plants can maximize growth.

These questions are at the intersection of 3 scientific disciplines: the Haber-Bosch process and the production of the other reactive compounds is in the realm of chemistry and chemical engineering; how plants utilize nutrients falls in the field of crops sciences; and the broader question of soil health is in soil science. Developing breakthrough solutions to concurrently address food security and environmental protection will require cross-disciplinary research. Unfortunately, there appears to be very little cross-disciplinary work underway today. There are 4 potential breakthroughs to address the problem of affordable, sustainable fertilizers and plant nutrients.

**New methods for nitrogen fixation and producing other fertilizer components, instead of the energy-intensive and capital-intensive methods used currently**

Perhaps the single most significant hurdle to the availability of affordable fertilizer for smallholder farmers in sub-Saharan Africa is that the known processes for producing usable forms of the key components of fertilizer—nitrogen, phosphorus and potassium—are extremely capital intensive, and need to be located near the sources of particular natural resources. For example, a facility for the Haber-Bosch process, the only known synthetic, scalable process for nitrogen fixation, costs hundreds of millions of dollars to build, and needs to be located near a source of natural gas. As a result, there is virtually no fertilizer produced in sub-Saharan Africa (outside of South Africa), and what little is used has to be shipped in. This means that the same fertilizer costs the African smallholder farmer considerably more than it costs a farmer in countries where the fertilizer is produced. An ideal alternative will be significantly less capital-intensive, less energy-intensive, and will not require close proximity to sources of natural gas or other extractive resources. This will enable production at a larger number of smaller and lower cost facilities that are closer to market.

However, there are significant technical challenges involved, especially in splitting nitrogen bonds. The fact that the only scientists to solve this problem in the past (Fritz Haber and Carl Bosch) won the Nobel Prize, underscores the magnitude of the challenge. The solution can be biological or electrochemical. While some emerging technologies offer promise (such as intra-cellular transplantation of nitrogen-fixing bacteria from natural host crops to other crops), a scaled solution still appears to be far away. There is limited incentive for private sector investment to address this problem, given that synthetic fertilizer is very well accepted in most of the world. Therefore, we believe it will take more than 10 years for such a technology to come to market.

Even when developed, such a technology will still face some deployment challenges, the most important being low demand from African smallholder farmers. Even if demand is created, low income farmers will need some form of financial support, possibly through micro-credit programs, so that they have the working capital to invest in fertilizer. Extension services will likely be necessary for training farmers on how to use fertilizer appropriately. Overall, deployment will be EXTREMELY CHALLENGING.
Breakthrough 1 – Difficulty of deployment

A mechanism to improve the viability and effectiveness of biological fertilizers, in particular, those made from human waste

Processes to convert biological waste—from plants, animals, and in particular humans—into fertilizer, can be much more cost effective than producing synthetic fertilizer. However, unlike many industrialized countries, most developing countries don’t create enough food waste to generate large quantities of compost, and there is an opportunity cost to farmers if animal waste is used as a source of fertilizer.

Using human waste to make fertilizer presents its own set of challenges. Collecting human waste safely for converting it to fertilizer can help tackle the spread of diarrheal diseases—mostly caused by the spread of fecal pathogens—that are one of the biggest drivers of childhood mortality. The process will require relatively low capital expenses, and the waste does not have to be transported over long distances if a large number of smaller facilities are built. Safe collection and processing, however, is crucial. While safe collection remains challenging in resource-constrained settings with a weak sanitation infrastructure, the methods currently employed to process human waste are slow too. It can take weeks or months for the pathogens to be destroyed and the waste to be fully composted. There is a high risk that before the composting process completes the pathogens leach into the environment, potentially exacerbating diarrheal disease. Therefore, a new process will have to dramatically accelerate pathogen destruction.

Furthermore, it will be important to ensure that the resulting fertilizer releases nutrients in a timely manner, so that farmers can see benefits of using the product in a single season. A number of promising mechanisms have been identified to accelerate the composting rate (e.g., based on microbes, and particular types of enclosures). Considering the current trajectory, there is no reason a feasible technical solution should take longer than 2-3 years.

Some organizations are producing and selling fertilizer made from human waste, but at a small scale, and with limited technical enhancements. The challenges faced by these organizations suggest that when an improved process is developed, it will need to overcome a number of major hurdles: the sanitation infrastructure required to collect the waste, cultural acceptance of human waste as an input to food production, low demand from smallholder farmers, the need for financing, and training on appropriate
application. In addition, stringent safety regulations will be necessary to ensure that careless collection
and shoddy production methods do not exacerbate diarrheal disease. Each of these can pose a significant
obstacle. Collectively, they make deployment EXTREMELY CHALLENGING.

Breakthrough 2 – Difficulty of deployment

A low cost, point-of-use kit to evaluate soil nutrient content, and recommend tailored use of fertilizers for specific crops

Understanding exactly how much fertilizer to apply, and at what stage of the plant’s lifecycle, is very critical for maximizing returns on the farmers’ investment. Smallholder farmers in Africa rely on advice from knowledgeable peers (e.g., farmer cooperative leaders) or from extension workers. A low cost kit, with a simple user interface, for rapid chemical analysis of the soil—tailored to the crop, underlying soil type, season, and crop lifecycle—can prove extremely helpful in improving nutrient uptake, yield, and eventually demand for fertilizer. Using mobile technology for underlying computation, access to additional information, and easy communication with appropriate extension workers, can make such a tool more attractive for smallholder farmers.

Such toolkits are common in more developed markets. A recent wave of technological innovation has made them even more precise, and enhanced the benefits for farmers using such kits. However, these kits are still cost prohibitive for the smallholder farmer in Africa, and not necessarily intuitive to use by a farmer with limited education. While considerable reengineering is required to make such kits useful for the African smallholder farmer, there are no major scientific challenges involved. Based on the above assessment, the projected time to market readiness is about 3-5 years.

We anticipate that when such a technology is developed, there will be limited initial demand and it will have to overcome marketing and distribution challenges. Presumably, demand for such a tool will depend on the demand for fertilizer, and the value proposition of reducing the amount of money that farmers spend on fertilizer will be appealing. The rapid proliferation of smartphones and ICT tools
for smallholder farmers is a positive trend that may help in the acceptance of such a technology. Still, until fertilizer demand and use increases, such a technology will not take off. Considering the above, deployment will be EXTREMELY CHALLENGING.

**Breakthrough 3 – Difficulty of deployment**

<table>
<thead>
<tr>
<th>Extremely Challenging</th>
<th>Challenging</th>
<th>Complex</th>
<th>Feasible</th>
<th>Simple</th>
</tr>
</thead>
<tbody>
<tr>
<td>Policies</td>
<td>Infrastructure</td>
<td>Human capital</td>
<td>Access to user finance</td>
<td>Behavior change</td>
</tr>
<tr>
<td>Minimal role of policy/regulation</td>
<td>Requires high level of training for large numbers of people</td>
<td>Moderate financing needed, viable mechanisms identified</td>
<td>Significant behavior change needed on daily basis, changes contrary to cultural norms</td>
<td>Extremely low demand or not a perceived need</td>
</tr>
</tbody>
</table>

A low cost system for precision application of agricultural inputs, ideally combining fertilizers and water

Crop yields respond very well with initial inputs of fertilizer, but as additional nutrients are supplied the marginal yield increase becomes smaller. Optimal results occur somewhere along that gradient, depending on the cost of fertilizer and seeds, land, and selling price of harvested crops. For maximum returns, it is necessary to not just apply the right quantity of fertilizer, but apply it at the right time and right place for optimal nutrient uptake by the plant.

The efficiency of using agricultural inputs such as fertilizer is low in conventional farming. It is estimated that overall efficiency of applied fertilizers is about 50% for nitrogen, less than 10% for phosphorus, and about 40% for potassium. The rest is wasted as runoff. The mismatched timing between availability of nitrogen and crop need for nitrogen is likely the single greatest contributor to excess nitrogen loss in annual cropping systems. Ideally, nutrients should be applied in multiple small doses and when plant demand for them is greatest.

A low cost, robust, scalable technology is needed to precisely meter and distribute plant nutrients and/or other inputs. This would allow farmers to apply the right amounts of fertilizer (not too much and not too little), at the right time, to maximize economic returns and reduce nutrient loss. This breakthrough would be strongly leveraged by low cost soil nutrient analysis and low cost precision irrigation methods (identified as breakthoughs in other chapters). This will help farmers better predict crop nutrient requirements over time, avoid over-fertilization, and schedule irrigation better. If complemented with adjusted crop rotation patterns and additional biotic complexity, it could improve the plant community’s ability to take up more of the available nutrients. By allowing better
management of the timing, placement, and formulation of fertilizer in cropping systems, such a technology would ensure that nutrients are available where and when needed by the plant, and the farmer gets maximum return on his investment. This would also protect watersheds and populations downstream from farm fields, by greatly reducing runoff.

If resources are devoted to accomplish this breakthrough, we expect that it will take less than 5 years to be market ready. Once ready, it will face some deployment challenges including a fragmented market (of farmers), access to finance for potential users, and training of farmers to install, use and maintain the technology. The difficulty of deployment in this case would be CHALLENGING.

Note that an additional avenue to explore is alternative mechanisms for nutrient intake. Most plants absorb nutrients through their roots. Research has shown that some nutrients (e.g., nitrogen, iron, zinc) can be absorbed rapidly through leaves or stems, via foliar sprays. In addition, ‘airplants’ which grow in tree canopies, and other aquatic plants, get nutrient through leaves. However, there are number of open questions about the broader applicability of foliar sprays, and this is an area of active research (Virtual Fertilizer Research Center, 2013).
BIOTIC STRESSES

Biotic stresses—weeds, pests and pathogens—can collectively cause the loss of more than half the potential yield of smallholder farmers in sub-Saharan Africa and South Asia. Mechanized tilling—one of the most common methods of dealing with weeds in industrialized countries—is too expensive for most smallholders in Africa, and so are the chemical herbicides and pesticides commonly used in commercial agriculture. In addition, weeds and pests can develop resistance to herbicides and pesticides, thereby rendering them ineffective in the long run. They can also cause considerable damage to the farmers’ health and environment if used inappropriately. While many industrialized countries also rely on GMOs for combating biotic stresses, these enhanced seed varieties pose a number of unique challenges in developing countries. In order to overcome these biotic stresses, smallholder farmers need 4 technological breakthroughs.

- A low cost (under $50) tilling machine
- Herbicides or other affordable mechanisms to control weeds, ideally ones that are more environmentally friendly than herbicides currently on the market
- Novel, low cost and environmentally friendly pesticide(s), specifically targeting the most destructive insects
- Spatial repellent for on-farm pests

USAID
A significant portion of agricultural produce is lost even before the crops are harvested, due to weeds, pests and pathogens. Addressing these stresses can lead to tremendous increase in food production among smallholder farmers.

**CORE FACTS AND ANALYSIS**

Biotic stresses refer to the damage done to cultivated crops by other living organisms, primarily weeds, pests, and pathogens such as fungi, bacteria and viruses. These stresses can collectively reduce yield by more than 50% for smallholder farmers, who typically do not have the tools to combat them.

*Exhibit 1* shows estimated losses (compared with potential yield) due to weeds, animal pests and pathogens (disease), from an aggregation of studies of cereal crops in sub-Saharan Africa (Shetto & Kwiligwa, 1990) (Oerke, 2006). Losses in South Asia can also be significant.

<table>
<thead>
<tr>
<th></th>
<th>Losses (%)</th>
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<tbody>
<tr>
<td>Potential yield</td>
<td>100%</td>
</tr>
<tr>
<td>Weeds</td>
<td>30%</td>
</tr>
<tr>
<td>Animal pests</td>
<td>15%</td>
</tr>
<tr>
<td>Disease</td>
<td>15%</td>
</tr>
<tr>
<td>Actual yield</td>
<td>40%</td>
</tr>
</tbody>
</table>

*Exhibit 1:* Based on a representative study of biotic stresses on cereal crops in sub-Saharan Africa, weeds constitute the largest driver of losses, followed by pests and diseases caused by a range of pathogens. Collectively, these stresses can reduce potential yield by as much as 60%.

**Weeds represent the most significant biotic stress on crops**

Weeds are a major cause of crop loss in both sub-Saharan Africa and South Asia. By aggressively competing with crops for soil nutrients and water, weeds can cause up to 30% losses for maize, and between 10% and 20% for other crops, across Africa (Shetto & Kwiligwa, 1990) (Oerke, 2006). Losses in South Asia can also be significant, although farmers tend to have greater access to tools to deal with the problem. The specific variety and strain of weeds varies by geography, but the example of *Striga* is illustrative of the challenges posed by weeds. Also known as ‘witchweed’, *Striga* is among the most destructive weeds, causing losses of up to US $1 billion each year across Africa (Berner, et al., 1995) (African Agricultural Technology Foundation, 2014). Two species, *Striga hermonthica* and *Striga asiatica*, cause the most...
The weed is difficult to control because each plant can produce thousands of small and light seeds, which can be easily and widely dispersed by wind, water, animals, and agricultural implements. The weed can also remain dormant for many years, before proliferating (Integrated Striga Management in Africa, 2014). Three weed-control mechanisms are commonly used in industrialized countries, but none of them are used by the majority of smallholder farmers.

**Mechanized rotary tillers or cultivators**
These implements dig into the soil in order to aerate it, and to pull out weeds at their roots. Larger tillers are tractor-mounted, and smaller ones are usually diesel-powered. The smallest and least expensive of these cost more than $200-$300. Larger ones can easily cost several thousand dollars. All of them are currently far too expensive for low income smallholder farmers. While animal-drawn cultivators can help reduce a farmer’s workload, their effectiveness is limited (Shetto & Kwiligwa, 1990). Despite its value in aerating soil and weed control, tilling can have negative consequences like soil erosion. The topsoil, loosened by tilling, can get washed away during heavy rain. Tilling and subsequent water-induced erosion also leads to CO₂ emissions (Chaploza, et al., 2012).

**Herbicides**
Chemical herbicides, over the past few decades, have been a relatively low cost, easy-to-use method for killing weeds in industrialized markets. However, these are too expensive for the typical smallholder farmer in developing countries, and usually make economic sense only for high-value cash crops or in very heavily infested sites (Shetto & Kwiligwa, 1990). A downside with using herbicides is that by the time the weeds are visible, they are already firmly rooted, and the damage to the crop is already done. Hence, spraying herbicide above the ground may not be the most effective means for weed control (Integrated Striga Management in Africa, 2014). Herbicides can also damage the crops themselves (Kanampiu, et al., 2002), and traditional seed varieties in some contexts have been replaced by transgenically modified (GMO) varieties so that the crop can resist the effects of the herbicide. The best known example is the non-specific herbicide Roundup® and the subsequent ‘Roundup Ready’ seeds, in the US (Monsanto, 2014). In Africa, efforts are underway to test the effectiveness of conventionally bred seeds to the herbicide Imazapyr (African Agricultural Technology Foundation, 2014). Another problem with using chemicals to tackle weeds is that the weeds themselves have shown the ability to adapt to the herbicide. This means that new varieties of herbicide, and consequently, newer varieties of genetically modified seeds resistant to the modified herbicide, may be required to maintain yields. Furthermore, using GMOs remains highly controversial in Africa, and many countries have placed policy restrictions on their usage. Regardless, the combination of effective non-specific herbicides and modified seeds resistant to that herbicide (through transgenic modification or conventional breeding) is in its infancy in developing countries.

**Improved agronomic practices**
Practices such as crop rotation, intercropping, and biomass density management can reduce weed prevalence. However, most smallholder farmers in South Asia and sub-Saharan Africa alike, struggle to maintain farm yield of staple crops; as a result they practice monocropping, thereby increasing vulnerability of their crop to weeds and other biotic stresses. As discussed in the chapter on extension services, farmers in these regions receive very little training on improved agronomic practices.

In the absence of appropriate tools and agronomic training, the most common method employed by smallholder farmers to deal with weeds is to pull them out by hand. This is a very time consuming process. The typical farmer spends 40-55% of the total time spent farming on weeding manually. A single hectare

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1 GMOs are discussed in greater detail the chapter on Sustainable Agriculture.
Genetically modified seeds

The most commonly cited example of transgenic modification as a mechanism to deal with pests, is the insertion of a portion of the *Bacillus thuringiensis* (Bt) bacterium, which is naturally abundant in many insects and ecosystems, into seeds. Bt-enhancements to cotton have been deployed in India and China, but results have been mixed compared with results from similar products in industrialized markets. In China, for example, cultivation on Bt-enhanced cotton appears to have led to a resurgence of secondary pests (Wang, et al., 2008), leading to an erosion of the initial benefits from the enhanced seeds. In Kenya, trials of Bt-enhanced maize have shown mixed results on economic returns for the farmers (Gouse, et al., 2006).

In general, such genetic enhancements can get technically challenging as seeds need to be adapted to local conditions, and current evidence suggests that low-income farmers cannot afford the costs that stem from repeated seed enhancements. As a result, GMOs are facing considerable policy hurdles, with the majority of African countries placing significant controls or outright bans.

Improved agronomic practices

Practices such as crop rotation and intercropping increase biodiversity and can reduce pest density (Neuenschwander, et al., 2003). In particular, push-pull mechanisms, which ‘push’ pests away from crops

Animal pests are the second leading cause of crop losses, and the range of pests makes it difficult to develop specific solutions that do not have long-term negative consequences

Animal pests cause up to 15% of the yield losses for many crops across sub-Saharan Africa and South Asia, in ways that are more visible than the damage done by weeds. The major on-farm pests include insects (e.g., borers, mealybugs, mites), nematodes, and to some extent slugs and snails. Rodents, birds and mammals also cause damage, but these pests contribute to a larger portion of post-harvest damage rather than on-farm. Some of these pests are endemic to their geographies. In other parts, alien species have encroached local ecosystems. In some cases, populations of endemic pests appear to have increased due to reductions in ecosystem biodiversity from monocropping, deforestation and heavy pesticide use. There are a number of possible mechanisms for dealing with pests, each with different degrees of effectiveness and its own set of negative consequences (Oerke, 2006) (Williamson & Pretty, 2008) (Khan, et al., 2000).

Pesticides

Chemical pesticides can be effective against a broad range of pests. However, they can also have considerable negative health and environmental impact, especially if they are used inappropriately. According to a recent study by the UN Environment Programme, “Between 2005 and 2020, the accumulated cost of illness and injury linked to pesticides in small scale farming in sub-Saharan Africa could reach US$90 billion.” (UNEP, 2012) (Associated Press, 2012). Currently pesticides are too expensive for most smallholder farmers in Africa, although usage is increasing.

Genetically modified seeds

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Improved agronomic practices

Practices such as crop rotation and intercropping increase biodiversity and can reduce pest density (Neuenschwander, et al., 2003). In particular, push-pull mechanisms, which ‘push’ pests away from crops
through intercropping with plants that repel the insects and ‘pull’ them into less sensitive areas, have shown some promise (Adhiambo, 2011). Examples of successful ‘push-pull’ systems include demonstrations in Ethiopia of using cover crops (desmodium, in combination with vetiver and napier grass), to control borers and weeds attacking maize (ATA, 2014). However, in the absence of strong extension systems it has proven very difficult to get smallholder farmers to change agronomic practices.

**Biological control measures**
These measures include the introduction of predators, or even diseases targeting the pests. Such methods, however, require significant, dedicated R&D. Needless to mention, they also carry a very high risk of major unintended and sometimes unpredictable consequences.

**Crop yield losses caused by diseases are similar to those caused by pests, but few interventions have shown results yet**

Like pests, a broad range of pathogens—fungi, bacteria, viruses, and chromista—are responsible for about 15% of on-farm losses. Fungal infections, which contribute to the bulk of disease in major staple crops like maize, are transmitted when fungal spores spread via the air, water or soil. Viruses and bacteria are generally spread through vectors such as weeds and insects. Monocropping, which is practiced by the majority of smallholder farmers in Africa, increases susceptibility to these pathogens.

Due to the number and variety of potentially destructive pathogens in Africa, the absence of an R&D ecosystem to develop pathogen-specific solutions, and the sparse nature of the African smallholder farmer market, there have been few proven interventions (Oerke, 2006). Fungicides are expensive for smallholder farmers, and require usage training. Hence they are used—if at all—only for high value cash crops.

Seeds can be bred (conventionally, and through transgenic modification) to be tolerant to specific diseases. However, the sheer diversity of diseases across sub-Saharan Africa makes this approach unfeasible for more than a handful of highly prevalent diseases. Even then, the pathogens can evolve and become resistant, thereby requiring subsequent seed enhancements. Cassava is among the few staple crops that has demonstrated sustainable resistance to disease through (conventionally bred) improved seed varieties (Nweke, 2000).
KEY CHALLENGES

There are 5 main reasons why biotic stresses—which are dealt with easily in more industrialized economies—lead to such heavy losses for African smallholder farmers.

1. Integrated pest and weed control requires knowledge of sophisticated agronomic practices, which is beyond reach for most African smallholder farmers

Crop rotation, intercropping, push-pull mechanisms, and management of soil and biomass, all require a robust understanding of agronomy. Most African farmers practice monocropping, and have very limited understanding of the nuances of modern agronomy. Low rates of literacy, limited education, and the absence of an adequate system for agricultural extension services, all contribute to the continued lack of awareness of better agronomic practices. This greatly increases their vulnerability to both infestation and to large-scale loss.

2. Mechanized farming tools are not affordable

There are a large number of mechanized tillers available in industrialized countries, at prices that are quite affordable to middle class farmers (e.g., US$200-$500). In a single use, such machines allow farmers to till the soil, and effectively pull out and destroy weeds for the duration of the crop cycle. However, such mechanized tools are too expensive for the typical African smallholder farmer. The lack of a larger distribution and repair services landscape across the region makes it less attractive for international companies to invest in developing lower cost mechanized tools specifically for African markets.

3. General herbicides have not been available to smallholder farmers. Even if they were easily available, herbicides present secondary complications

Weeds are typically treated with general herbicides. While many of them have proven effective, they can also damage the crops they are intended to protect. In industrialized countries, farmers typically use enhanced (often transgenically modified) seed varieties. The lack of affordable herbicides, limited awareness of the value of herbicides, and the absence of a distribution infrastructure for appropriate herbicides, have all contributed to their limited use in sub-Saharan Africa. There are also very few national-level R&D ecosystems, public or private, for developing improved seed varieties which are resistant to general herbicides, and appropriate for local soils and other contextual factors. The absence of reliable local R&D ecosystems is particularly important, because seed varieties may need to be continuously improved in order to keep up with the evolving herbicide-resistance of the weeds. Where transgenic modification is the only option for continuous seed enhancement, the potential negative externalities associated with GMOs—and the policy restrictions—add further barriers.

4. Appropriate pesticides are either unavailable or unaffordable. Even where available, the risk of harm to health and the environment due to improper use is high

Pesticides tend to be available to farmers who live closer to urban areas. However, they have proven to be hazardous for both health and environment, especially when used inappropriately. In sub-Saharan Africa, virtually all available pesticides are imported and are not generally affordable to smallholder farmers living in remote areas. There has also been very limited R&D into pesticides using locally or regionally available raw materials and smaller scale production processes.
Dealing with native species of pathogens that adapt very well to local conditions often requires a range of localized products and interventions

Many pathogens tend to have 2 confounding characteristics: they come in a large number of locally-adapted strains, and they can develop resistance to chemical/biochemical interventions. That, combined with many of the factors mentioned above (the unattractiveness of the African smallholder market, limited local/national R&D capabilities, the capital-intensive nature of factories to manufacture chemical/biochemical products, and the difficulty of distributing the products to remote areas) has meant that African farmers do not have access to the necessary products—biological or synthetic—to deal with pathogens.
SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

A small number of important systemic interventions are required to make fundamental improvements in the ability of African smallholder farmers to combat biotic stresses. These include improving agricultural extension systems, and building an extensive, regularly updated registry of weeds, pathogens and animal pests in order to continuously collect local-level data on the evolving response of these biotic elements to changes in the ecosystem. Beyond these interventions, 4 technology breakthroughs are required.

A low cost (under $50) tilling machine

Weeds represent the single largest cause of on-farm losses for smallholder farmers in Africa. Currently, the only way smallholder farmers in South Asia and sub-Saharan Africa deal with weeds is to spend countless hours pulling them out by hand once they surface. By this point the damage has already been done to the crops that the farmers plant for the upcoming season. Mechanized tillers used by farmers in industrialized countries are far too expensive for smallholders, and typically need diesel. A partly or fully mechanized tiller that costs less than $50 (i.e., less than 10% of the annual income of farmers earning about $1.25 a day) can help African farmers remove weeds before sowing. Ideally, it will run on renewable energy.

The obvious technical challenge is to generate enough force to dig through dry—often hard—topsoil, with as little fuel input as possible. This problem is the same as others involving mechanization across a range of work genres: creating a higher mechanical advantage using limited power. Machines supplemented by human power (e.g., ‘pedal power’ machines using bicycle-type movement) have been used to power some devices, but the amount of power generated by such machines (typically 0.5 horsepower or less) tends to be significantly less than what is required for mechanized tilling (the smallest tillers tend to be 3-5 horsepower). In principle, the technical challenges involved in building a partially mechanized tiller can be overcome with some innovative engineering, without the need for much R&D. As such, there is reason to believe such an implement can be on the market within the next 3-5 years.

However, even once such an implement becomes available, it will face tremendous deployment barriers. Most importantly, farmers may not clearly see the value in changing their traditional practice of pulling out the weeds after they become visible. Beyond that, such an implement will face the usual challenges of market fragmentation, sparse distribution networks, and limited financing options for smallholder farmers. Deployment will likely be EXTREMELY CHALLENGING.
Breakthrough 1 – Difficulty of deployment

Herbicides or other affordable mechanisms to control weeds, ideally ones that are more environmentally friendly than herbicides currently on the market

Herbicides are the most widely used method of dealing with weeds in industrialized markets. However, most of them are non-specific, in that they can damage the crops, in addition to the weeds. As such, for optimum results they need to be accompanied by (conventionally or transgenically) enhanced seeds. In addition, the ability of the weeds to develop resistance to herbicides means that the enhanced seeds will need to be periodically modified to keep up with modifications in the herbicide, to maintain crop yield. Given the limited R&D capacity in Africa and South Asia to continuously generate improved seeds, and the capital-intensive nature of herbicide production, it is not surprising that few customized solutions have been developed or scaled-up.

Herbicides that specifically attack the most destructive weeds, but are harmless to the crops, can be very beneficial. It will be easier to build a large number of smaller factories if such herbicides are made with non-synthetic (ideally from natural local sources) ingredients that do not require a capital-intensive production facility, thereby easing a major barrier to supply and distribution. Synthesizing such an herbicide will require significant R&D, and will likely take 10 years (or more) to be market ready.

Once such an herbicide becomes available, it will have to overcome limited demand, need for farmer financing, a highly fragmented market, and a very sparse distribution network. The difficulty of deployment will be EXTREMELY CHALLENGING.
Novel, low cost, environmentally friendly pesticide(s), specifically targeting the most destructive insects

Borers and other insects constitute the 2nd most significant biotic cause of on-farm losses. Due to weak agricultural extension services, especially across Africa, it has proven extremely difficult to train smallholder farmers in optimal agronomic practices for integrated pest control. A few farmers have access to general pesticides, but these tend to be harmful to the health of the farmers, as well as for the environment. Transgenic modifications to make crops repel pests (e.g., through the *Bacillus thuringiensis* bacterium, or Bt) have many complicated externalities. Introducing them into any environment without the necessary infrastructure to study and manage these externalities can be a very risky proposition.

As in the case with weed control, a new type of pesticide, specific to the most destructive pests and ideally made from locally (or regionally) available non-synthetic ingredients, can help catalyze the development of a large number of less capital-intensive production facilities closer to the market. Also, as in the case with the novel herbicide recommended earlier, such a pesticide will require significant R&D; a major undertaking that may take more than 10 years before it becomes a reality. It will also face many of the same challenges as a novel herbicide: low demand, need for financing, market fragmentation, and the absence of reliable distribution networks. We expect that the difficulty of deployment will similarly be EXTREMELY CHALLENGING.
Breakthrough 3 – Difficulty of deployment

Spatial repellent for on-farm pests

As described above, insects and other pests constitute a major cause of on-farm losses. The limited knowledge among smallholder farmers about sophisticated agronomic techniques, combined limited access to pesticides, has meant that the farmers have few tools to combat pests. There are many technical challenges involved in developing novel pesticides from ingredients that are locally available.

In this context, it may be possible to build spatial repellents (e.g., ones which emit particular sound frequencies), which irritate the pests and keep them away from the crops. The obvious technical challenge is that there is limited scientific understanding of the sensory sensitivities of the many species of pests. Considerable research is required to understand these sensitivities over the lifecycle of the pests, including variations between different sub-species. Such an undertaking may take 8-10 years before it becomes a reality. It will also face many of the same challenges as a novel pesticide discussed above: low demand, need for financing, market fragmentation, and the absence of reliable distribution networks. We expect that the difficulty of deployment will similarly be EXTREMELY CHALLENGING.
Breakthrough 4 – Difficulty of deployment

<table>
<thead>
<tr>
<th>Difficulty</th>
<th>Policies</th>
<th>Infrastructure</th>
<th>Human capital</th>
<th>Access to user finance</th>
<th>Behavior change</th>
<th>Existing demand</th>
<th>Market fragmentation/Distribution channels</th>
<th>Business model innovation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extremely Challenging</td>
<td>Simple</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Low demand</td>
<td>No identified deployment model, major hurdles identified</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Challenging</td>
<td>Feasible</td>
<td>Complex</td>
<td>Behavior</td>
<td>High demand</td>
<td>Highly fragmented, challenging to reach customers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complex</td>
<td>Moderate</td>
<td>Feasible</td>
<td>Existing</td>
<td>Regulated market with supportive policies</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simple</td>
<td>Complex</td>
<td>Moderate</td>
<td>Markets</td>
<td>Dependent on existing infrastructure</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Policies**: Regulated market with supportive policies
- **Infrastructure**: Dependent on existing infrastructure
- **Human capital**: Moderate need to train a limited number of people
- **Access to user finance**: Moderate financing needed, viable mechanisms identified
- **Behavior change**: Moderate behavior change required with evidence of behavior change being viable
- **Existing demand**: Low demand, needs to be built
- **Market fragmentation/Distribution channels**: High demand, needs to be built
- **Business model innovation**: No identified deployment model, major hurdles identified
A substantial portion of produce in sub-Saharan Africa and South Asia—20% of cereals, over 50% of fruits and vegetables, and over 25% of meat—is wasted before it can be consumed. Considering the already low levels of productivity among smallholder farmers due to the factors discussed in other chapters (e.g., lack of irrigation, fertilizers and nutritious fodder for livestock), this waste poses a significant additional economic burden on farmers, exacerbating the food insecurity they face. It is also a major contributor to the dearth of nutrient-rich food year-round for farmers and their families. A number of reasons are behind these losses. To begin with, the lack of access to markets forces farmers to store their cereal for many months, in structures that offer inadequate protection from moisture and pests. This problem is compounded by the lack of access to adequate transport, and limited local capacity to process the food. The absence of materials to appropriately package fruits and vegetables significantly reduces their shelf life. Finally, the lack of refrigeration makes it very difficult to preserve perishables like meat, dairy, fruits and vegetables. Three technology breakthrough can address these problems.

- Easy-to-install, low cost structures for long-term grain storage
- Affordable (under $50) off-grid refrigeration for smallholder farmers and small agribusinesses
- Low cost (under $5,000) refrigerated vehicles, sturdy enough for unpaved roads in rural areas
One-third of the food produced around the world for human consumption—totaling 1.3 billion tons—is lost or wasted. In industrialized countries most of the food wastage occurs after it reaches the consumer, and is therefore not a burden on the farmer. In sub-Saharan Africa and South Asia, on the other hand, the bulk of the losses occur on the farm and during storage. This deprives smallholder farmers and small agribusiness of much needed income, and exacerbates food insecurity (FAO, 2011).

**CORE FACTS AND ANALYSIS**

Food losses and waste occurs everywhere, although the types of losses vary substantially between different parts of the world. As Exhibit 1 shows, North America, Oceania and Europe have the most per capita food losses, while South Asia\(^1\) and sub-Saharan Africa suffer the least. However, a much larger share of losses in sub-Saharan Africa and South Asia occur before the food reaches the consumer, and are therefore borne by the farmers. Combined with the comparatively lower production yields in both regions, these losses place a significant economic burden on smallholder farmers.

**Per capita food losses and waste across the world**

<table>
<thead>
<tr>
<th>Region</th>
<th>Consumer</th>
<th>Production to retailing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe</td>
<td>300</td>
<td>150</td>
</tr>
<tr>
<td>North America &amp; Oceania</td>
<td>250</td>
<td>200</td>
</tr>
<tr>
<td>Industrialized Asia</td>
<td>200</td>
<td>150</td>
</tr>
<tr>
<td>sub-Saharan Africa</td>
<td>150</td>
<td>100</td>
</tr>
<tr>
<td>North Africa, West &amp; Central Asia</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>South &amp; Southeast Asia</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>Latin America</td>
<td>350</td>
<td>250</td>
</tr>
</tbody>
</table>

*Exhibit 1:* While food is wasted or lost in every part of the world, most of the losses in sub-Saharan Africa and South Asia occur before it reaches the consumer (FAO, 2011).

\(^1\) Note that this exhibit from FAO combines data from South Asia and Southeast Asia.
While there are substantial losses of all types of food in sub-Saharan Africa and South Asia, perishable foods suffer much greater losses

Exhibit 2 shows the losses across regions and across stages of the farm-to-consumer chain, for cereals, fruits & vegetables, and meat. For all food types, a substantial portion of food loss in sub-Saharan Africa and South/Southeast Asia occurs well before it reaches the consumer. This is true of cereals, fruits and vegetables, and meat. The exhibit also shows that compared with cereals, perishables see higher losses between being harvested and distribution, because storing and preserving fruits, vegetables and meat requires more effort and resources. Cereal losses occur due to moisture, temperature, pests, improper storage, and incorrect handling, while the perishables are lost due to inadequate packaging and lack of access to refrigeration (FAO, 2011) (Gockel, et al., 2009). In addition to the economic loss, the wastage of such large quantities of fruits, vegetables and meat also deprives households and communities of much-needed nutrients.
Food losses and waste: cereals, fruits & vegetables and meat

Exhibit 2: Across all types of commodities, smallholder farmers in sub-Saharan Africa and South Asia lose a substantial portion of their produce before it reaches the consumer, or can be consumed by the farmers’ families. Losses for perishables (fruits, vegetables, meat) are higher than for cereals (FAO, 2011).
The specific causes of losses vary by type of commodity

The losses occur at various stages of the value chain, and vary by type of commodity. Most of the losses for staple crops occur on the farm and post-harvest; cash crop losses occur on-farm, post-harvest and during processing, and the majority of horticulture losses occur during processing (FAO, 2011). While the underlying drivers of these losses vary somewhat by type of crop, the absence of appropriate and affordable means for handling, storage and transport are the predominant factors.

Cereals

Smallholder farmers who grow staple crops typically do not have access to farm machinery like threshing machines during or after harvest. As a result, 5-10% of the output is lost during harvest and preparation. Another 10-15% of their produce is lost during on-farm storage (Gockel, et al., 2009). Farmers typically store the produce at (or near) their farms, in structures that are highly vulnerable to pests such as rodents, weevils, large grain borers, moisture and excessive heat. Further losses occur when farmers try to access markets or processing facilities that are often far away and require transport. The specific problems affecting staple crops are outlined below.

Drying

Inadequately dried produce results in diseases such as aflatoxicosis, mold and rot. Many climates, like that in much of West and Central Africa, are not appropriate for effectively sun-drying crops. Most smallholder farmers do not have drying facilities, and end up moving their produce to storage (which, as described below, is virtually always sub-standard) before it has dried adequately. Low-cost solar dryers are beginning to be used in some countries, but have not yet achieved broad market penetration.

Packing/bagging

Grains must either be sealed (vacuum or hermetic) or packed with adequate ventilation. However, this is not common in Africa.

- 40-60% of smallholder farmers store grains for many months at home in bags made of plastic, jute or other fiber. Over-packing in such non-sealed bags can trap moisture and cause mold. Inadequate sealing allows additional moisture and pests into the bags. As a result, 30-45% of grain stored in such bags can be lost.

- 20-30% of smallholder farmers use metallic drums or clay pots to store grain at home. If stored in such containers without proper drying, the grain can rot due to moisture. Exposure of such containers to direct sunlight can accelerate grain deterioration. Between 20% and 30% of grain stored in such containers can be lost (FAO, 2011) (Gockel, et al., 2009).

- 5-15% of farmers use mud or brick silos, which offer adequate storage, but are too expensive for most smallholder farmers. Inadequate training in construction and maintenance can lead to losses of 5-10% (FAO, 2011) (FAO, 1986) (Natural Resources Institute, 2004).

- Fewer than 5% of smallholder farmers have access to reliable metal silos for storage. Even those who do, face the risk of theft (FAO, 2008).

Cash crops

Smallholder farmers tend to grow cash crops (e.g., coffee, cocoa) only when they have reasonable access to markets, typically through a dealer or processor, as part of a value chain. There is a major
Cash crops have very specific requirements in the harvest and preparation stages that are necessary for preservation and ensuring market-level quality of the output. Rough handling during harvest can cause damage (e.g., cotton stripping). Picking or harvesting when the produce is too immature, over-ripe, or not uniformly ripe, leads to quality that is too low for buyers. (For example, coffee becomes too bitter if too many green cherries get mixed in). Post-harvest, when the produce takes too long to prepare (e.g., because the farmer does not have the right tools, such as coffee pulpers), it deteriorates in quality and causes additional wastage. When specific moisture-control conditions are not maintained during a crop’s drying period, the produce can be susceptible to mold. Failure to adhere to crop-specific agronomic best practices results in up to 20% losses for many cash crops (FAO, 2001) (International Cocoa Organization, 2012).

Crop-specific agronomy
Cash crops have very specific requirements in the harvest and preparation stages that are necessary for preservation and ensuring market-level quality of the output. Rough handling during harvest can cause damage (e.g., cotton stripping). Picking or harvesting when the produce is too immature, over-ripe, or not uniformly ripe, leads to quality that is too low for buyers. (For example, coffee becomes too bitter if too many green cherries get mixed in). Post-harvest, when the produce takes too long to prepare (e.g., because the farmer does have the right tools, such as coffee pulpers), it deteriorates in quality and causes additional wastage. When specific moisture-control conditions are not maintained during a crop’s drying period, the produce can be susceptible to mold. Failure to adhere to crop-specific agronomic best practices results in up to 20% losses for many cash crops (FAO, 2001) (International Cocoa Organization, 2012).

Transport
Cash crop farmers generally have target markets they need to access for their produce. However, limited availability of transport can lead to extended holding times, which leads to deterioration of quality. Across the various types of cash crops, up to 10% of market ready produce is lost due to transportation delays (Hopper, 2013).

Processing
Most cash crops grown in Africa are processed elsewhere, because there is very little food processing capacity across the continent. Food processing equipment is capital-intensive and unaffordable to most African agribusinesses, and financing is not easily available. Consequently, African farmers capture a small fraction of the potential economic value of their produce.

Fruits and vegetables
Horticulture products (e.g., fruits, vegetables, flowers) require very careful handling, packaging and often refrigeration in order to extend their life and maximize market value. Due to the lack of strong value chains and access to markets, few smallholder farmers who grow horticulture commodities sell their products—which are usually damaged to some extent during and after harvest—in local markets, and that too for very low prices, or consume them at home. The specific problems affecting horticulture crops are outlined below.

Handling, sorting and disinfecting
Rough handling causes bruising and disease. Produce is often harvested too early (when it is not ripe), or too late (when it is overripe). Not eliminating decaying produce before storing it along with the rest
of the produce causes fungi and bacteria to spread. Inadequate washing (e.g., without soap or warm water) and poor short-term storage lead to infestation by insects and pathogens. Up to 30% of produce is lost due to such reasons (Kitinoja & Kader, 2003).

Refrigeration
Most fruits and vegetables are temperature-sensitive. Absence of reliable, affordable refrigeration for storage and transport, causes 10-30% of produce to be lost (Kitinoja & Kader, 2003).

Transport and processing
There is very limited food processing in Africa due to weak market linkages, high capital requirements and seasonal supply, which peaks immediately after harvest. As a result, farmers do not have the option of selling their produce in a functioning value chain.

Meat and dairy
Livestock food products are highly temperature sensitive, and need to be consumed, processed, or refrigerated very soon after production. With milk, for instance, most of the losses occur during post-harvest, processing and distribution stages (Exhibit 3), because rural smallholder farmers have little to no access to refrigeration, and find it difficult to reach markets within the short shelf life of the product. The lack of access to affordable, off-grid refrigeration is especially challenging for livestock farmers, since products deteriorate rapidly in warm temperatures (Exhibit 4). Fresh milk can last up to a day in 15°C, but needs to be kept at 10°C to last 2 days and at 5°C to last 3 days. Fish needs to be at 10°C to last 3 days, while meat and butter can last longer in sub 20°C temperatures (Practical Action, 2012). However, daily temperatures routinely get over 20°C in many tropical countries. In Kenya for example, the average daily temperature over the course of the year, across a nationwide cross-section of locations, is nearly 25°C. In many other countries, the average temperature is higher. Only 14% of the rural population in sub-Saharan Africa have access to electricity (International Energy Agency, 2013), and only 3-4% of milk processors in countries like Ghana and Tanzania have access to refrigeration (ILRI, 2009). Even in Kenya, Africa’s largest milk producer, only 10-15% of all marketed milk is packaged or processed; most of it is consumed unpasteurized (Meridian Institute, 2012). Similarly, over 90% of milk in Tanzania and Ghana, and 80% in India, is unpasteurized (ILRI, 2009) (ILRI, 2011). This is equally true of all other livestock food products. Because of their distance from markets and limited access to transportation, only a small fraction of cattle herders are able to take their milk to a sale-point. In Ghana, for example, virtually 100% of milk producers and over 70% of market intermediaries transport their milk by foot. As a result, almost 90% of milk producers sell their product at their farms or homes itself (ILRI, 2009). The only producers who have access to markets are those living near urban areas (World Bank, 2008).
Waste in various stages of the livestock product value

Exhibit 3: The most significant losses in beef (and other meat products) occur in the production phase due to animal death from diseases or other causes. For milk, on the other hand, greater losses occur post-production, due to the absence of processing and storage infrastructure en route to the market.

Temperature sensitivity of various livestock products

Exhibit 4: Livestock products such as milk, fish, meat and butter, are highly temperature-sensitive. They need to be stored well below the average temperatures common to most tropical countries (Practical Action, 2012). Only 14% of the rural population in Africa has access to electricity, and only 3-4% of milk processors have access to refrigeration. Not surprisingly, there are few options for livestock farmers to get their produce to market. Note: Y axis scale is not linear.
KEY CHALLENGES

There are 7 major gaps in post-harvest handling and storage, which lead to large losses in food and economic opportunity for smallholder African farmers. These have been discussed above in detail. The following is a summary of the main issues.

1. Limited access to markets
   When farmers do not have access to markets for their produce, they are forced to either store the produce on (or near) their farms, or sell it to intermediaries at below-market prices. Fewer than 30% of smallholder farmers in countries like Kenya, Ethiopia and Zambia sell higher value non-grain produce (Jayne, et al., 2005).

2. Poor grain storage facilities
   Grain storage facilities need adequate temperature control and must be protected from moisture and pests. Nearly 70% of grain grown by African smallholder farmers is stored on-farm, in structures they construct themselves, from found material (Gockel, et al., 2009). Such structures provide inadequate protection against the elements and pests.

3. Lack of access to packaging materials for medium-term storage
   In addition to larger storage structures, there are also no robust, affordable bags or smaller containers which African farmers can use to safely store their produce on or near their farms (Gockel, et al., 2009).

4. Lack of access to refrigeration
   The optimum storage temperature for most temperate horticultural crops is close to 0°C (FAO, 1983). Such temperature sensitive commodities—fruits, vegetables, flowers—deteriorate rapidly without refrigeration. There is no viable cold chain in the African agricultural ecosystem, near the farm, for transport, or in much of the marketplace. Refrigerators, both standalone and for transport, are far too expensive for smallholder farmers. Moreover, farmers have very limited access to electricity, and owning a refrigerator then means the added cost of a diesel generator and fuel.

5. Limited local processing capabilities
   Virtually all cash crops, as well as a sizable portion of grains—need to be processed so that they can be sold to the market in a form that is usable or consumable. There are currently very few commodities that can be processed fully in-country. The farther the processing sites, the greater the likelihood of damage due to inadequate storage during shipping (Gockel, et al., 2009). The lack of transportation infrastructure, primarily usable roads and access to trucks, exacerbates the situation.

6. Poor transportation infrastructure, and limited access to transport
   Only 16% of the roads in Africa are paved (Exhibit 5), and there are only 6.7 automobiles (cars, buses or trucks) for every 1 km of road. Smallholder farmers are often unable to transport their produce to markets not in the immediate vicinity of their farms, unless they have access to a dealer, which happens only for high value cash crops.
Inadequate understanding of appropriate agronomic practices

In a demanding marketplace, buyers have much more negotiating power than smallholder farmers, and small differences in handling can lead to major differences in the quality of produce. In such a scenario, the lack of adequate extension support and a clear understanding of subtle differences between various agronomic practices leads to considerable losses for the farmers.

Transportation infrastructure in different parts of the world

Exhibit 5: Smallholder farmers in Africa do not have any realistic means of transporting their produce to markets far from where they live. Only 16% of the roads are paved, and there is a serious dearth of automobiles for transport.
SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

In the absence of national-level systemic interventions like promoting agribusinesses and increasing local processing capacity, improving market access, and improving transport infrastructure, training aimed at farmers themselves can help reduce agricultural losses to some extent. Such training can help change the core handling and storage practices farmers use—especially for market-facing cash and horticulture crops, delivered by others in the value chain. Keeping in mind the unique challenges African (and, to a somewhat smaller extent, South Asian) smallholder farmers face, it is promising to see programs like the World Food Programme’s Purchase for Progress (P4P) that aims to increase local procurement of aid food (WFP, 2013), and the emergence of technologies like low cost, ventilated solar dryers making their way into different markets. Notwithstanding these developments, we believe 3 technological breakthroughs can make a meaningful impact on food losses in Africa.

**Easy-to-install, low cost structures for long-term grain storage**

Most smallholder farmers in sub-Saharan Africa are subsistence farmers and primarily grow cereal crops. They have to store their produce for several months on (or near) their farm, because a large portion of it is for their own consumption. Currently, most storage structures used by such farmers are made from mud, twigs, straw and other easily and locally available raw materials, and are highly vulnerable to the elements and pests. As fragile as such structures are, they do not cost the farmers much in cash terms. On the other hand, a reasonably durable structure (e.g., with a concrete foundation, sturdy beams, and walls and roof resistant to rain and pests) could cost several thousand dollars, which is decidedly unaffordable to the farmers. A structure made with a new type of material, which is lightweight (so it can be easily transported to remote areas that may not be connected by paved roads), easy to assemble (so it does not require the technical skill necessary to build traditional brick-and-mortar structures), durable (does not need extensive or regular maintenance), and with some form of ventilation (to prevent accumulation of internal moisture), can address this problem. The value of such structures can be augmented by durable, low cost material for constructing medium-term storage containers (boxes or bags), which offer similar levels of protection.

Durable, lightweight materials (e.g., structured insulated panels, flexible PVC) as well as promising materials for short and medium-term storage exist, but have not penetrated the African market yet. These products are currently too expensive and/or untested for use at a large scale. With a lack of developed markets and scarce economic incentives to invest in R&D, it is unlikely that there is enough private investment going into adapting existing materials for use by smallholder farmers. We believe a solution is 3-5 years away from being market-ready for the African smallholder farmer.

Once such a product becomes available, it will face a number of major deployment challenges: the extent of market fragmentation; the likely lack of initial demand; the need for financing; and the absence of established distribution channels. Based on the above factors, the difficulty of deployment is EXTREMELY CHALLENGING.
Breakthrough 1 – Difficulty of deployment

Affordable (under $50) off-grid refrigeration for smallholder farmers and small agribusinesses

Horticulture products like fruits and vegetables are highly sensitive to temperature, and the lack of refrigeration dramatically reduces their shelf life, especially in tropical climates. While there are some inexpensive refrigerators available in emerging markets like India and China, they still cost more than $100, need reliable electricity and are difficult to repair once damaged.

Of late, there appears to be a resurgence of very affordable age-old traditional cooling technologies (e.g., clay pots). While this showcases the potential demand for an affordable and durable solution, traditional options like clay are subject to biological contamination, and difficult to clean. Moreover, as agricultural systems advance, there will be greater need for commodity-specific temperature control, and it is difficult to see traditional cooling solutions leading to modern, profitable agricultural value chains.

To serve the needs of rural, low income farmers, refrigerators need to be operable off-grid (e.g., solar-powered), considerably less expensive than the current $100 range, and easy to repair. Such technologies appear to be on the horizon. A new generation of refrigerators using thermoelectrics are beginning to reach the market. Given the broad demand for refrigeration there is reason to believe that an affordable product will gradually reach a critical mass of smallholder farmers—notwithstanding the usual problems of market fragmentation and distribution.

Based on the above, it is likely only a matter of 3-4 years before low cost refrigerators become practical for rural farmers. Despite the need and expected demand, such a technology will face considerable barriers to deployment due to the fragmented nature of the market, the absence of a value chain for distribution and maintenance, and the need for financing for farmers. Hence, deployment will be CHALLENGING.
Low cost (under $5,000) refrigerated vehicles, sturdy enough for unpaved roads in rural areas.

The ability to transport food to markets while preserving freshness will not only reduce post-harvest losses, but also create new value propositions for smallholder farmers. The absence of such refrigerated vehicles is one of the factors limiting access to market for higher-value produce (e.g., horticulture; and as the section on livestock discusses, meat and dairy). The lack of refrigeration also reduces everyday access to a diverse base of nutrients for children and the population in general.

Refrigerated trucks available on the market today are extremely expensive (costing tens of thousands of dollars), require diesel, and are built for smooth roads. To be useful to dealers and agribusiness entrepreneurs who serve smallholder farmers in remote areas, refrigerated transport vehicles will have to be robust and cost significantly less (under $5,000, rather than tens of thousands of dollars). While advances in stationary refrigeration technologies can also help advance transport refrigeration, there are a number of significant differences. First, stationary refrigerators normally operate indoors, whereas transport refrigerators will have to operate outdoors, under much warmer ambient temperatures and harsher conditions. Second, while a major challenge for stationary refrigeration is the absence of reliable electricity, transport refrigerators can use the fuel used to power the vehicles. Third, refrigerated vehicles will become affordable only after general-purpose vehicles become affordable. Based on the above analysis, the projected time to market for such technologies is 5-7 years.

Even when such a technology is developed, deployment will be difficult. The market is extremely fragmented, and adoption will depend on the growth of the broader market for the relevant agricultural commodities. In addition, poor road infrastructure and the sparse presence of fueling stations will be a major hurdle in the usability of refrigerated transport. Finally, a maintenance and repair infrastructure (currently absent) will be necessary to keep these refrigerated vehicles functioning. We estimate that deployment will be EXTREMELY CHALLENGING.
Breakthrough 3 – Difficulty of deployment

- **Extremely Challenging**
  - Policies: Low role of policy / regulation
  - Infrastructure: Requires high level of training for large numbers of people
  - Human capital: Requires moderate improvements to infrastructure
  - Access to user finance: Significant financing required, no identified mechanism
  - Behavior change: Major behavior change required, potentially on daily basis
  - Existing demand: Extremely low demand or not a perceived need
  - Market fragmentation/Distribution channels: No identified deployment model, major hurdles identified
  - Business model innovation: Highly fragmented, challenging to reach customers

- **Challenging**

- **Complex**

- **Feasible**

- **Simple**
The training and technical support provided to farmers by professional agents, collectively known as extension services, are very important for improving food security. Significant improvements in yields and quality can be achieved through better management of inputs like fertilizers, maintaining soil health, and using appropriate harvest and post-harvest techniques and processes. Changing traditional agronomic practices is extremely difficult, particularly when the ‘new’ recommendations seem counterintuitive to farmers, or require more effort and investment. Bringing about such a change needs ongoing training, support, and follow-up from knowledgeable and committed extension agents. Government-provided extension services are usually the only form of training available to smallholder farmers in sub-Saharan Africa. In many countries across the region, the quality, relevance and accountability of extension systems are questionable, and the meager government budgets allocated for providing these services do not offer much scope for improvement.

In recent years, ICT innovations have helped improve content quality, reach, and efficiency of extension work. While the current state of ICT devices (smartphones, tablets) allows the creation and dissemination of valuable information, there is still a dearth of appropriate and engaging content. Moreover, training alone is not sufficient for farmers. Extension services need to include value-added interventions for saving crops and livestock from disease, and for improving quality (and hence income potential) of high-value commodities such as cash crops. One technological breakthrough, which is an amalgam of a number of smaller advances, can enable such services.

- An affordable and portable toolkit for extension workers, which includes a core set of devices for testing crop health, livestock health, and quality of outputs
Extension services refer to training of farmers on a range of issues: agronomic practices (e.g., general crop management, appropriate use of fertilizer and other inputs, pest control), mechanisms to access financial support, natural resource management, livestock health and management, and access to markets or intermediaries. Given the low level of technical knowledge among African smallholder farmers,\(^1\) revamping extension services constitutes a major opportunity for improving agricultural yields and incomes in the region.

**CORE FACTS AND ANALYSIS**

Extension services can be characterized along 3 dimensions: provider type, content type, and channel. In principle, extension services are delivered by a broad range of providers across the public-private spectrum (Exhibit 1). Some are free services provided by government agencies, NGOs, or value-chain partners (e.g., food companies, processors, or intermediaries). Some services are fee-based, provided by private individuals or organizations, representatives of farmer organizations, or others. The topics cover the full range of issues relevant to crop and livestock farmers: crop management, usage of inputs like water and fertilizer, pest management, understanding of market prices and dynamics, information about weather patterns and changes, treatment and management of livestock, negotiating with value chain partners, etc. These services can be provided in-person (individually, to a group, or to representatives of farmer organizations who can then serve as trainers to others), or through ICT tools and devices using video recordings or interactive platforms like call-in radio programs and phone services, phone messages, etc. In short, there is no single modality for delivering extension services.

About 80% of extension services in sub-Saharan Africa are provided by local government agencies, with most of the remaining split between international and local NGOs. Private sector actors (e.g., value chain partners, or fee-for-service providers) account for less than 5% of the total volume of services. Funding for these services, on the other hand, comes from a broad range of sources including country governments, multilateral and bilateral donor institutions, and private foundations. Most of these services are free, with farmers paying for a very small portion of the services. Exhibit 2 shows this data, estimated from aggregation across various sources (Interview, 2013).

---

\(^1\) As with other aspects of agricultural development, there has been considerable work in recent decades to strengthen extension systems in South Asia (Swanson B., 2006) (Swanson B., 2008). As such, this discussion focuses on sub-Saharan Africa.
Types of extension services and models

<table>
<thead>
<tr>
<th>Provider type</th>
<th>Content type</th>
<th>Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Government</td>
<td>Inputs usage</td>
<td>In-person, verbal</td>
</tr>
<tr>
<td>NGO (with fee-for-service)</td>
<td>Plant management</td>
<td>In-person, demonstration</td>
</tr>
<tr>
<td>NGO (free service)</td>
<td>Livestock rearing</td>
<td>Train-the-trainer</td>
</tr>
<tr>
<td>Private value chain partner</td>
<td>Post-harvest processing</td>
<td>Peer-to-peer sharing</td>
</tr>
<tr>
<td>Private fee-for-service</td>
<td>Market information</td>
<td>Two-way ICT (Internet or mobile)</td>
</tr>
<tr>
<td>Farmer organization</td>
<td>Weather information</td>
<td>One-way ICT (radio, video)</td>
</tr>
<tr>
<td>Community member</td>
<td>Farming business training</td>
<td>Written/print</td>
</tr>
<tr>
<td>Universities or research institutions</td>
<td>Natural resource management</td>
<td></td>
</tr>
</tbody>
</table>

Exhibit 1: Extension services cover a broad range of topics including usage of inputs like water and fertilizer, plant management, livestock rearing and treatment, business best practices, understanding of the market, etc. This content can be delivered by a range of providers (e.g., government, private for-profit, private non-profit), through a range of channels.

Sources of funding and management of extension services in sub-Saharan Africa

Total: $600 million

<table>
<thead>
<tr>
<th>Sources</th>
<th>Operators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farmer pays</td>
<td>Private sector</td>
</tr>
<tr>
<td>African governments</td>
<td>200</td>
</tr>
<tr>
<td>Private sector</td>
<td>25</td>
</tr>
<tr>
<td>Local NGOs</td>
<td>100-115</td>
</tr>
<tr>
<td>International NGOs</td>
<td>90-100</td>
</tr>
<tr>
<td>Bilateral donors</td>
<td>100-100</td>
</tr>
<tr>
<td>Multilateral donors</td>
<td>100-115</td>
</tr>
</tbody>
</table>

Exhibit 2: About 80% of the extension services for farmers in Africa are provided by their governments, with most the remainder of the services provided by NGOs. Private providers account for a very small portion of the services. About one-third of the funds for these services come from the local governments. Multilateral, bilateral and private philanthropic donors account for the bulk of funds.
There are many case examples of the value of extension services in improving agronomy and thereby, agricultural output

Perhaps the most important focus of extension services is the improvement of agronomic practices. It is very difficult to conclusively determine the contribution of improved agronomy—in exclusion of other factors—on improvements in yield and quality of produce. There are, however, some prominent examples. In Ethiopia, farmers of teff (the national grain) have traditionally broadcast their seeds (i.e., manually scattered) to sow them. Conventional belief was that more seed would result in more teff. Five years ago, researchers in Ethiopia showed that teff seeds that were planted in rows (rather than being scattered all over the field) showed a 50-80% yield improvement with 90% reduction in the amount of seeds needed for sowing (which represent a significant cost for the farmer). The teff also had stronger stalks and bigger leaves (Ethiopia ATA, 2012) (IFPRI, 2013). There other many other similar examples of the value of extension services (Swanson, 2006) (Swanson, 2008).

Despite the evident need and opportunity, African farmers receive little in the way of quality extension services

The predominant form of extension service delivery is in-person verbal advice, also known as travel-and-visitation or T&V (Swanson, 2008). Naturally, this is a labor-intensive process and heavily dependent on the ability of the extension workers to spend adequate time with farmers. However, as Exhibit 3 shows, low government budgets (about $13 per farm per year) mean that a very small force of extension agents has to cover a large number of farmers, with an average annual coverage capacity of 0.9 days per agent per farm, including travel to and from the farms. Hence, barely 30% of the farmers get any extension service support (Interview, 2013). Crucially, extension workers have little in the way of on-farm tools to help farmers diagnose or address questions specific to their farms in real-time. They do not have access to devices that can quickly test soil quality to recommend appropriate fertilizer use, or to diagnose livestock or crops for particular diseases.
Coverage of extension services across Africa

<table>
<thead>
<tr>
<th>Country</th>
<th>Percent of Farmers Reached by Extension Workers</th>
<th>Public Extension Budget, per Farm (US$)</th>
<th>Number of Agent Days Available per Farm, Including Time Required for Traveling etc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Malawi</td>
<td>14%</td>
<td>16</td>
<td>0.9</td>
</tr>
<tr>
<td>Mali</td>
<td>15%</td>
<td>9</td>
<td>0.4</td>
</tr>
<tr>
<td>Mozambique</td>
<td>19%</td>
<td>8</td>
<td>0.4</td>
</tr>
<tr>
<td>Ghana</td>
<td>27%</td>
<td>34</td>
<td>0.9</td>
</tr>
<tr>
<td>Uganda</td>
<td>29%</td>
<td>26</td>
<td>0.5</td>
</tr>
<tr>
<td>Tanzania</td>
<td>35%</td>
<td>6</td>
<td>0.4</td>
</tr>
<tr>
<td>Ethiopia</td>
<td>37%</td>
<td>8</td>
<td>2.3</td>
</tr>
<tr>
<td>Kenya</td>
<td>41%</td>
<td>10</td>
<td>2.3</td>
</tr>
<tr>
<td>Nigeria</td>
<td>60%</td>
<td>Avg $13.3</td>
<td>Avg 0.9</td>
</tr>
<tr>
<td>Avg 31%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Exhibit 3: A very small percentage of African farmers—barely 30% across a sample of countries—are reached by extension workers. With an annual extension budget of $13 per farm, and average availability of less than 1 day per extension agent per farm, few farmers receive any quality advice. This is particularly true since the predominant mode of extension is travel-and-visitation.

Extension services are not geared towards women farmers, even though women perform a substantial portion of the agricultural work

While precise country-by-country statistics are not available, there is strong evidence to suggest that women are responsible for a significant portion of agricultural work, which constitutes the single largest type of economic activity undertaken by women (Interview, 2013) (World Bank, 2012) (World Bank, 2014). In countries like Ghana, available data suggests that women perform a greater share of the work, across a broad range of on-farm and post-harvest functions (Exhibit 4). Still, only a small fraction (10-15%) of extension workers are women. The traditional gender dynamics of agricultural extension in Africa lead to a gross exclusion of women (Due, et al., 1997). Male extension agents interact very little with women, and male farmers do not typically share their learnings with their wives or other women in the family. As a result, the volume and quality of extension support that women farmers get is significantly worse than that received by their male counterparts (which is itself very weak).
Gender disparity in extension services

Exhibit 4: Even though a substantial portion—in many countries, more than half—of agricultural work is done by women, extension agents are primarily men. As a result, the quality of extension support received by women does not address the needs and constraints of women farmers.
KEY CHALLENGES

Based on the above discussion, there are 2 main reasons why smallholder farmers in Africa do not receive adequate extension support.

1. **The predominant mode of providing extension services in Africa is travel-and-visitation, which is labor-intensive and largely ineffective**

   Most extension agents conduct their work in-person, either on an individual farm, or at group events organized by farmer organizations. Given the low government budgets, there simply aren’t enough agents to cover a critical mass of farmers, even through group events. ICT channels to improve reach and efficiency, while rapidly emerging, are still far from achieving scale. The labor-intensive nature of current extension models is a fundamental hurdle to reaching enough farmers with quality, relevant and updated content during every planting cycle.

2. **While public extension systems suffer from limited capacity accountability and few incentives, there is scant scope for developing private services, especially for staple crops and subsistence farmers**

   The vast majority of extension programs are run by government agencies, and provided free of cost to the farmers. Unfortunately, this often means that the farmers have very limited leverage on the quality and frequency of service, and there is very limited accountability in the system to ensure that whatever services do exist are actually helping farmers. At the same time, the low demand from farmers—and their meager capacity to pay for services—has meant that there has been very limited scope for private services to enter the picture (which are, presumably, more accountable to the farmers). This has proven particularly true for subsistence farmers and staple crops. Unlike cash crops, staple crops do not have value chain partners with an interest in improving quality and output.
Extension workers need to add tangible value to farmers’ food production and livelihoods. Currently, there is neither an adequate supply of effective extension services, nor strong demand for it. Without adequate government budgets to employ and train a critical mass of extension workers, and adequate measures to ensure accountability, it will be extremely challenging to provide the necessary support to farmers. It is also clear that extension services in Africa have to make a fundamental shift towards being more relevant to women farmers.

There is substantial opportunity for providing improved learning tools with existing ICT devices like smartphones and tablets. Even if access to high speed networks or broadband Internet is sparse, these devices can be helpful offline. Creative, gender inclusive multimedia content produced in local languages, and combined with other interactive media platforms (e.g., call-in radio) can significantly increase the relevance, timeliness, and quality of disseminated information. In addition, tools for providing feedback on the responsiveness and effectiveness of individual extension agents—with creative mechanisms to escalate feedback to appropriate decision-makers—can help increase the entire system’s accountability.

Even as efforts are made to develop standardized training packages, strengthen farmer organizations, etc., 1 technological breakthrough can help advance the quality of extension services.

**An affordable and portable toolkit for extension workers, which includes a core set of devices for testing crop health, livestock health, and quality of produce**

Training farmers, while helpful, is often not sufficient on its own to add tangible value. Extension workers should also be able to provide specific on-farm products and services, to help farmers improve the volume and quality of their produce. The most important of such on-farm services include:

- Testing crops for particular, common pathogens and providing information about appropriate remedies. If combined with the provision of appropriate remedies, such a tool can help prevent potentially devastating losses for farmers.
- Diagnosing livestock at the point-of-care for particular diseases, and providing appropriate medication and disease management advice. As discussed in the chapter about livestock, disease is a significant contributor to livestock losses, and an effective veterinary service—enabled by such a toolkit—combined with regular extension support, can prove invaluable.
- Testing the composition (chemical, water, etc.) of high-value cash crops and produce, to give realtime advice on maximizing the quality of the output. This, in turn, can lead to higher market prices.

Such a toolkit currently does not exist in developing countries. Even in industrialized countries such tests are typically performed at labs and other centralized locations, or carried out using expensive portable equipment. Even though there is nothing fundamentally complex about the underlying science for developing such a toolkit, it will take considerable effort to build a practical product. While our research found that there is some interest in such technologies (especially from buyers of cash crop and livestock output), it is not clear that the necessary R&D and product development is being conducted. As such, we believe such a toolkit is 5-7 years from being available in the market.

When such a technology becomes available, it has the potential to catalyze a range of valuable services for farmers. This, in turn, can help spawn private service providers who will intrinsically be more accountable to their customers. However, it will face many of the familiar challenges: overcoming
a lack of demand, the need for user finance, and training. On the whole, we believe such a toolkit can gain significant traction because it can demonstrate value within a short time-frame. We expect deployment in this case will be COMPLEX.

**Breakthrough 1 – Difficulty of deployment**
Livestock farming is the primary source of food and income for 900 million smallholder farmers in sub-Saharan Africa and South Asia. That accounts for more than 60% of all smallholder farmers in sub-Saharan Africa, and over 40% in South Asia. Livestock farming provides farmers income that increases their resilience to economic and environmental shocks, and also serves as an important asset for financing. However, the vast majority of livestock farmers in sub-Saharan Africa practice pastoral, agro-pastoral, or extensive mixed crop-livestock systems, all of which are characterized by limited inputs for animal health, grazing on whatever forage is available, and very little access to markets for any produce from the livestock. Climate heavily influences the productivity of livestock in all 3 systems, as a result of which climate change and related environmental stresses are posing major challenges to traditional practices (Thornton, et al., 2002).

Inputs considered essential for productive, profitable livestock farming, such as nutrient-rich fodder, germplasm and appropriate cold storage for artificial insemination and cross-breeding, and drugs to prevent and treat diseases, are largely absent in such systems. As a result, animal health and productivity is very poor, and 25% of livestock in sub-Saharan Africa dies from preventable conditions. These livestock systems also have a very high environmental footprint. Systemic interventions are
required to encourage a shift towards more intensive systems, broad provision of veterinary and extension services, and the development of local value chains for processing and preserving meat, dairy and other animal products. Eight technological breakthroughs can help facilitate these systemic interventions.

- Affordable ‘stall-side’ diagnostics for the major livestock diseases
- A low cost mechanism to preserve animal semen (including new methods to produce liquid nitrogen, or alternatives to liquid nitrogen)
- Affordable veterinary pharmaceuticals (ideally thermostable) for the most virulent diseases with geography-specific strains
- Low cost ($500-$1,000) off-grid refrigerators for preserving vaccines and other temperature sensitive pharmaceuticals in remote settings
- Nutritious, affordable and environmentally sustainable animal fodder, ideally using local agricultural byproducts
- Affordable (under $50) off-grid refrigeration for smallholder farmers and small agribusinesses
- Low cost (under $5,000) refrigerated vehicles, sturdy enough for unpaved roads in rural areas
- A veterinary/extension toolkit, combining many of the above, which can enable commercially sustainable services for improving livestock health and productivity
Livestock is often the highest value asset for rural households (The World Bank, 2008). In arid and semiarid settings in particular, livestock is often the only major viable agricultural commodity. It provides income generating produce, serves as a key source of nutrition for the household (protein, vitamin B12, calcium, zinc, and riboflavin), and its byproducts have economic value as well; manure is used for fertilizer, and animal hide is sold as raw material for various products.

**CORE FACTS AND ANALYSIS**

Nearly 900 million low income people in sub-Saharan Africa and South Asia rear livestock as a primary source of income (McDermott, et al., 2010)(Gates Foundation, 2010). Livestock can have a high return-on-investment, and therefore represents a major opportunity to increase smallholder incomes.

There are 3 major types of livestock production, each employing very different rearing practices

The most common mode of livestock production in both Sub-Saharan Africa and South Asia is extensive mixed crop-livestock farming, which is characterized by limited labor, rain-fed agriculture, and few inputs. Mixed crop-livestock farming accounts for 85% and 62% of smallholder livestock farmers in sub-Saharan Africa and South Asia, respectively (Herrero, et al., 2012) (Exhibit 1). However, because of its reliance on limited inputs to improve animal health and productivity, this is also the least productive form of livestock farming. The animals are used for food, manure for fuel and fertilizers, draft power to facilitate agriculture, and a buffer against the price volatility which other agricultural commodities are often subject to. In an extensive mixed crop-livestock system, cattle manure may form up to 70% of all fertilizer use (Smith, 2012), and crop residues provide up to 70% of all animal feed (Smith, 2013).

Intensive mixed crop-livestock systems are usually concentrated in agriculturally productive regions with established supply chains to urban markets. About 35% of livestock farmers in South Asia practice intensive mixed crop-livestock farming, but it is negligible in sub-Saharan Africa (Herrero, et al., 2012). In such a system, production tends to involve access to irrigation and other farming inputs, a dense population of smallholder farmers, and a reasonably developed agricultural infrastructure.

Pastoral and agro-pastoral livestock farming is practiced by 15% of livestock farmers in sub-Saharan Africa and 3% in South Asia, almost all on marginal lands. Pastoralists focus only on livestock, whereas agro-pastoralists also grow crops to varying degrees. These systems are characterized by high number of animals, limited use of purchased inputs, and weak linkages to markets. In pastoral systems, livestock form the bulk of protein consumption, and is the main source of food and income. Despite accounting for only 15% of all low income livestock holders in sub-Saharan Africa, agro-pastoralists provide 36% of the region’s cattle meat production, and almost half of its milk (Herrero, et al., 2012). Climate heavily influences the choice and productivity of livestock systems. Exhibit 2 shows a map of production systems across various agroclimatic zones (Thornton, et al., 2002).
Distribution of livestock production systems in South Asia and sub-Saharan Africa

Exhibit 1: There are 3 major forms of livestock production: extensive mixed crop-livestock farming is the most common both in sub-Saharan Africa and South Asia. Agro-pastoral and pastoral farming is primarily an African phenomenon, and mixed intensive farming is common in South Asia. Currently, mixed extensive systems are the most prevalent in both regions.

Livestock production systems across various agroclimatic zones

Exhibit 2: Livestock production practices and output are heavily influenced by agroclimatic zones (Thornton, et al., 2002).
Most livestock farmers keep a very small number of animals, predominantly cattle, which serve a source of food and an asset.

The most important livestock animals in sub-Saharan Africa and South Asia are cattle, followed by small ruminants (sheep and goats) and poultry. Water buffalo are reared as livestock in South Asia (Exhibit 3). About 90% of all livestock keepers also raise chickens (Bill & Melinda Gates Foundation, 2012). Most livestock keepers—especially those practicing mixed-intensive and mixed-extensive livestock farming—maintain a very small number of animals. In India, for example, the world’s largest producer of dairy products by volume, 70% of milk is produced by farmers with 3 or fewer dairy cows (ILRI, 2011). In Kenya, the largest milk producing country in sub-Saharan Africa, the average dairy farmer only owns 2 cows (ILRI, 2009). Such farmers sell only 20-40% of their output, while the rest is consumed in the farmer’s household (FAO, 2009). For most farmers engaged in mixed crop-livestock systems, a few units of livestock are used for crop-tending activities like ploughing the fields and irrigation, and some are sold if the need for supplemental income emerges. Agro-pastoralists tend to have more animals, which contribute to the bulk of their income (McDermott, et al., 2010).

### Population of key livestock animals in South Asia and sub-Saharan Africa

<table>
<thead>
<tr>
<th>Animal</th>
<th>South Asia</th>
<th>Sub-Saharan Africa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cows</td>
<td>6,880</td>
<td>232</td>
</tr>
<tr>
<td>Chickens</td>
<td>10,110</td>
<td>228</td>
</tr>
<tr>
<td>Goats</td>
<td>187</td>
<td>127</td>
</tr>
<tr>
<td>Sheep</td>
<td>29</td>
<td>10</td>
</tr>
<tr>
<td>Buffaloes</td>
<td>17</td>
<td>3</td>
</tr>
<tr>
<td>Camels</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Pigs</td>
<td>29</td>
<td>10</td>
</tr>
</tbody>
</table>

**Exhibit 3**: Livestock in South Asia and sub-Saharan Africa is dominated by cattle, chickens and small ruminants. Water buffaloes are kept primarily in South Asia.
Livestock is valuable to farmers in several ways

Livestock not only provides direct value as a source of food for agrarian households, but is also an asset and source of income for farmers

Owned livestock animals and dairy products are the key source of protein among smallholder livestock farmers. Livestock provides food for 830 million food insecure people around the world, where it constitutes 6-36% of total protein intake and 2-12% of total caloric intake (Smith, 2013). Livestock products (meat, milk, eggs), along with fish, are the main sources of protein and other essential micronutrients like vitamin B-12, calcium, zinc and riboflavin (not available from other crops) for human nutrition. There is some regional variation in food preferences though. For example, milk accounts for 30-40% of all proteins from livestock product consumption in South Asia (FAO, 2002).

Globally, 4 out of the 5 highest value agricultural commodities are livestock, which consistently provide higher profit margins than crops. Livestock contributes approximately 30-50% to the overall income of low income farmers (Exhibit 4), and is a major opportunity for poverty alleviation. Some studies found that diversification into livestock farming is among the most commonly cited reason among Kenyan farmers for measurably increasing their incomes and escaping poverty (Gates Foundation, 2010). Livestock serves as a means of savings and insurance, which can be sold in times of crisis, unlike crops that are subject to seasonal and economic cycles (BeVier, 2010) (Heffernan, et al., 2008) (Tjanson, et al., 2004).
Economic importance of livestock for low income farmers

Percent of income derived from livestock, by region

- South Asia: 34%
- Southern Africa: 32%
- West Africa: 37%
- East Africa: 47%

Percent of income derived from livestock, by income (Kenya)

- <$10: 41%
- $10-$50: 36%
- $51-$100: 29%
- $101-$200: 13%
- >$200: 4%

Reasons for escaping poverty among families (Survey in two districts in Kenya)

- Employment in private or public sector: 73%
- Cash income from crop farming: 57%
- Diversification into livestock farming: 42%
- Help from friends or relatives: 40%
- Petty trade or business: 36%
- Small family size: 33%
- Education: 18%
- Bride wealth: 9%

Exhibit 4: Livestock is a major source of income for smallholder farmers, and accounts for 30-50% of total income for farmers in different parts of sub-Saharan Africa and South Asia. Income from livestock is particularly important for lower income farmers; a greater portion of whose overall income depends on livestock. An ILRI survey in Western Kenya found that diversification into livestock was among the most commonly cited reason for families escaping poverty.

Beyond direct value, livestock also provides considerable indirect value to farmers

The International Livestock Research Institute (ILRI) estimates that up to 40% of the value of livestock may be due to indirect products and benefits, such as manure, animal labor for traction, as well as insurance and savings (Smith, 2012). In low income countries, cattle manure is the main source of soil fertilizer, accounting for 70% of all soil amendments (Smith, 2012). It is important to remember that livestock are regularly transferred between members of extended families and clans as a buffer against food shocks. These non-monetary transactions are extremely significant during times of disaster, as was seen during the 1984 Sahel drought, where livestock transfers accounted for 60% of all food aid to the poorest households (Fafchamps, et al., 1998).

Demand for livestock products is growing around the world, including developing countries, driven by urbanization and increasing incomes (Smith, 2013). By 2030, demand for milk products is expected to double, and demand for beef products is expected to increase by 75-100% in sub-Saharan Africa and South Asia. In the same time period, demand for poultry products will increase eight-fold in South Asia, and three-fold in sub-Saharan Africa. Global meat consumption per capita is expected to more

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1 The original article mentions income levels in Kenyan Shillings. It is converted here to US$, assuming an exchange rate of KSh 100 to US$ 1.
than double by 2050, leading to an increase in world trade in meat products of a factor of 5 (Rosegrant, 2009). These growing domestic and export markets provide a significant opportunity for profitable income.

Crucially, the status and living standards of women are closely linked to the number of livestock units they control. Two-thirds of low income rural livestock keepers are women. In sub-Saharan Africa, women tend to manage poultry and small ruminants, while men manage cattle. In India, on the other hand, 70% of dairy-related labor is performed by women (ILRI, 2011). Recent research has found that the greater a woman’s assets at the time of marriage, the larger the share of wealth the household tends to invest in children’s education (Kristjanson, et al., 2010).

Livestock output in sub-Saharan Africa and South Asia is extremely low, compared to industrialized countries

Livestock output in sub-Saharan Africa and South Asia is a fraction of that in industrialized countries (Exhibit 5). The annual beef output in the two regions is 0.06 and 0.04 kg per kg of biomass, respectively, compared with 0.2 kg per kg of biomass in industrialized countries. The per-cow milk output in sub-Saharan Africa and South Asia is only 6% and 14% that of industrialized countries, respectively. Output from chicken and pigs is slightly more favorable. Chicken meat production per kg of biomass, in sub-Saharan Africa and South Asia, is 46% and 76% that of industrialized countries, respectively. Pig meat output stands at 48% and 56% that of industrialized countries, respectively, in sub-Saharan Africa and South Asia.

Livestock output in South Asia and sub-Saharan Africa, vs. industrialized countries

Exhibit 5: Livestock output in sub-Saharan Africa and South Asia is a fraction of that in industrialized countries. Beef and milk output, in particular, lag far behind (FAO, 2006).

In this case, the biomass in the denominator = Number of livestock units x average live weight per unit.
There are 3 main drivers of livestock productivity

Nutrition: Quality and quantity of food and input for the animals
In mixed-extensive, pastoral and agro-pastoral systems, animals forage on whatever feedstock and water is naturally available. This can vary significantly, depending on the area’s natural vegetation and how denuded the land is. Inadequate food and nutrition weakens animals, reduces yield, and increases vulnerability to disease. In arid and semiarid regions such as the Sahel belt and the Horn of Africa, marginalized populations—already entirely dependent on whatever little is naturally available—are feeling increasing stresses from land degradation and water scarcity, caused by livestock farming, other human activities, and climate change. As Exhibit 6 shows, a significant portion of livestock systems across sub-Sahara Africa are facing current and future degradation (Thornton, et al., 2002) (Herrero, et al., 2012).

Regions in sub-Saharan Africa where livestock farming is being threatened by environmental degradation

Exhibit 6: A large portion of the agro-pastoral, pastoral and extensive mixed-crop systems in sub-Saharan Africa are facing serious threats due to environmental degradation (current and projected). These stresses deplete the already meager food and water sources for livestock (Thornton, et al., 2002) (Herrero, et al., 2012).

Health: Protection from disease
Across the various types of livestock in sub-Saharan Africa and South Asia, a total of 14 major diseases—all of which are preventable and/or treatable—collectively cause $33.5 billion in economic losses. In sub-Saharan Africa, treatable diseases prematurely kill a quarter of all animals owned by poor livestock keepers, and represent the single largest driver of economic losses (Gates Foundation, 2012). Animal mortality in South Asia is also significant, although considerably less than in sub-Saharan Africa. Exhibit 7 lists the 14 predominant diseases, the economic damage they cause, and the animals they commonly effect, including (World Organization for Animal Health, 2009):

- A highly diverse range of indigenous endoparasites (which live inside the host) and ectoparasites (which live outside the host).
Peste des Petits Ruminants (PPR), or goat plague, which is spread by a virus through airborne animal discharges. The virus spreads before sheep or goats exhibit symptoms (with an incubation period as long as 21 days), making it difficult to isolate animals in time. Morbidity can be as high as 90-100%, and mortality up to 50-100%. No medication exists to treat the disease. Although vaccines exist, they require cold storage, and are not accessible to many livestock keepers.

Contagious Bovine Pleuropneumonia (CBPP), which involves multiple strains of mycoplasma bacteria spread through airborne animal discharges. The incubation period can be longer than 4 months. Contagious Caprine Pleuropneumonia (CCPP) are mycoplasma bacteria that affect goats in a similar manner. Although there is no treatment, several vaccines exist. However, their efficacy and side-effects on local breeds of livestock and local strains of pleuropneumonia vary.

Foot and mouth disease (FMD), which is caused by a virus with seven different serotypes that do not confer cross-immunity. The virus is spread through airborne animal discharges and is highly contagious. While mortality among adult animals is low, it can be 20% or higher among young animals. Quarantining is extremely important for controlling this disease. One important factor in sub-Saharan Africa is the prevalence of FMD in wildlife, as a result of which spillover to livestock populations requires intensive control through vaccinations. A number of FMD vaccines exist.

### Major livestock diseases in South Asia and sub-Saharan Africa

<table>
<thead>
<tr>
<th>Diseases</th>
<th>Economic value lost (US$ billions)</th>
<th>Total losses (US$ billions)</th>
<th>Cattle</th>
<th>Small ruminants</th>
<th>Poultry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Endoparasites</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peste des Petits Ruminants (PPR)</td>
<td>4.4</td>
<td>7.7</td>
<td>☑</td>
<td>☐</td>
<td>☐</td>
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<tr>
<td>Contagious Bovine Pleuropneumonia (CBPP)</td>
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<td></td>
</tr>
<tr>
<td>Ectoparasites</td>
<td>2.5</td>
<td>4.3</td>
<td>☑</td>
<td>☐</td>
<td></td>
</tr>
<tr>
<td>Contagious Caprine Pleuropneumonia (CCPP)</td>
<td>3.7</td>
<td>3.7</td>
<td>☑</td>
<td>☑</td>
<td></td>
</tr>
<tr>
<td>Foot and Mouth Disease</td>
<td>1.4</td>
<td>2.3</td>
<td>☑</td>
<td>☑</td>
<td></td>
</tr>
<tr>
<td>Trypanosomias</td>
<td>1.6</td>
<td>2.1</td>
<td>☑</td>
<td>☑</td>
<td></td>
</tr>
<tr>
<td>Newcastle Disease</td>
<td>-0.6</td>
<td>1.2</td>
<td>☑</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sheep/Goat Pox</td>
<td>0.5</td>
<td>1.2</td>
<td>☑</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brucellosi</td>
<td>0.5</td>
<td>1.1</td>
<td>☑</td>
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<td></td>
</tr>
<tr>
<td>Bovine Tuberculosis</td>
<td>-0.4</td>
<td>0.7</td>
<td>☑</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rift Valley Fever (RVF)</td>
<td>0.6</td>
<td>0.6</td>
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<td></td>
<td></td>
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<tr>
<td>Lumpy Skin Disease</td>
<td>0.6</td>
<td>0.6</td>
<td>☑</td>
<td></td>
<td></td>
</tr>
<tr>
<td>East Coast Fever</td>
<td>0.4</td>
<td>0.4</td>
<td>☑</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Exhibit 7: Fourteen livestock diseases collectively cause US$33.5 billion in losses to smallholder farmers in sub-Saharan Africa and South Asia. In sub-Saharan Africa, these diseases kill a quarter of livestock animals owned by low income farmers.
Superior genetic inputs through cross-breeding of animals have led to significant increases in livestock production efficiency in middle and high income countries. For example, cross-breeding of cattle in South Africa has shown a 26% increase in cattle weight, with minimal increase in feed requirements (Scholtz & Theunissen, 2010). In other parts of the developing world, between 1980 and 2005, increases in yield output per animal—54% for chicken and 135% for pigs—occurred due to successful North-South genetic transfers (World Bank, 2008). Around the developing world, 100 million cattle and pigs are bred annually using artificial insemination, but this is mostly outside of sub-Saharan Africa and South Asia (World Bank, 2008). Only 12% of dairy cattle in India are cross-bred (ILRI, 2011). Across both regions, improved genetic inputs are seldom used and improvements in livestock health and productivity remain stagnant. It is important to note that cross-breeding and improving genetics should be site-specific. One example of a common mistake due to lack of understanding of site-specific issues is in Ethiopia, where AI with Hereford cattle are in demand due to their high milk production; however, since these cattle do not have strong parasitic resistance, the cross-bred animals often suffer heavy morbidity and mortality (Interview, 2014).

While all the above drivers are important to all the major types of livestock, they have different levels of impact on different animals (Exhibit 8). Cattle productivity—with respect to both beef and milk—will require improved genetics (through cross-breeding), along with healthcare and nutrition (BeVier, 2010). Genetics can be valuable in poultry farming as well, as can better health and nutrition. Such improvements can collectively add US$11.5 billion in economic value for the smallholder livestock farmers of sub-Saharan Africa.
Contribution of various drivers to potential livestock productivity gains in sub-Saharan Africa

**Exhibit 8**: Improvements in animal genetics are the single largest driver of productivity for cattle products (beef and milk). Improvements to animal health (through both vaccines and treatment) can also have significant impact. For poultry (chicken meat and eggs), the primary driver is improvement in health (through vaccines and treatment for parasites and Newcastle Disease), and nutrition. In aggregate, this represents US$11.5 billion in incremental value for the farmers (BeVier, 2010).

Livestock production causes significant environmental damage

Livestock systems occupy 30% of the planet’s ice-free terrestrial surface (Thornton, 2010) and contribute to 18% of all global greenhouse emissions (McMichael, et al., 2007). The primary drivers of these emissions are deforestation or desertification due to grazing, manure (which releases nitrous oxide), and enteric (digestive) fermentation in cattle and small ruminants, which leads to methane release through belching and flatulence (Exhibit 9). Pastoral and extensive systems contribute over twice as much greenhouse gases to the atmosphere as intensive livestock systems (McMichael, et al., 2007) because of free grazing and the ever increasing need for more land to graze on. While most of the environmental damage from livestock production is concentrated in industrialized countries, deforestation and desertification—caused by a number of factors including livestock rearing—are a major problem in sub-Saharan Africa and South Asia.
Greenhouse gas emissions from different elements of livestock production

Exhibit 9: Agriculture accounts for 22% of all greenhouse gas emissions, and 80% of the agriculture-related emissions—18% of all GHG emissions—are from livestock rearing. While this predominantly comes from industrialized countries, desertification and deforestation are a major concern in parts of sub-Saharan Africa and South Asia.
KEY CHALLENGES

There are 4 major hurdles preventing smallholder livestock farmers from developing productive and profitable systems. These hurdles are much more prevalent in sub-Saharan Africa than in South Asia.

1. Healthcare services for livestock are extremely limited

There is strong evidence to show that cattle losses from disease are directly related to public expenditures on livestock health (World Bank, 2008). However, access to health services, particularly for the majority of agro-pastoral, pastoral, and mixed-extensive livestock keepers in remote areas, is heavily constrained due to poor infrastructure and a lack of properly trained animal health workers. Only a fraction of livestock farmers (e.g., 20% in Uganda) have access to any extension services (CGIAR, 2013), let alone quality advisory services. While animal health inputs are sometimes offered free of cost through government programs, such services tend to be limited to intensive and industrial livestock production systems (Upton, 2004). Similarly, even private animal health practices have only proven viable for intensive livestock production systems where veterinary service providers have a dense market. In addition, vaccines and veterinary pharmaceuticals in low income markets are often of poor quality, leading to a vicious cycle in which farmers from remote and rural areas, who only occasionally use pharmaceutical products for animals, lose further confidence in the value of such interventions when they don’t see dramatic or immediate results (Upton, 2004) (IFAD, 2011). Animal vaccines, like human vaccines, require refrigeration to remain viable, and the absence of a cold chain for animal pharmaceuticals makes delivery of vaccines very difficult. Beyond pharmaceuticals, the lack of a veterinary infrastructure means that there is very limited diagnosis, monitoring or reporting, for timely disease control. Lastly, the low investment in animal health research is inhibiting the production of new vaccines, diagnosis tools, and drugs (World Bank, 2008).

2. Smallholder farmers have very limited access to genetic material for cross-breeding

Smallholder farmers usually procure animals through informal networks and markets, equipped with limited knowledge—or means—of strengthening their herd with animals with the appropriate genetic composition. Successful livestock breeding programs rely on artificial insemination (AI) with appropriate superior breeds. While AI has made some headway in South Asia, its penetration been extremely limited in sub-Saharan Africa. The 3 main reasons are:

- Animal semen must be stored at extremely low temperatures (well below -100°C), using liquid nitrogen. While the process has become fairly standardized over the decades in much of the world, it has not reached rural farmers in sub-Saharan Africa because of its reliance on liquid nitrogen (for freezing), and the need for specific AI training.
- Successful AI requires a high number of genetically distinct livestock variants, to preserve genetic diversity over time. This is not possible with small herds in extensive or pastoral settings, where the number of livestock units is too low to allow for diversification. It also takes technical skill to conduct artificial insemination.
- Livestock in tropical areas face very different stresses from those in more temperate climates. In industrialized countries (most of which are in temperate areas), animals are reared in clean surroundings, have access to high-nutrition feed, and are adequately protected from major diseases. This means that these animals often do not develop resistance to tropical diseases, and their genetic material may have limited usefulness in tropical countries.

This section focuses only on livestock productivity. The issue of livestock sustainability is addressed (along with broader agricultural sustainability) in a separate chapter in this section.
Limited access to appropriate local storage, processing, or markets

Livestock food products are highly temperature sensitive, and need to be consumed, processed, or refrigerated very soon after production. With milk, for instance, most of the losses occur post-harvest, during the processing and distribution stages (Exhibit 10), because rural smallholder farmers have little to no access to refrigeration and find it difficult to reach markets within the short shelf life of the product. The lack of access to affordable, off-grid refrigeration is especially challenging for livestock farmers, since products deteriorate rapidly in warm temperatures. As Exhibit 11 shows, fresh milk can last up to a day in 15°C, but needs to be kept at 10°C to last 2 days and at 5°C to last 3 days. Fish needs to be at 10°C to last 3 days, while meat and butter can last longer in sub 20°C temperatures (Practical Action, 2012). However, daily ambient temperatures routinely get over 20°C in many tropical countries. In Kenya for example, the average daily temperature over the course of the year, across a nationwide cross-section of locations, is nearly 25°C. In many other countries, the average temperature is higher. Only 14% of the rural population in sub-Saharan Africa have access to electricity (IEA, 2013), and only 3-4% of milk processors in countries like Ghana and Tanzania have access to refrigeration (ILRI, 2009). Even in Kenya, Africa’s largest milk producer, only 10-15% of all marketed milk is packaged or processed; most of it is consumed unpasteurized (Meridian Institute, 2012). Similarly, over 90% of milk in Tanzania and Ghana, and 80% in India, is unprocessed (ILRI, 2009) (ILRI, 2011). This is equally true of all other livestock food products.

Because of their distance from markets and limited access to transportation, only a small fraction of livestock farmers are able to take their milk to a sale-point. In Ghana, for example, virtually 100% of milk producers and over 70% of market intermediaries transport their milk by foot. As a result, almost 90% of milk producers sell their product at their farms or homes itself (ILRI, 2009). The only producers who have access to markets are those living near urban areas (World Bank, 2008) (ILRI, 2009). As a consequence, the majority of livestock products from smallholder farmers are used in the farmers’ households, and both sub-Saharan Africa and South Asia import livestock products from higher income countries to satisfy urban consumer demand, despite a very large population of local livestock farmers.
Temperature sensitivity of various livestock products

Exhibit 10: The most significant losses in beef (and other meat products) occur in the production phase due to animal death from diseases or other causes. For milk, on the other hand, greater losses occur post-production, due to the absence of processing and storage infrastructure en route to the market.

Exhibit 11: Livestock products such as milk, fish, meat and butter, are highly temperature-sensitive. They need to be stored well below the average temperatures common to most tropical countries (Practical Action, 2012). Only 14% of the rural population in Africa has access to electricity, and only 3-4% of milk processors have access to refrigeration. Not surprisingly, there are few options for livestock farmers to get their produce to market. Note: Y axis scale is not linear.
The cost of inputs is a significant barrier for pastoral, agro-pastoral and mixed-extensive farmers to convert to intensive farming.

The cost of animal feed has traditionally prevented the transition from pastoralism to intensive livestock systems (World Bank, 2008). For example, feed accounts for 70% of the production cost of dairy in India (ILRI, 2011). Consequently, most poor livestock producers, particularly pastoralists, rely on public grazing lands to keep animal production costs low. However, due to shrinking land resources and alternative feed crop demand, feed prices are expected to increase at a faster rate than livestock product prices (Thornton, 2010). Water for livestock accounts for 30% of all water used in agriculture (Herrero, et al., 2009). Affordable access to water is especially critical to mixed crop-livestock systems, where both plant and animal water needs must be met. In arid and semiarid regions, access to water is the main reason for not transitioning to more intensive livestock production systems. Climate change and changing weather patterns are further eroding pastoralists’ ability to convert to intensive systems, by reducing the amount of water in the dry seasons, and decreasing the availability of forage.
SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

Livestock is not only a source of food for smallholder farmers, but also an asset. Recent research proves that owning livestock can help smallholder farmers escape poverty. Yet, in the absence of functioning markets and value chains for livestock produce, smallholder farmers can derive only limited economic benefits. This lack of income in turn impacts livestock production and yield—no high-nutrition feed, no genetic diversification through artificial insemination, little protection against diseases and high wastage of produce because of a lack of on-farm refrigeration facilities. While broader systemic interventions including increasing local processing capacity, incentivizing a shift to more intensive systems, improving market access, and improving transport infrastructure, are necessary to make fundamental long-term changes, 8 technological breakthroughs can drive significant targeted improvements in animal health and productivity.

Low cost ‘stall-side’ diagnostics for the major livestock diseases

Farmers, and the few service providers they usually have access to, are typically not able to diagnose a sick animal. This prevents them from seeking timely treatment, even if it were available. More importantly, it keeps farmers from preventing the disease from spreading to the rest of the herd. A simple low cost stall-side diagnostic that can be used by an extension worker or veterinarian—for the most deadly diseases specific to animal type and geography—can be a powerful tool to reduce livestock losses. Given the range of potential diseases and a lack of laboratory facilities to test samples, a point-of-care suite of diagnostics would be required.5

Existing reliable diagnostics are expensive, highly technical and involve culturing (which takes time). There is limited R&D and product development activity because the private sector does not find the market for animal diagnostics attractive. At the same time, there is limited public or philanthropic funding because animal health—unlike human health or crop health—has not been a major donor priority. Advances in animal diagnostics will likely build on similar point-of-care platforms for human health diagnostics, many of which are still several years from becoming a reality. Given these facts, low cost and reliable point-of-care animal health diagnostics are likely 7-10 years away from being market ready.

Once ready, such technologies will face a highly fragmented market and limited demand from smallholder livestock keepers, who understand little about the need for such technologies and can scarce afford them. This is particularly true in extensive and pastoral systems. As such, deployment will be EXTREMELY CHALLENGING.

4 Stall-side diagnostics are those which can be used where the animals are, rather than requiring a veterinary center or lab.
5 Please refer to the section on Diagnostics for Global Health, for an overview of the various diagnostic techniques.
A low cost mechanism to preserve animal semen (including new methods to produce liquid nitrogen, or alternatives to liquid nitrogen)

Cross-breeding has proven to be one of the most effective mechanisms for continuously improving the stock of animals. Artificial insemination is the only realistic means of cross-breeding. Preservation and transport of animal semen requires extremely low (sub -100°C) temperatures, currently achieved only with liquid nitrogen. While it is possible to build small-scale liquid nitrogen production units with limited investment (e.g., cryogenics enthusiasts have built 1 liter/day production units for about US$500-$1,000), large-scale production facilities are expensive. A less expensive mechanism to produce liquid nitrogen, or an alternative to liquid nitrogen as the means of preserving semen, can be a significant enabler of germplasm delivery.

Nitrogen liquefaction is intrinsically energy-intensive and hence, expensive. At the same time, there is no other proven mechanism to preserve a particularly thermosensitive substance like animal semen. Currently, limited R&D is underway for such technologies. It is likely that such a breakthrough will take at least 5-7 years to materialize.

Such a technology will face significant deployment challenges: there is very limited demand for artificial insemination from smallholder livestock farmers and the highly fragmented nature of the market means that distribution will be very difficult. Moreover, collection and administration of AI takes a certain amount of technical knowledge. Overall, deployment will be EXTREMELY CHALLENGING.
Breakthrough 2 – Difficulty of deployment

Breakthrough 3

Low cost veterinary pharmaceuticals (ideally thermostable) for the most virulent diseases with geography-specific strains

Smallholder livestock farmers lose about 25% of their animals each year due to diseases which are preventable by existing vaccines and medications. This is largely because of inadequate diagnosis, lack of access to medicines, and the poor quality of whatever pharmaceutical products that are available. However, for a number of the major geography-specific diseases and strains (e.g., East Coast Fever) new vaccines and/or treatment medications are needed. Developing drugs for animals is just as complicated as it is for humans, which means that the timelines for new drugs not already in the pipeline will be long. Given the relative unattractiveness of the market, it is unlikely that pharmaceutical companies are making any significant investments in such products. We expect it will take more than 10 years before all the necessary vaccines and pharmaceuticals become available.

Once available, a significant amount of work will be necessary for creating appropriate regulations, standards, quality control mechanisms, distribution, and administration. The absence of a cold chain for vaccines and pharmaceuticals makes preservation and transport of thermostensitive pharmaceuticals that much more difficult. However, as effective pharmaceuticals become available, their benefits will likely become apparent to livestock keepers in a relatively short time. This will help strengthen the market in the longer term. The value of preventive vaccines, however, will be less immediately apparent. As such, deployment will be CHALLENGING.
Low cost ($500-$1,000) off-grid refrigerators for preserving vaccines and other temperature sensitive pharmaceuticals in remote settings

Many vaccines are thermosensitive, and need to stay between 2°C and 8°C continuously, from the point of production to the point of administration. Due to the very limited rates of electrification in rural areas of sub-Saharan Africa (and to a smaller extent, South Asia), the relatively high cost of fuels like diesel, and the high cost and limited availability of refrigerators for storage or transport, vaccine cold chains are extremely weak. While institutions like GAVI, WHO and UNICEF have created some infrastructure for development, procurement and distribution of vaccines and vaccine refrigerators for human health, the corresponding institutional support for animal vaccine development and distribution is much weaker. Still, technologies developed for human vaccine cold chains can be leveraged for animal vaccines as well, and some promising refrigeration technologies appear to be on the horizon. It will likely take 3-5 years for such technologies to become available on the market. Once developed, the deployment challenges for these technologies will closely reflect those impacting livestock vaccines, which include a highly fragmented market with limited access to finance, sparse distribution channels, limited technical capacity along the value chain, and a difficult path to creating demand. Hence, deployment will be CHALLENGING.
Nutritious, affordable and environmentally sustainable animal fodder, ideally using local agricultural byproducts

In sub-Saharan Africa and South Asia, livestock fodder in extensive, pastoral and agro-pastoral settings consists almost entirely of what the animals can forage. While intensive livestock systems in both regions tend to have access to greater quantities of feed, even that fodder lacks the nutrition content required to raise healthy and highly productive animals. The techniques used for producing nutritious fodder are relatively established in industrialized countries (e.g., pelleting a mix of various high-nutrition inputs like sprouted grains and legumes), and can be customized to geography-specific inputs and practices with relative ease. With modest investments, such mechanisms can be made available in sub-Saharan Africa and South Asia too, within 1-2 years. However, there are a number of systemic hurdles that will make large-scale deployment challenging. Most importantly, smallholder livestock farmers and their communities have very limited nutritious food for themselves and their families. Hence, providing high-quality food for animals is not likely to be a high priority. Even if nutrient-rich fodder with inputs unfit for human consumption were available on the market, affordability, low demand, the centuries-old practice of grazing, a highly fragmented market, and the absence of a value chain for distribution, will pose significant challenges. Therefore, deployment will be EXTREMELY CHALLENGING.
Affordable (under $50) off-grid refrigeration for smallholder farmers and small agribusinesses

Horticulture products like fruits and vegetables are highly sensitive to temperature, and the lack of refrigeration dramatically reduces their shelf life, especially in tropical climates. While there are some inexpensive refrigerators available in emerging markets like India and China, they still cost more than $100, need reliable electricity and are difficult to repair once damaged.

Of late, there appears to be a resurgence of very affordable age-old traditional cooling technologies (e.g., clay pots). While this showcases the potential demand for an affordable and durable solution, traditional options like clay are subject to biological contamination, and difficult to clean. Moreover, as agricultural systems advance, there will be greater need for commodity-specific temperature control, and it is difficult to see traditional cooling solutions leading to modern, profitable agricultural value chains.

To serve the needs of rural, low income farmers, refrigerators need to be operable off-grid (e.g., solar-powered), considerably less expensive than the current $100 range, and easy to repair. Such technologies appear to be on the horizon. A new generation of refrigerators using thermoelectrics are beginning to reach the market. Given the broad demand for refrigeration there is reason to believe that an affordable product will gradually reach a critical mass of smallholder farmers—withstanding the usual problems of market fragmentation and distribution.

Based on the above, it is likely only a matter of 3-4 years before low cost refrigerators become practical for rural farmers. Despite the need and expected demand, such a technology will face considerable barriers to deployment due to the fragmented nature of the market, the absence of a value chain for distribution and maintenance, and the need for financing for farmers. Hence, deployment will be CHALLENGING.
Breakthrough 6 – Difficulty of deployment

- **Extremely Challenging**
  - Policies
  - Infrastructure
  - Human capital
  - Access to user finance
  - Behavior change
  - Existing demand
  - Market fragmentation/Distribution channels
  - Business model innovation

- **Challenging**
  - Low role of policy / regulation
  - Requires some improvements to existing infrastructure
  - Moderate need to train a limited number of people
  - Moderate financing needed, viable mechanisms identified
  - Moderate demand
  - Fragmented market, weak distribution channels
  - Deployment model(s) being tested; major hurdles outstanding

- **Complex**
- **Feasible**
- **Simple**

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**Low cost (under $5,000) refrigerated vehicles, sturdy enough for unpaved roads in rural areas.**

The ability to transport food to markets while preserving freshness will not only reduce post-harvest losses, but also create new value propositions for smallholder farmers. The absence of such refrigerated vehicles is one of the factors limiting access to market for higher-value produce (e.g., horticulture; and as the section on livestock discusses, meat and dairy). The lack of refrigeration also reduces everyday access to a diverse base of nutrients for children and the population in general.

Refrigerated trucks available on the market today are extremely expensive (costing tens of thousands of dollars), require diesel, and are built for smooth roads. To be useful to dealers and agribusiness entrepreneurs who serve smallholder farmers in remote areas, refrigerated transport vehicles will have to be robust and cost significantly less (under $5,000, rather than tens of thousands of dollars). While advances in stationary refrigeration technologies can also help advance transport refrigeration, there are a number of significant differences. First, stationary refrigerators normally operate indoors, whereas transport refrigerators will have to operate outdoors, under much warmer ambient temperatures and harsher conditions. Second, while a major challenge for stationary refrigeration is the absence of reliable electricity, transport refrigerators can use the fuel used to power the vehicles. Third, refrigerated vehicles will become affordable only after general-purpose vehicles become affordable. Based on the above analysis, the projected time to market for such technologies is 5-7 years.

Even when such a technology is developed, deployment will be difficult. The market is extremely fragmented, and adoption will depend on the growth of the broader market for the relevant agricultural commodities. In addition, poor road infrastructure and the sparse presence of fueling stations will be a major hurdle in the usability of refrigerated transport. Finally, a maintenance and repair infrastructure (currently absent) will be necessary to keep these refrigerated vehicles functioning. We estimate that deployment will be EXTREMELY CHALLENGING.
A veterinary/extension toolkit, combining many of the above, which can enable commercially sustainable services for improving livestock health and productivity.

When animals fall sick, extension workers are usually the only help livestock farmers have—if one is available. Veterinarians are usually not an option, especially outside intensive systems. Typically, the main responsibility of extension workers is to train farmers, rather than treat animals. Training farmers, while helpful, is often not sufficient on its own to add tangible value. Extension workers should also be able to provide services, to help farmers improve the health and output of their animals. These services include diagnosis, provision of appropriate medication, and advice on disease management. Hence the toolkit should include many of the devices described above: stall-side diagnostics, pharmaceuticals, cold chain equipment for the pharmaceuticals, nutritional supplements, and other veterinary equipment. While veterinary toolkits exist, they are unaffordable in the context of smallholder livestock farmers. Given the technical challenges involved, as well as the limited effort currently underway, we believe such a toolkit is 5-7 years from being available in the market.

When such a toolkit becomes available, it has the potential to catalyze a range of valuable services for livestock holders. This, in turn, can help spawn private service providers who will intrinsically be more accountable to their customers. However, it will face many of the familiar challenges: overcoming a lack of demand, reaching a highly fragmented market, addressing the lack of financing mechanisms on the part of the farmers to pay for the services, and training of veterinarians and extension workers. There will likely be regulatory requirements as well. We expect deployment in this case will be EXTREMELY CHALLENGING.
Breakthrough 8 – Difficulty of deployment

- **Policies**: Requires high level of training for large numbers of people. Requires new regulations likely required.
- **Infrastructure**: Minimal need for infrastructure.
- **Human capital**: Moderate financing needed, viable mechanisms identified.
- **Access to user finance**: Major behavior change required, potentially on daily basis.
- **Behavior change**: Low demand, needs to be built.
- **Existing demand**: No identified deployment model, major hurdles identified.
- **Market fragmentation/Distribution channels**: Highly fragmented, challenging to reach customers.
- **Business model innovation**: Extremely challenging.

**Difficulty Levels**:
- Simple
- Feasible
- Complex
- Challenging
- Extremely Challenging
Most of today’s prevalent food production systems have unsustainable environmental footprints. Collectively, they are causing depletion of non-renewable groundwater, fertilizer runoffs leading to dead zones in waterways, soil erosion, deforestation, greenhouse gas emissions, environmental toxicity from the use of chemical pesticides and herbicides, and a range of other problems. All of these challenges are exacerbated by population growth and increased consumption levels, as incomes around the world rise. Each of the various forms of food production systems discussed in this section—large-scale industrial, Green Revolution intensified, resource-constrained smallholder, and high-cost organic—imposes a different set of challenges. By all accounts, the pressure on smallholder farmers in sub-Saharan Africa and South Asia to increase yields will likely lead to significantly greater damage to the environment, especially since sustainable agriculture is much more expensive than existing practices. New forms of food production, facilitated by a new generation of technologies and tools to help farmers be both profitable and sustainable, will be required to preserve the planet’s ecological health. Eight technological breakthroughs can make this possible.
Low cost, easy-to-construct rainwater storage repositories where harvested rainwater can be stored for several months without contamination

New methods for nitrogen fixation and producing other fertilizer components, instead of the energy-intensive and capital-intensive methods used currently

A mechanism to improve the viability and effectiveness of biological fertilizers, in particular, those made from human waste

Herbicides or other affordable mechanisms to control weeds, ideally ones that are more environmentally friendly than herbicides currently on the market

Novel, low cost, and environmentally friendly pesticide(s), specifically targeting the most destructive insects

A scalable low cost method to desalinate water using renewable energy

A low cost system for precision application of agricultural inputs, ideally combining fertilizers and water

New seed varieties that are tolerant to drought, heat, and other emerging environmental stresses
A commonly used definition of sustainable development is “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (UNWCED, 1987). With respect to agriculture, sustainable development requires that adequate food supplies (in terms of both quantity and quality) be made available to all people now, and also that the systems used to produce this food be sufficiently resilient such that adequate food supplies will continue to be available indefinitely without compromising the environment.

CORE FACTS AND ANALYSIS

Based on the above definition, prevalent forms of food production are not sustainable. Not only are fixed resources for agriculture, such as groundwater, steadily shrinking, but food production systems also are causing several other negative externalities in the broader environment. For the purposes of our discussion, there are 4 major agricultural systems:

- Large-scale industrial agriculture is practiced in the US and much of Europe. This is characterized by heavy mechanization, sophisticated agronomic practices, and heavy use of inputs like groundwater irrigation, chemical fertilizers, chemical pesticide, and GMOs (genetically modified organisms).\(^2\)
- Green Revolution intensive agriculture, practiced in South Asia, Southeast Asia, much of Latin America, and parts of China. This is characterized by smallholder animal-assisted farming, but with heavy use of inputs like groundwater irrigation, chemical fertilizers and chemical pesticide. GMOs are rare in such systems, but are likely to become more common in the near future.
- Resource-constrained smallholder systems, restricted primarily to sub-Saharan Africa and same parts of South Asia (e.g., the lower Gangetic Indian states of Orissa and Bihar). These smallholder systems exist without access to inputs like irrigation and fertilizer, and without adequate extension services support.
- High-cost organic systems that have grown in recent years to a profitable niche market, mostly in industrialized countries.

To illustrate the relative prevalence of each of these systems, Exhibit 1 shows the yield, cost, and total output for maize from India, Africa, US conventional (industrial) systems, and US organic systems.\(^3\) Of these systems, US conventional farms constitute the largest share, producing about 328 million tons, African farmers produce 65 million tons, Indian farmers produce 21 million tons, and US organic farms produce 0.65 million tons. Per-hectare yields experienced by African and Indian farmers is a small fraction that of US conventional and US organic systems. The cost of production also varies dramatically. The low cost of labor in India and Africa leads to relatively lower production costs, while US organic systems are significantly more expensive than all the other systems.

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\(^1\) Please note that much of the material in this chapter is also discussed in other parts of this study.

\(^2\) GMOs, and our perspective on their applicability to smallholder farmers, are discussed at the end of this chapter.

\(^3\) Please note that this data is not fully representative of typical food production systems in the three regions, for two reasons. First, maize is a major crop in Africa and the US, but only a minor crop in India; hence, this may be representative of the cost of typical cereals. Second, US maize is heavily subsidized, and a large portion is used to produce ethanol (rather than as food). This illustration shows data for both food and biofuel production. Please also note that ‘US organic’ is defined by the US Department of Agriculture, as an ecological production system that fosters resource cycling, promotes ecological balance, and conserves biodiversity. Organic farmers are required to avoid most synthetic chemicals and must adopt practices that maintain or improve soil conditions and minimize erosion.
Exhibit 1: This exhibit illustrates the differences between 4 major agricultural production systems, using the example of maize. The US conventional system is the most prolific, producing 328 million tons annually. However, it also has a significant environmental footprint. Smallholder systems in Africa and India produce 65 million tons and 21 million tons, respectively, with much lower yields per hectare. US organic systems (based on some measures of environmental sustainability) are the most expensive. As discussed below, each of these systems poses stresses on the environment.

Table 1 summarizes the sustainability challenges posed by each of these agricultural systems. As the table shows, none of the four systems is entirely sustainable. Large-scale industrial systems (like those used for conventional US farming) have been built on the strength of heavy use of water (increasingly non-renewable groundwater), fertilizers, pesticides and herbicides. Many of these factors also apply to the intensified practices of the Green Revolution. Even the practices of resource-constrained smallholder African farmers cause problems with deforestation (due to extensification and increased land use), soil erosion (due to livestock rearing practices) and soil nutrient mining (because they cannot easily replenish the nutrients harvested with the crops). Somewhat surprisingly, even organic farming (at least as it is defined by the US Department of Agriculture) can cause environmental damage, since it places no restrictions on water use.
Sustainability challenges posed by different agricultural production systems

Table 1: None of the agricultural production systems prevalent today is entirely sustainable. Each exists within specific socio-economic contexts and poses a different set of environmental challenges. Even organic farming does not necessarily guarantee preservation of groundwater and topsoil.

<table>
<thead>
<tr>
<th>Agricultural system</th>
<th>Typical sustainability challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Groundwater depletion</td>
</tr>
<tr>
<td>Large-scale industrial (US-Conventional)</td>
<td>High</td>
</tr>
<tr>
<td>Green Revolution intensive (India)</td>
<td>High</td>
</tr>
<tr>
<td>Resource-constrained smallholder (sub-Saharan Africa)</td>
<td>Low</td>
</tr>
<tr>
<td>High-cost organic (US Organic)</td>
<td>Medium</td>
</tr>
</tbody>
</table>

Food demand will increase substantially as population and affluence grows

Global human population was relatively stable until recent generations; varying between 200 million to 700 million individuals between the years 1AD and 1700 (Exhibit 2) (US Census Bureau 2014). This represents an average population growth of 2% per 30-year human generation. During this time, the concept of ‘agricultural sustainability’ largely meant using farming techniques handed down from one generation to the next. Population has increased notably since then, requiring a much more proactive approach to ensuring food sufficiency. Between 1700 and 1950, population increased at an average rate of 35% per generation. Since 1950, global population has been increasing by 88%—almost doubling—each 30-year generation (UN 2013). Human population reached 1 billion people in about 1800, 2 billion in the 1920s, 4 billion in 1975, and 6 billion people in 1999. Current (2014) human population is about 7.2 billion. Agricultural sustainability has become more challenging during this period of rapid population growth, especially since 1950. This demands not just continuity of food production levels, but continually increasing total production levels as well. Ironically, conventional agricultural development efforts have focused on the immediate need for increasing food production to nourish current populations, with less concern for longer-term consequences.
Future success in agricultural sufficiency faces a moving target, as global population continues to rise; though more slowly than during the period of maximum growth rate in the 1960s. The human population is expected to increase about 32% by the year 2050, from the current number of 7.2 billion to about 9.6 billion (with a range of 9.1 to 10.1 billion, within a 95% confidence interval) (UN 2013) (Gerland et al. 2014). This represents a 27% growth per 30-year generation. By the year 2100, a 50% increase, to about 10.9 billion, is projected (95% confidence interval: 9.0 to 13.2 billion). Much of this population increase is expected to occur in Africa, from its current population of about 1 billion people to a projected 4.2 billion people in 2100 (95% confidence interval: 3.1 to 5.7 billion).

The total demand for food is a function not only of the number of people, but also of per capita food demand. Successful global development implies greater affluence and more room for personal choices. This, in practice, results in more food consumption, and of types that are more resource-intensive, such as meats. Globally, there is a consistent relationship between per capita GDP and per capita demand for crop calories and protein (Tilman et al. 2011) (Exhibit 3). Although population is expected to rise by 32% by 2050, food production must increase by 56% from 2014 levels to meet the demands of this larger, richer and more urban population (FAO, 2009) (UN, 2013) (FAO, 2014).

Exhibit 2: Global human population was relatively stable for much of the past 2 millennia, with fewer than 1 billion individuals until the year 1800. Population has increased markedly since then, and especially since 1950. Future population is projected to increase to 10.9 billion (95% confidence interval: 9.0 to 13.2 billion) people by 2100.

Historical and projected global human population
Exhibit 3: Total food production requirements are determined not just by total human population but also per capita food demand. Both have risen substantially since 1960, and are projected to continue rising through 2050 and beyond.

Historically, agricultural production has increased by both intensification and extensification

Broadly speaking, crop production can be increased in two ways. Agriculture can be made more intensive, by obtaining larger or more frequent harvests from a hectare of farmland. Or, agriculture can become more extensive, by expanding the area to include more hectares of farmland. Exhibit 4 shows that since 1961, South Asia has increased cereal production primarily through intensification, while sub-Saharan Africa has increased cereal production mainly through extensification (Virtual Fertilizer Research Center, 2012).

Intensification can be achieved by removing constraints such as lack of water (through irrigation) and nutrient deficiencies (through fertilization). Another means of intensification is to increase the land utilization intensity (also known as ‘cropping intensity’), which determines how frequently a hectare of farmland is cultivated and harvested. Land utilization intensity is the ratio of the land area that is cultivated and harvested per year compared to the total arable land area. This may be less than 1, where some land is left fallow and not used every year. It may also be greater than 1, when multiple harvests are made per year on the same land, particularly in well irrigated areas. The lowest land utilization intensities related to total cropland extent (including fallow land) are in Southern Africa (0.45), Central America (0.49) and Middle Africa (0.54), while the highest intensities are in East Asia (1.04) and South Asia (1.0) (Seibert et al. 2010).
Exhibit 4: South Asian countries have increased agricultural yield dramatically over the past few decades using intensified agricultural practices. Compared with 1961, per hectare cereal yield in South Asia has increased by 165%, leading to a total output increase of 210%, with only a small increase in cultivated land. During the same period, sub-Saharan Africa saw a 140% increase in cultivated land and only a 60% increase in per hectare yield, for a total increase in output of 259%.

With more demand for food, land utilization intensities will continue to rise due to shorter fallow periods and more multiple cropping. Many traditional farming systems rely on periodically leaving land fallow to allow natural ecological processes to restore soil fertility. Reducing or eliminating fallow may require other agricultural interventions such as fertilization. Multiple cropping is the practice of growing 2 or more crops in the same space during a single growing season, and can take the form of double-cropping (in which another crop is planted after the first has been harvested) or may be relay cropping (in which the second crop is started amidst the first crop before the first has been harvested). Increasing the area of irrigated land also allows more multiple cropping. About one-third of the arable land in South and East Asia is already irrigated, and this high share of irrigation of total arable land is one reason why the average land utilization intensities in these regions are higher than in others.

Future increases in crop production are likely to be achieved through somewhat different means than past increases. Exhibit 5 details the sources of past (since 1961) and projected future (through 2050) increases in crop production in different regions. Agricultural extensification, or expanding the overall area of arable land, is likely to be relatively less significant in the future, especially in Asia. Intensification of agricultural practices, particularly by increasing the yield of crop harvests, is expected to be more important.
Crop production can be increased by extensification (expanding the area of farmland) or by intensification (getting bigger or more frequent harvests from existing farmland). Agricultural intensification can come from increasing yield, which gives more food per harvest, or by increasing land utilization intensity, which gives more frequent harvests. Compared to past sources of crop production increase, projected future increases are expected to rely more on increased yields (FAO 2012).
Current methods of increasing agricultural production (including both intensive and extensive systems) have major implications for sustainability.

Most current models of agricultural production entail numerous, and often interlinked, sustainability stressors. These are expected to become more serious under business-as-usual development scenarios.

Cropland expansion is reducing biodiversity

Expanding the area of arable land typically involves conversion of wild land to cropland. Exhibit 6 shows the past and projected area of arable cropland in use in different regions across the world. Since the 1960s, cropland area has increased substantially in sub-Saharan Africa and Latin America, with smaller increases in Asia (FAO 2012). Arable cropland area is expected to continue to increase modestly through 2050 in sub-Saharan Africa and Latin America. Very little future increase in cropland area is anticipated for Asia and North Africa. These estimates for expansion of arable land are estimates of net expansion of arable area, and do not take into account the need for additional land to compensate for erstwhile arable land taken out of production due to severe land degradation. It is estimated that about 3 million hectares of cropland worldwide are abandoned each year because of productivity declines due to land degradation (FAO, 2012).

Exhibit 6: The area of arable cropland in use has increased substantially since the 1960s in sub-Saharan Africa and Latin America, with smaller increases in Asia. Arable cropland area is expected to continue to increase modestly through 2050 in sub-Saharan Africa and Latin America. Very little future increase in cropland area is anticipated for Asia and North Africa.
Humans have, over a span of centuries, converted substantial portions of land once covered by wild forests and grassland into managed cropland and pastures. Exhibit 7 shows that about 10 million km$^2$ of forest land has been converted during the last three centuries (Ramankutty & Foley, 1999) (Pongratz, et al., 2008) (FAO, 2010) (World Bank, 2013). Cropland area (the extent of which may vary, depending on the definition used), increased by about 15 million km$^2$ during the same period. The rates of forest land decrease and cropland increase have remained fairly steady over the last 300 years, though they have accelerated somewhat since about 1850. The current rate of deforestation is in line with this centuries-old trend.

**Global forest and cropland area since 1700**

![Global forest and cropland area since 1700](image)

**Exhibit 7**: Over the last 3 centuries, humans have converted about 10 million km$^2$ of forest land to other uses, and have turned about 15 million km$^2$ of land into agricultural cropland. During the same period, natural grassland area has decreased, and pasture land area has increased (not shown in figure).

This population shift from wild to domesticated animals and plants necessarily involves the simplification of the structure and functioning of ecosystems. Humans are causing ecosystems to lose complexity at several levels: species diversity (the number and variety of species), genetic diversity (the genetic possibilities a species contains), and ecosystem diversity (the variation between global ecosystem characteristics) (MEA, 2005). The distribution of species on earth is becoming more homogenous, meaning that the differences are, on average, diminishing between the group of species at one location on the planet and groups at other locations. Different types of species evolved in ecosystems in different regions, through the combination of natural barriers to migration and local adaptations. These regional differences in the biota of the earth are now diminishing. Genetic diversity, which serves as a way for populations to adapt to changing environments, is being lost.

Human actions (including destruction of habitat) are now leading to the extinction of other species at a rate 1000 times greater than the natural background rate of extinction (Pimm, et al., 2014). This ongoing simplification is illustrated in Exhibit 8, based on the Living Planet Index that is calculated...
Plants need a supply of nutrients to support their growth, as discussed in the chapter on fertilizers. This supply increasingly takes the form of chemical fertilizers, manufactured offsite and applied to the farmland. Only a part of the fertilizer is absorbed by the plant roots, and the rest is typically washed away by rain into streams and rivers. This then causes water pollution, and increasingly leads to aquatic dead zones.

Nitrogen is essential to life on earth, as it is needed to make amino acids, nucleotides and other basic building blocks of plants, animals and other life forms. Nitrogen comprises about 78% of earth’s atmosphere, but in the very stable N\(_2\) form, with two nitrogen atoms bound tightly together, unwilling to form partnerships. A limited amount of nitrogen, known as reactive nitrogen, is ‘fixed’ from the atmosphere and then made available to living organisms in a more reactive form. There are several natural routes of nitrogen fixation, including by particular bacteria living in symbiosis with some types of plants periodically by WWF International (WWF, 2014). This index estimates changes in the state of the planet’s biodiversity, using trends in population size for vertebrate species from different biomes and regions to estimate average changes in abundance over time (Collen, et al., 2008). Trends in the Living Planet Index suggest that across the globe, wild populations of vertebrate animals were on average 52% smaller in 2010 than they were in 1970. The greatest reductions occurred in tropical regions, in particular the Neotropical biogeographical area that includes South and Central America, and the Indo-Pacific area that includes South Asia and Australasia. Temperate regions show smaller reductions, largely because those lands were cleared for agricultural use long before 1970, and now include abandoned farmlands that are reverting to natural processes. Acknowledging the imprecision of such simple proxy indicators, the global trends toward lower biodiversity and simpler ecosystems are robust.

**Change in animal biodiversity since 1970**

<table>
<thead>
<tr>
<th>Region</th>
<th>-100%</th>
<th>-75%</th>
<th>-50%</th>
<th>-25%</th>
<th>0%</th>
<th>25%</th>
<th>50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Afrotropical</td>
<td></td>
<td></td>
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<tr>
<td>Nearctic</td>
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</tr>
<tr>
<td>Palearctic</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Indo-Pacific</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Neotropical</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Global</td>
<td></td>
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</tbody>
</table>

**Exhibit 8:** Regional and global biodiversity has generally decreased in recent decades, as estimated by WWF’s Living Planet Index, based on wild populations of vertebrate animals between 1970 and 2010. Error bars represent 95% confidence limits. The 5 regions are biogeographic realms, where terrestrial species have evolved in relative isolation over long periods of time. Afrotropical includes sub-Saharan Africa. Nearctic includes North America. Palearctic includes Europe, North Africa, the Middle East, and most of Asia. Indo-Pacific includes South Asia and Australasia. Neotropical includes South and Central America.

Agricultural fertilization leads to water pollution and other environmental consequences. Plants need a supply of nutrients to support their growth, as discussed in the chapter on fertilizers. This supply increasingly takes the form of chemical fertilizers, manufactured offsite and applied to the farmland. Only a part of the fertilizer is absorbed by the plant roots, and the rest is typically washed away by rain into streams and rivers. This then causes water pollution, and increasingly leads to aquatic dead zones.

Nitrogen is essential to life on earth, as it is needed to make amino acids, nucleotides and other basic building blocks of plants, animals and other life forms. Nitrogen comprises about 78% of earth’s atmosphere, but in the very stable N\(_2\) form, with two nitrogen atoms bound tightly together, unwilling to form partnerships. A limited amount of nitrogen, known as reactive nitrogen, is ‘fixed’ from the atmosphere and then made available to living organisms in a more reactive form. There are several natural routes of nitrogen fixation, including by particular bacteria living in symbiosis with some types of
plants. Humans have long managed croplands to incorporate these types of plants within crops rotation systems, to fix a modest amount of nitrogen within agroecosystems. During the last 50 years, the amount of nitrogen that is fixed through human actions has increased steadily, and now occurs at a scale similar to that of all natural land ecosystems (Robertson & Vitousek, 2009) (Exhibit 9). Most of this increase is due to fertilizer production based on the Haber-Bosch process, using non-renewable natural gas as feedstock. The temporary reduction in nitrogen fertilizer production during the early 1990s was due to the collapse of the Soviet Union. Other human actions that fix atmospheric nitrogen include fuel combustion and managed biological fixation. This alteration of the nitrogen cycle has allowed us to grow significantly more food for consumption than otherwise would have been possible. However, the increased overall availability of nitrogen fertilizer, coupled with the difficulty of precisely targeting application to ensure complete absorption by plants, has led to nitrogen runoff well beyond the farmlands the fertilizer is applied to.

**Reactive nitrogen fixed by human actions**

![Exhibit 9: Human production of reactive nitrogen has increased substantially during the last 50 years, and now occurs at the same rate as it does in all natural land ecosystems put together. Most of this increase is due to fertilizer production using the Haber-Bosch process.](image)

Another important plant nutrient is the chemical element phosphorus, which is essential for plant growth and is an important input to intensive agriculture. Phosphorus fertilizers are necessary because of the slow natural cycling of phosphorus, the low solubility of natural phosphorus-containing compounds, and the essential nature of phosphorus to living organisms. Traditional sources of agricultural phosphorous are animal manure and guano (bird droppings). Exhibit 10 shows that phosphate rock mining expanded considerably after 1950, and is now the dominant source of phosphorous fertilizer (Cordell and White, 2014). Three countries currently mine 70% of global phosphate rock production: China, USA and Morocco (USGS, 2014). Global reserves of high-quality phosphate rock are concentrated in the Western Sahara region of Africa, a disputed region controlled by Morocco. Sustained disruption of supply, whether due to geological or geopolitical forces, could significantly affect food security (Dawson & Hilton, 2011).
Runoff of nitrogen and phosphorus fertilizers from agricultural land is a major source of water pollution. Just as fertilizing agricultural fields can stimulate crop growth, increasing nutrient levels in rivers, lakes and estuaries can cause eutrophication or excessive growth of algae and other aquatic plants. Huge blooms of cyanobacteria (also known as blue-green algae), and other organisms can come to dominate aquatic ecosystems, seriously degrading water quality (Smith, 2003). Negative effects include hypoxia, or depletion of oxygen in the water, which causes the death of fish and other animals in the water. Over 400 marine ‘dead zones’ resulting from nutrient runoff are reported worldwide, having approximately doubled each decade since the 1960s (Diaz & Rosenberg, 2008). Many cyanobacteria also produce toxic compounds that are hazardous to humans and domesticated animals. Mass blooms of toxic cyanobacteria occur regularly in water subject to nutrient runoff, with the timing and duration of the bloom season varying by location. In recent decades, the amount of reactive nitrogen in rivers has increased dramatically (Green, et al., 2004) (MEA, 2005), with river basins in North America, continental Europe, and South and East Asia showing the greatest change (Exhibit 11). Even as recently as August, 2014, the water supply for the city of Toledo (Ohio, USA) was interrupted for several days in due to an algae bloom caused largely by phosphorous fertilizer runoff. In the absence of mechanisms to protection sources of drinking water from pollution, it is likely that developing countries with fertilizer overuse face a continuing degradation of their water sources. Africa suffers little from nutrient pollution, mainly because fertilizer use in Africa is still very low.

Exhibit 10: Mining of phosphate rock expanded considerably after 1950, and is now the dominant source of phosphorous fertilizer used in agriculture.
Increase in nitrogen runoff leading to aquatic dead zones

Exhibit 11: Reactive nitrogen flows in many river systems have increased dramatically in recent decades—primarily due to fertilizer runoff from agricultural lands—especially evident in Europe, Asia and North America. This has led to ‘dead zones’ in waterways.

Irrigation (especially in South Asia) is using an increasing amount of non-renewable groundwater. Irrigation has proven to be a fundamental requirement to adequate agricultural yields. Over time, irrigation has increasingly tapped into groundwater, which currently supplies at least half of all irrigation water globally (Famiglietti, 2014). Groundwater sources used for irrigation are either renewable or non-renewable. The former get periodically replenished when sufficient precipitation infiltrates the soils or when floodplains become inundated, while the latter are from fossil groundwater sources, locked in deep aquifers that have little or no long-term source of replenishment. When such water is extracted, it is effectively ‘mined’ and the aquifer is eventually depleted. In the last few decades, an increasing amount of irrigated farming is being supported by such non-renewable groundwater extraction. This is especially problematic in South Asia, where Green Revolution successes in yield increases were achieved (in part) through exploitation of water resources that have now been permanently depleted. Globally, about 18% of gross irrigation water demand for the year 2000 was met with non-renewable groundwater extraction (Wada, et al., 2012). Exhibit 12 shows the sources of water used globally for irrigation in 1960 and 2000, during which time the share of non-renewable groundwater increased from 12% to 18%. In absolute terms, however, the use of non-renewable groundwater more than tripled, from 75 to 230 cubic kilometers per year.
Relatively few countries, notably India, Pakistan and USA, are responsible for most of the non-renewable groundwater use (Gleason, et al., 2012). Exhibit 13 shows that in the year 2000, India used more non-renewable groundwater for irrigation than any other country. About 19% of India’s irrigation water came from non-renewable sources. Other countries used a smaller volume of non-renewable water, but it comprised a larger proportion of their total irrigation water use. In both Pakistan and USA, the share of non-renewable groundwater was 24% and in Iran it was 40%. Over 70% of irrigation water in Libya and Saudi Arabia was sourced from non-renewable groundwater (Wada, et al., 2012).

Groundwater depletion affects food security by limiting the amount of water available for agriculture and other human uses, and making the available water more difficult and costly to obtain. As groundwater supply becomes more limited, wells may go dry intermittently or constantly. Wells may need to be extended deeper to reach water, and more energy is needed to pump water from greater depths. Water quality of depleting freshwater aquifers may deteriorate due to intrusion of brackish water from surrounding aquifers. South Asia is particularly affected by shrinking groundwater resources, and strategies for future food security must now account for constrained groundwater extraction.
Sources of irrigation water used by select countries, in 2000

Exhibit 13: Non-renewable groundwater is a significant part of gross irrigation water used in several major countries. India uses more non-renewable groundwater for irrigation than any other country (68 km³ per year, in year 2000). Iran uses less in absolute terms (20 km³ per year) but more as a percent of total irrigation water: 40% of Iran’s irrigation water is sourced from non-renewable groundwater. ‘Other irrigation water’ includes non-local water and renewable local water.

Sub-Saharan Africa appears to have relatively abundant renewable groundwater resources (MacDonald, et al., 2012) but faces economic water scarcity. While tapping into the seemingly abundant groundwater resources may be critical for improving overall agricultural yields across Africa, it will be equally critical to remember the lessons from South Asia to ensure future sustainability of an important resource. Unsustainability of groundwater use for irrigation is a concern not only for countries that are using groundwater intensively, but also the world at large since international trade directly links food production in one country to consumption in another.

Current agricultural practices cause soil erosion and reduce the long-term fertility of farmland

Soil erosion is the removal of soil from the land surface, typically carried away by rain or wind. Some level of soil erosion is natural. Soil erosion under native vegetation occurs at roughly the same rate at which new soil is produced through natural geomorphologic processes (Exhibit 14). However, agricultural practices such as tillage and heavy grazing remove vegetative cover and expose the soil surface to rain and wind. Soil erosion from agricultural fields occurs at rates 10 to 100 times greater than erosion from natural land surfaces (Pimentel, 2006) (Montgomery, 2007). Soil erosion is widespread: about 80% of global agricultural land suffers moderate to severe erosion (Pimentel & Burgess, 2013). Erosion is much greater on sloping land, where soil particles are carried away downhill by flowing water. Wind can also carry soil particles for long distances.
Loss of fertile soil due to erosion from cropland

Exhibit 14: On average, about 1 to 3 millimeters of soil are lost each year from typical farmland. Soil erosion rates in mountainous regions can be 10 times greater. Under natural conditions, rates of natural soil formation and of soil erosion from land are at least 10 times lower.

The loss of fertile, nutrient-rich soil reduces the productive capacity of cropland and causes lower harvest yields. This is a major problem for poor rural populations living on marginal land with low soil quality and steep topography since their farms are their primary source of food and sustenance. As productivity of agricultural fields is reduced, farmers are compelled to apply fertilizers to maintain yields (Lal, 2009), which increases their cost of food production. Eventually, when enough productive soil is lost, the land is not worth using, and is abandoned. As mentioned earlier about 3 million hectares of cropland worldwide—slightly smaller than the area of Switzerland—are abandoned annually because of productivity declines due to severe land degradation (FAO, 2012).

Agricultural practices that reduce soil disturbance and ensure a continuous cover of vegetation on the land surface can reduce soil erosion. Depending on approach, these may require more human labor input or chemical herbicides, for selective weeding.

A related issue is desertification, which is the gradual degradation of drylands to become unfertile. Drylands occupy 41% of Earth’s land area and are home to more than 2 billion people. Drylands include all terrestrial regions where water scarcity limits the production of crops, forage, wood, and other ecosystem provisioning services (Exhibit 15). While less arid than deserts, drylands are characterized by low and erratic precipitation, high temperatures and high rates of evapotranspiration. At least 90% of dryland populations are in developing countries, and on average have lower human wellbeing and development indicators than the rest of the world. Outside of cities, many inhabitants of dryland regions are either pastoralists or agro-pastoralists. Over millennia they have developed a range of coping strategies to overcome variable rainfall and frequent droughts. Traditional drylands livelihoods represent a complex form of natural resource management, involving a continuous ecological balance between people, livestock, crops and land. Increasingly, this balance is disturbed by environmental, socio-economic and demographic factors, rendering many of these strategies insufficient (UNDP 2009).

While desertification was traditionally ascribed to overgrazing, it is now known that it is caused by many interlinked factors, including soil erosion, climate change, soil nutrient depletion and loss of vegetation cover (D’Odorico, et al., 2013). Underlying driving forces include demographic, economic,
technological, institutional, socio-cultural, and meteorological factors. Land degradation and desertification are caused by interactions between natural processes such as weather variability including droughts and floods, and human actions of unsustainable land use practices on fragile resources. External forces are also key drivers, including inadequate governance mechanisms, ineffective land tenure, and global economic forces. Locally, this leads to decreased land productivity, overexploitation, and a worsening spiral of land degradation, poverty, and food insecurity.

**Desertification vulnerability across the world**

![Desertification vulnerability map](image)

**Exhibit 15:** Dryland regions, which occupy 41% of Earth’s land area and are home to more than 2 billion people, are at particular risk of land degradation and desertification (USDA 1998).

**Climate change will alter temperature and precipitation patterns, and increase the challenges faced by smallholder farmers**

Global climate change will challenge future agricultural development and food security by altering temperature and precipitation patterns. Climate change is a long-term shift in global weather patterns, due to increased heat energy accumulated in the earth system, largely as a result of greenhouse gases emitted into the atmosphere (IPCC, 2013). **Exhibit 16** shows global average surface temperature since 1900, and projected until 2100 (IPCC WG2, 2014). Average temperature has increased by about 1°C since 1900. Temperature increase through 2100 will depend on future greenhouse gas emission trajectories. If emissions remain high (corresponding to the RCP8.5 scenario modeled by climate scientists), a global mean temperature increase of about 4°C can be expected by 2100 (relative to average 1986-2005 temperature). If emissions are greatly reduced (the RCP2.6 scenario), the average temperature is expected to increase about 1°C by 2100.
Historical and projected global average surface temperature, 1900 to 2100

Exhibit 16: Global average surface temperature is projected to increase during this century. The temperature increase will be greater if greenhouse gas emissions continue at high levels, following the RCP8.5 emission scenario. A smaller temperature increase is projected to occur if emissions are limited to the lower RCP2.6 scenario. Temperature changes are shown relative to average 1986-2005 temperature.

Over most land areas, the coldest days and nights will be warmer and fewer, and the hottest days and nights will be warmer and more frequent. At lower latitudes, especially in seasonally dry and tropical regions, crop productivity is projected to decrease with even a small rise in average temperature (IPCC WG2, 2014). At mid to high latitudes, crop productivity is projected to increase slightly with a small rise in temperature, and eventually decrease as temperatures rise further due to limited heat tolerance by crop plants. The ranges of many crop pests are expected to expand, providing additional challenges to agricultural development. Exhibit 17 summarizes numerous estimates from the peer-reviewed literature of the impact of climate trends on yield of several major crop species. Yields of wheat, rice and maize are projected to decrease by several percent per decade. Soy is more heat tolerant, and should be less affected.
Projected impact of climate change on yields of 4 food crops

Exhibit 17: Yields of wheat, rice and maize are expected to decline due to climate trends including rising temperatures. This exhibit summarizes estimates from peer-reviewed literature of the impact of recent climate trends on yields for four major crops. The boxplots indicate the median (vertical line), 25th - 75th percentiles (box), and 10th - 90th percentiles (whiskers) for estimated impacts, and n indicates the number of estimates. The studies were taken from the peer-reviewed literature and used different methods (i.e., physiological process-based crop models or statistical models), spatial scales (stations, provinces, countries, or global), and time periods (median length of 29 years). Some included positive effects of CO$_2$ fertilization trends but most did not. Values from all studies were converted to percentage yield change per decade. Each study received equal weighting as insufficient information was available to judge the uncertainties of each estimate.

Changes in the global water cycle are projected to occur as the climate warms, affecting the water supply for rain-fed and irrigated farming. Average global precipitation is projected to gradually increase in the 21st century. The global hydrological cycle will intensify generally due to global warming, and mean water vapor, evaporation and precipitation are projected to increase on global average. Changes of average precipitation in a much warmer world will not be uniform, with some regions experiencing increases, and others with decreases or little change. Precipitation is expected to increase in many wet tropical areas and at high latitudes. Many mid-latitude and subtropical arid and semiarid regions will likely experience less precipitation. Cycles for recharge of freshwater resources will change due to altered precipitation patterns, as well as reduced water storage in glaciers and snowpack. The Asian monsoon will likely increase in average total precipitation, but with greater variation year on year. Africa faces high risk from climate change, given the magnitude of existing stresses in the continent (UNDP, 2009). Significant areas of African drylands are likely to experience changing rainfall patterns in the coming decades.

Global climate change is expected to result in more frequent and intense extreme weather events. Warm spells and heat waves will very likely occur more frequently (IPCC WG2, 2014). Storms such as tropical cyclones are expected to become more severe, including storm surges in coastal areas. Precipitation is more likely to come as heavy rainfall (even in regions that receive less total precipitation), leading to increased erosion, landslides and flooding. The most significant impact of extreme weather events on human development will likely be due to frequent and prolonged droughts in some regions. Many climate models project an increased likelihood of agricultural droughts in regions that are presently dry, with extended decreases in soil moisture (IPCC WG2, 2014). Farmers and pastoralists in drylands with insufficient access to drinking and irrigation water risk the loss of agricultural productivity. This will affect the livelihoods of rural people, particularly those depending on water-intensive agriculture. There is a corresponding risk of food insecurity and conflict over available water and food resources (UNDP, 2009).
KEY CHALLENGES

Human population is growing, which demands greater absolute levels of food production

Satisfying food demand for rising populations requires not just sustaining current agricultural production, but achieving continually increasing production levels. Global population is expected to rise by 32% by 2050, to about 9.6 billion people (95% confidence interval: 9.1 to 10.1 billion). Many stressors to agricultural sustainability are directly related to the amount of food produced. Conventional agricultural development strategies have necessarily focused on increasing immediate farm productivity (measured, say, as the number of tons of grain that may be harvested this year from a hectare of cropland), often at the expense of longer-term sustainability.

An increasing share of crop production is used for non-food purposes

Sustainability of agriculture and the broader food system is strongly affected by how we choose to use the primary farm output. The greater affluence and personal choice that result from global human development leads to higher per capita consumption of resource-intensive foods including meats. About 40% of annual US maize production is used as feed for livestock rearing, rather than for direct human consumption (USDA 2014) (Exhibit 18). For each unit of animal biomass (meat) produced, the animals themselves consume many units of feed. Livestock rearing methods that use human food are less sustainable than food systems that use inedible plant byproducts to feed the animal biomass. An additional 40% of US maize production is used to make ethanol for use as biofuel. More maize is used in the US to make ethanol fuel than is produced in all of Africa.

Uses of US maize production since 1980

Exhibit 18: About 40% of current US maize production is used to produce ethanol, of which 97% is used as fuel. Another 40% is used to feed domesticated animals. ‘Sweeteners’ include high-fructose corn syrup, glucose and dextrose. ‘Other’ uses include cereals, starch and seeds.
Global climate change is altering the accustomed patterns of temperature and precipitation

Global climate change entails different—and more challenging—future temperature and precipitation regimes, relative to the past climate conditions in which agriculture developed. Some level of future climate change is unavoidable due to previous greenhouse gas emissions, which remain in the atmosphere for long time spans. The extent of future climate change impacts will depend on levels of current mitigation efforts and future adaptation efforts. Current greenhouse gas emission trajectories correspond closely to high emission scenarios (RCP8.5) modeled by climate scientists. Continuation of such trends can be expected to result in a global mean temperature increase of about 4°C by 2100 (Exhibit 16). Global cooperation towards greatly reducing emissions (corresponding to the RCP2.6 scenario) could result in a smaller temperature rise. Such cooperation has not been forthcoming, to date.

Sustainable forms of agriculture are more expensive than conventional agriculture

Currently, there is no economically viable mechanism—at the production scales required globally—to sustainably intensify agricultural production. Of the various forms of agriculture practiced around the world, very few are fully sustainable—even at a small scale. As discussed at the beginning of this chapter (Exhibit 1 and Table 1), even forms of agriculture that are ostensibly ‘sustainable’ (e.g., US Organic), do not fully address all the environmental stresses. Nonetheless, accepting US Organic farming as a benchmark for sustainability, the costs of replicating such agronomic practices—at more the three times current costs in sub-Saharan Africa and South Asia—will be far too prohibitive for smallholder farmers to adopt.
It is becoming increasingly clear that current models of food production—especially combined with population pressures—will exact an increasingly irreversible toll on our planet’s finite resources and fragile ecosystems. New forms for production, facilitated by a new generation of technologies, will be required. In that context, we believe there are 8 technological breakthroughs which can make a significant improvement in the sustainability of food production (7 of these have been identified in other chapters).

**Low cost, easy-to-construct rainwater storage repositories where harvested rainwater can be stored for several months without contamination**

A feasible mechanism to capture and store rainwater for several months at a time, can prevent runoff-related losses, and create shallow groundwater reserves. There is considerable research on the artificial recharging of groundwater (Government of India, 2007), but most techniques (e.g., percolation tanks) require intensive construction and technical expertise. Some type of material or structure, which can easily be laid or constructed underground to store several months’ worth of water, can serve as an easily accessible, low maintenance, and environmentally sustainable source for irrigation.

Different types of materials are currently used for capturing rainwater in developed markets, as well as in some emerging markets like India. However, the lack of infrastructure in Africa makes it difficult to transport any type of material to rural areas. Technically, it is feasible to adapt these materials (e.g., making them lighter) for the rural African context. We believe it will take 3-5 years for such a technology to become a reality, at least at a small scale.

However, it is not clear that the market will prefer such a system over simply digging for groundwater. Even with innovative and low cost technologies, capturing a meaningful volume of rainwater, which can be used by a large number of local farmers, will require constructing what will essentially be a series of shallow wells. Building this infrastructure will need a large number of trained workers. Moreover, it will require some form of financial commitment from farmers and their communities, and a large number of trained workers to build these repositories. Overall, the deployment of such a technology in Africa will be EXTREMELY CHALLENGING.

Note that in South Asia, where water scarcity is reaching critical levels, the demand for a technology like this is likely to be higher. That prospect, combined with the market density and strength of the private sector, likely means that it will be significantly more feasible in countries like India.
New methods for nitrogen fixation and producing other fertilizer components, instead of the energy-intensive and capital-intensive methods used currently

Perhaps the single most significant hurdle to the availability of affordable fertilizer for smallholder farmers in sub-Saharan Africa is that the known processes for producing usable forms of the key components of fertilizer—nitrogen, phosphorus and potassium—are extremely capital intensive, and need to be located near the sources of particular natural resources. For example, a facility for the Haber-Bosch process, the only known synthetic, scalable process for nitrogen fixation, costs hundreds of millions of dollars to build, and needs to be located near a source of natural gas. As a result, there is virtually no fertilizer produced in sub-Saharan Africa (outside of South Africa), and what little is used has to be shipped in. This means that the same fertilizer costs the African smallholder farmer considerably more than it costs a farmer in countries where the fertilizer is produced. An ideal alternative will be significantly less capital-intensive, less energy-intensive, and will not require close proximity to sources of natural gas or other extractive resources. This will enable production at a larger number of smaller and lower cost facilities that are closer to market.

However, there are significant technical challenges involved, especially in splitting nitrogen bonds. The fact that the only scientists to solve this problem in the past (Fritz Haber and Carl Bosch) won the Nobel Prize, underscores the magnitude of the challenge. The solution can be biological or electrochemical. While some emerging technologies offer promise (such as intra-cellular transplantation of nitrogen-fixing bacteria from natural host crops to other crops), a scaled solution still appears to be far away. There is limited incentive for private sector investment to address this problem, given that synthetic fertilizer is very well accepted in most of the world. Therefore, we believe it will take more than 10 years for such a technology to come to market.

Even when developed, such a technology will still face some deployment challenges, the most important being low demand from African smallholder farmers. Even if demand is created, low income farmers will need some form of financial support, possibly through micro-credit programs, so that they have the working capital to invest in fertilizer. Extension services will likely be necessary for training farmers on how to use fertilizer appropriately. Overall, deployment will be EXTREMELY CHALLENGING.
A mechanism to improve the viability and effectiveness of biological fertilizers, in particular, those made from human waste

Processes to convert biological waste—from plants, animals, and in particular humans—into fertilizer, can be much more cost effective than producing synthetic fertilizer. However, unlike many industrialized countries, most developing countries don’t create enough food waste to generate large quantities of compost, and there is an opportunity cost to farmers if animal waste is used as a source of fertilizer.

Using human waste to make fertilizer presents its own set of challenges. Collecting human waste safely for converting it to fertilizer can help tackle the spread of diarrheal diseases—mostly caused by the spread of fecal pathogens—that are one of the biggest drivers of childhood mortality. The process will require relatively low capital expenses and the waste does not have to be transported over long distances if a large number of smaller facilities are built. Safe collection and processing, however, is crucial. While safe collection remains challenging in resource-constrained settings with a weak sanitation infrastructure, the methods currently employed to process human waste are slow too. It can take weeks or months for the pathogens to be destroyed and the waste to be fully composted. There is a high risk that before the composting process completes the pathogens leach into the environment, potentially exacerbating diarrheal disease. Therefore, a new process will have to dramatically accelerate pathogen destruction.

Furthermore, it will be important to ensure that the resulting fertilizer releases nutrients in a timely manner, so that farmers can see benefits of using the product in a single season. A number of promising mechanisms have been identified to accelerate the composting rate (e.g., based on microbes, and particular types of enclosures). Considering the current trajectory, there is no reason a feasible technical solution should take longer than 2-3 years.

Some organizations are producing and selling fertilizer made from human waste, but at a small scale, and with limited technical enhancements. The challenges faced by these organizations suggest that when an improved process is developed, it will need to overcome a number of major hurdles: the sanitation infrastructure required to collect the waste, cultural acceptance of human waste as an input to food
production, low demand from smallholder farmers, the need for financing, and training on appropriate application. In addition, stringent safety regulations will be necessary to ensure that careless collection and shoddy production methods do not exacerbate diarrheal disease. Each of these can pose a significant obstacle. Collectively, they make deployment EXTREMELY CHALLENGING.

Breakthrough 3 – Difficulty of deployment

Herbicides or other affordable mechanisms to control weeds, ideally ones that are more environmentally friendly than herbicides currently on the market

Herbicides are the most widely used method of dealing with weeds in industrialized markets. However, most of them are non-specific, in that they can damage the crops, in addition to the weeds. As such, for optimum results they need to be accompanied by (conventionally or transgenically) enhanced seeds. In addition, the ability of the weeds to develop resistance to herbicides means that the enhanced seeds will need to be periodically modified to keep up with modifications in the herbicide, to maintain crop yield. Given the limited R&D capacity in Africa and South Asia to continuously generate improved seeds, and the capital-intensive nature of herbicide production, it is not surprising that few customized solutions have been developed or scaled-up.

Herbicides that specifically attack the most destructive weeds, but are harmless to the crops, can be very beneficial. It will be easier to build a large number of smaller factories if such herbicides are made with non-synthetic (ideally from natural local sources) ingredients that do not require a capital-intensive production facility, thereby easing a major barrier to supply and distribution. Synthesizing such an herbicide will require significant R&D, and will likely take 10 years (or more) to be market ready.

Once such an herbicide becomes available, it will have to overcome limited demand, need for farmer financing, a highly fragmented market, and a very sparse distribution network. The difficulty of deployment will be EXTREMELY CHALLENGING.
Breakthrough 4 – Difficulty of deployment

 phá 4 – Khó khăn trong triển khai

### Breakthrough 5

Novel, low cost, environmentally friendly pesticide(s), specifically targeting the most destructive insects

Borers and other insects constitute the 2nd most significant biotic cause of on-farm losses. Due to weak agricultural extension services, especially across Africa, it has proven extremely difficult to train smallholder farmers in optimal agronomic practices for integrated pest control. A few farmers have access to general pesticides, but these tend to be harmful to the health of the farmers, as well as for the environment. Transgenic modifications to make crops repel pests (e.g., through the Bacillus thuringiensis bacterium, or Bt) have many complicated externalities. Introducing them into any environment without the necessary infrastructure to study and manage these externalities can be a very risky proposition.

As in the case with weed control, a new type of pesticide, specific to the most destructive pests and ideally made from locally (or regionally) available non-synthetic ingredients, can help catalyze the development of a large number of less capital-intensive production facilities closer to the market. Also, as in the case with the novel herbicide recommended earlier, such a pesticide will require significant R&D; a major undertaking that may take more than 10 years before it becomes a reality. It will also face many of the same challenges as a novel herbicide: low demand, need for financing, market fragmentation, and the absence of reliable distribution networks. We expect that the difficulty of deployment will similarly be EXTREMELY CHALLENGING.
A scalable low cost method to desalinate water using renewable energy

Desalination is the process of making potable water from saline water sources (sea water or brackish water). The mineral/salt content of water is typically measured in milligrams of total dissolved solids (TDS) per liter of water. The salinity of ocean water averages 35,000 mg/L globally, varying from about 32,000 to 38,000 mg/L. Water is considered potable when it contains TDS less than 500 to 1000 mg/L. The vast majority, about 97.5%, of the earth’s water is seawater. Of the remaining 2.5% fresh water, 70% is frozen in polar ice and snow, and the rest is mostly groundwater (MEA, 2005). A breakthrough technology for scalable desalination using renewable energy would allow greater access to the huge resource of ocean water.

Desalination is currently used in select regions of the world. There are more than 7500 desalination facilities worldwide, over half of which are located in the Middle East (Shatat & Riffat, 2012). Virtually all are powered by fossil fuels, and are often integrated with, and use waste heat from, electricity generating stations.

There are currently two main types of desalination processes: thermal and membrane. Thermal desalination involves evaporating and condensing water, as in distillation. Various thermal processes operate at different temperatures and pressures, including the dominant multi-stage flash process, and the multi-effects distillation process (Shatat & Riffat, 2012). In recent decades, membrane technologies have matured and most new desalination installations use membranes. Of these, the reverse osmosis (RO) process is the most common, and uses a semi-permeable membrane through which pressurized saline water is forced. Other membrane processes include electrodialysis and membrane distillation. A major difference between the various processes is the source of energy that drives desalination; heat, pressure, and electricity are used in different processes. The cost of the energy supply strongly affects the cost of desalination. The cost of the various processes also varies, and is heavily dependent on scale. Larger facilities are far less expensive per cubic meter of fresh water (Exhibit 18).
Exhibit 19: The cost of current desalination processes ($ per m³ of fresh water) varies depending on the technology used and the scale of the process. The cost of energy inputs is also a significant variable. Conventional desalination technologies are too expensive and energy intensive to scale sufficiently to provide fresh water for significant global human development (Shatat & Riffat 2012).

As an illustration of desalination costs, let’s consider the 68 million km³ of non-renewable groundwater used for irrigation by Indian farmers each year (Exhibit 13; contribution of non-renewable groundwater to irrigation water demand). If this water were produced from sea water using the least expensive process (large-scale reverse osmosis), it would cost $30 billion per year, equivalent to about 1.5% of India’s GDP. Furthermore, based on the energy intensity of current RO processes (about 2 kWh of electricity per cubic meter of fresh water (Fritzmann, et al., 2007)), producing this amount of water would use 140 terawatt-hours (TWh) of electricity, or about 12% of total annual electricity generation in India (IEA, 2014). Conventional desalination technologies are clearly too expensive and too energy intensive to provide significant amounts of water, in order to contribute to global human development. For desalination to play a lasting role in human welfare, processes will have to be powered by renewable energy sources instead of fossil fuels. A breakthrough technology allowing low cost water desalination using renewable energy could mitigate future problems of groundwater salinization (e.g. due to over-extraction or sea level rise) as well as expand freshwater resources to cater for growing water demands.
Substantial research and development work is required, and we expect that it will take 5-10 years for this breakthrough to be ready. Deployment challenges include access to finance, and policies regarding location and discharge streams. We rate the difficulty of deployment, COMPLEX.

**Breakthrough 6 – Difficulty of deployment**

![Difficulty of deployment chart](chart)

- **Simple**
  - Policies
  - Infrastructure
  - Human capital
  - Access to user finance
  - Behavior change
- **Feasible**
  - Existing demand
  - Market fragmentation/Distribution channels
  - Business model innovation
- **Complex**
  - Regulated market with supportive policies
  - Requires some improvements to existing infrastructure
  - Moderate need to train a limited number of people
  - Minimal behavior change required
  - Fairly concentrated market and/or well defined channels
- **Challenging**
  - Significant financing required, limited mechanisms available
  - Strong existing demand
  - Deployment model(s) being tested
- **Extremely Challenging**
  - Requires some improvements to existing infrastructure

**A low cost system for precision application of agricultural inputs, ideally combining water and fertilizers**

The lessons from the Green Revolution in Asia, also discussed in other sections of this study, show that a few decades of overuse can devastate groundwater reserves for the long term. The additional stress of climate change and the consequent change in rainfall patterns increases the need for efficient use of water.

As discussed in other sections of this report, fertilizer overuse is a major problem, with overall efficiency of about 50% for nitrogen, less than 10% for phosphorus, and about 40% for potassium (Baligar, Fageria, & He, 2001). The rest of the applied fertilizer is unavailable to the plants and is wasted as runoff. The mismatched timing between availability of nitrogen and crop need for nitrogen is likely the single greatest contributor to excess nitrogen loss in annual cropping systems (Robertson & Vitousek, 2009). Ideally, nutrients should be applied in multiple small doses when plant demand for them is greatest. A low cost, robust, scalable technology is needed to precisely meter and distribute plant water and nutrients, based on soil and plant type.

In principle, variations of existing programmable irrigation systems used in industrialized countries can be downscaled and adapted to the needs of smallholder farmers. Already, small scale drip and sprinkler systems—along with other methods for increasing water usage efficiency—are beginning to emerge in markets like India. Their costs will continue to drop through the use of less expensive material, and manufacturing moving to lower cost geographies. With some attention, such technologies can be developed in 5 years.
However, there is limited evidence to suggest that users—farmers or otherwise—will be interested in spending money on technologies to conserve water, when the resource itself is available free of cost. The potential for saving fertilizer can prove to be a positive incentive, although the current demand for fertilizers is also very low. That, combined with the all the other structural barriers surrounding the African smallholder farmer market—fragmentation and the absence of an ecosystem for distribution and maintenance—means deployment will be CHALLENGING.

**Breakthrough 7 – Difficulty of deployment**

Objectives:
- Policies
- Infrastructure
- Human capital
- Access to user finance
- Behavior change
- Existing demand
- Market fragmentation/Distribution channels
- Business model innovation

**New seed varieties that are tolerant to drought, heat, and other emerging environmental stresses**

The global water crisis is continuing to worsen, and this has clear implications for food security. While this will likely have a significant impact in South Asia, parts of the Sahel, and the Horn of Africa, it most likely will not have as much of an effect on shallow renewable groundwater sources through most of sub-Saharan Africa. In most of Africa, the benefits of developing technologies for irrigation will far outweigh benefits from drought-tolerant seeds. This is because affordable irrigation systems can be used for a wide variety of crops to increase food production as well as farmer incomes. On the other hand, an improved seed variety—even assuming it works well and avoids the many potential unintended consequences associated with GMOs—will impact only one crop. There is unlikely to be enough R&D investment to produce drought-tolerant seeds for all the major crops in Africa, and certainly not enough to keep producing them on an ongoing basis, for the other stresses faced by the crops. It may, however, be more appropriate for South Asia. Drought-tolerant GMO varieties already exist for crops like maize in Africa, and it is reasonable to believe that they can be developed for other staple crops within 2-3 years (assuming there is interest and funding). However, they are facing significant barriers with respect to adoption by farmers and governments alike, which makes deployment EXTREMELY CHALLENGING.
Breakthrough 8 – Difficulty of deployment

- **Policies**: Feasible, requires moderate improvements to infrastructure.
- **Infrastructure**: Simple, highly regulated and controversial changes required.
- **Human capital**: Complex, requires national-scale training programs.
- **Access to user finance**: Feasible, moderate financing needed, viable mechanisms identified.
- **Behavior change**: Complex, significant behavior change needed on daily basis, changes contrary to cultural norms.
- **Existing demand**: Simple, low demand, needs to be built.
- **Market fragmentation/Distribution channels**: Challenging, highly fragmented, challenging to reach customers.
- **Business model innovation**: Extremely challenging, no identified deployment model, major hurdles identified.
GMOs: A PERSPECTIVE ON THEIR ROLE IN SMALLHOLDER AGRICULTURE

The question of genetically modified organisms (GMOs) represents one of the most controversial issues in agriculture and agricultural development (Gilbert, 2013). Each year, new articles are published in support of GMOs, and seemingly just as many opposing their use. Some recent meta-analyses have found them to be largely beneficial to farmers (Klumper & Qaim, 2014), while others have found evidence to the contrary (IAASTD, 2009). As our study contends with the role of breakthrough technologies in food security and agricultural development, the GMO question looms large.

While these controversies have not prevented GMOs from becoming a part of the mainstream food systems in industrialized countries like the US—with significant contributions to yield increases—serious concerns remain about their role in developing countries. The main concerns, many of which are equally relevant for industrialized countries, are:

► Unintended long-term effects on different life forms in the ecosystem, even if the seeds are used as intended.
► Economic burden on low income farmers who may come to depend on expensive GMO seeds which have to be renewed regularly.
► Impacts on the quality of seeds for farmers whose non-GMO seeds are accidentally cross-pollinated with GMO seeds used in the vicinity.
► The opportunity cost of investing development funds in creation of one-off GMOs, compared to more systemic investments in strengthening agricultural ecosystems.

On the basis of the aforementioned concerns, as well our analysis into the types of technological breakthroughs required to truly move the needle on food security and agriculture, we believe that GMOs are generally not appropriate for smallholder farmers in sub-Saharan Africa and South Asia (with the potential exception of the need to cope with the sudden, dramatic and long-lasting effects of climate change and water scarcity). However, before analyzing the issues, a look at the specific techniques under question may be helpful.

There are 4 techniques used for genetic modification of crops

Conventional cross-breeding
Seed genetics have been modified through cross-breeding since the earliest days of agriculture. After harvesting a crop, farmers would save and sow the seeds from plants with desired characteristics, and used the rest as food. This technique was formalized by Gregor Mendel—the ‘father of modern genetics’—in the mid-1800s. In this approach, the primary cultivar is bred with another variety of the same crop (i.e., a relative), but one that has some desirable traits. The first generation of the breeding will likely result in a new variety with some undesirable traits from the relative, as well as a loss of some desirable traits from the primary cultivar. The first generation variety is then bred with the primary cultivar to produce a variety that is closer to the target variety. This process of breeding each new variety with the original cultivar, is continued until the target variety is achieved. This type of conventional breeding was used to develop the seed varieties that launched the Green Revolution, and is currently used in a broad range of contexts to strengthen seeds. It is uncontroversial. However, the main disadvantage of this process is that the improvements are limited to ‘best of’ among the varieties of the same family of crops; if no known variety of the crop has the desired trait, it will not be possible to incorporate that trait into the crop.

Transgenic modification
The phrase ‘GMO’, in common parlance, typically refers to transgenic modification. Introduced in the 1990s, this process involves the insertion of genetic material from unrelated organisms—which cannot be crossed by natural means—into the genes of target crops. One well-known example of transgenic modification in the developing country context is Bt-Cotton, developed for use in India and China to combat bollworms, a particularly destructive pest. In this process, a portion of the gene of the Bacillus thuringiensis (Bt) bacterium is inserted into the gene of locally grown cotton. The results in countries like India and China appear to be mixed, compared with results from similar enhancements in
industrialized markets. In China, for example, cultivation of Bt-enhanced cotton appears to have led to a resurgence of secondary pests (Wang, Just, & Pimstrup-Andersen, 2008), largely eroding initial benefits from the enhanced seeds. In Kenya, trials of Bt-enhanced maize have shown diminishing economic returns for smallholder farmers after the third year of planting enhanced seeds (Gouse, Pray, Schimmelpfennig, & Kirsten, 2006). These studies highlight the main concerns about transgenic modification. First, unforeseen disruptions of the ecological system, especially from second-order and third-order changes that are not immediately perceptible, and occur only over time; second, economic losses for the farmers beyond any initial gains that they may achieve. As a result, GMOs are facing considerable policy hurdles, with the majority of African countries placing significant controls or outright bans.

Cisgenic modification
Cisgenic modification involves the insertion of genetic material from crops of the same broader species (i.e., a relative) into the primary cultivar. Because the relative can, in principle, be cross-bred with the primary cultivar crop using conventional methods, many consider cisgenic modification to be less controversial than transgenic modification, while offering the benefit of rapid and targeted improvements (Prasad, B.Raju, & Kumar, 2013) (Schouten, 2008) (Holme, Wendt, & Holm, 2013). In fact, the European Food Safety Authority recently concluded that the risks of cigenesis are similar to those associated with conventional breeding rather than with transgenesis (EFSA, 2012).

Intragenic modification
Intragenesis involves in vitro rearrangement of the genetic structure of the cultivar. While this technique also restricts modifications to the same gene pool available for conventional breeding, a recent European Food Safety Authority found that the risks associated are similar to those with transgenesis (EFSA, 2012). However, a number of studies suggest that intragenesis will be treated more like cross-breeding than like transgenesis, by the public as well as by regulatory agencies (Holme, Wendt, & Holm, 2013).

The role of transgenesis in smallholder agriculture

Transgenesis is the controversial form of genetic modification. The following discussion focuses on the role of transgenesis in the context of low income smallholder farmers. There are 5 specific types of enhancements for which transgenesis is used in the context of agricultural development in low income countries:

- Increasing the nutritional content of cereal crops, as in the case of golden rice (rice enriched with beta carotene, a precursor of vitamin A) (IRRI, 2014).
- Increasing resistance to pests (as in the case of Bt-cotton and Bt-maize, discussed above).
- Improving tolerance to drought and heat (CIMMYT, 2014).
- Increasing resistance to herbicides used to exterminate weeds (Rodenburg & Demont, 2009).
- General strengthening of the seeds to increase yields, independent of individual stresses.

We conclude that each of these interventions, while advancing solutions to individual problems, fail to consider broader systemic issues. We consider the following examples.

Fortification with nutrients
Vitamin A is one of the key micronutrients missing from the diets of many millions of low income individuals in South/ Southeast Asia, sub-Saharan Africa and Latin America. Transgenically enhanced golden rice offers the possibility of addressing that deficiency without the need for food sources that naturally contain vitamin A (e.g., carrots, green vegetables). The problem, however, is that there are several other nutrients which these populations also lack—iron, iodine, zinc and folic acid. Without also providing these micronutrients, the broader problem of malnutrition will not be addressed. Currently, it is unlikely that cereal crops can be implanted with more than a single nutrient through genetic
modification. Given that it has taken almost 30 years and tens of millions of dollars (Dawe & Unnevehr, 2007), to achieve progress on a single nutrient (with still many lingering doubts about whether it will accepted by governments, farmers and consumers), we do not believe the opportunity cost is justified. Broad-based interventions aimed at improving access to multiple nutrients (e.g., improving access to irrigation so that nutrient-rich vegetables can be grown year-round, or providing food supplements that are consistent with existing dietary practices) are likely to have greater impact on the nutritional wellbeing of populations, than transgenic implants of individual nutrients.

Drought tolerance
As discussed in the sections on Water and Irrigation, most of sub-Saharan Africa is facing economic water scarcity rather than physical scarcity (i.e., there appears to sufficient shallow renewable groundwater which can be accessed for irrigation). In such areas, we believe there are many more benefits to be gained from sustainable solutions to irrigation, rather than the introduction of transgenic crops. This is particularly true considering that irrigation solutions will impact multiple crops, whereas transgenic varieties will likely be available only for a small number of crops. In addition, irrigation solutions will help the cultivation of high-nutrient crops like vegetables, which can also lead to higher farmer incomes. It is important to note that providing access to irrigation has proven very difficult. Still, we believe the proliferation of off-grid electricity and affordable pumps will lead to increased use of irrigation. That said, in parts of the world (e.g., South Asia) that are now facing dramatic, seemingly permanent water shortages due to climate change, population growth and water overuse, transgenic modifications may be required (if improvements are not possible through other means).

Tolerance to specific herbicides or pests
One of the documented risks with modifications of seeds against particular pests, is the possibility of unintended second-order consequences (e.g., the proliferation of secondary pests when the seed is modified to deter primary pests, as well as the damage to biodiversity). If such modifications are deployed without a full understanding of their effect on the various forms of life in the ecosystem, the results could be severely damaging to the environment. The rich and complex ecosystems in tropical countries make it extremely difficult to analyze all the direct, second-order, and subsequent impacts with sufficient rigor. In the event that an unexpected effect is discovered after deployment of a first-generation GMO seed, it may become necessary to ‘recall’ all deployed first-generation seeds and replace them with a second-generation seed, which addresses the problem. In a mature market in which farmers have strong linkages to seed producers and distributors, such a response mechanism is feasible. However, in markets like sub-Saharan Africa, where the population is very sparse and smallholder farmers have very poor access to markets, such a response will not be feasible. Hence, any unforeseen negative effects will have significantly worse consequences in sub-Saharan Africa and similarly sparse markets.

General seed-strengthening for increasing yield
In industrialized countries, all other the avenues for increasing yields had already been exploited before market pressures led to the demand for additional measures like GMOs. In developing regions of the world, there are still many lower cost, lower risk mechanisms that can be implemented to increase yields (e.g., small-scale tilling to remove weeds instead of using herbicides combined with herbicide-resistant GMO seeds, as well as the other examples described above). The yield gains of the Green Revolution in Asia and Latin America were achieved without GMOs (although, in hindsight, a number of the practices were very damaging to the environment). With the benefit of this hindsight, it should be possible to improve yields in sub-Saharan Africa (as well as the parts of South Asia not impacted by the Green Revolution) through more sustainable intensification without relying on GMOs.

Given current technology, seeds implanted with multiple desirable traits, posing minimal environmental risks, and sustainably affordable to smallholder farmers, are far from being a reality. Presently, only individual traits can be implanted, and those too appear to pose too many long-term risks and opportunity costs. We believe, therefore, that smallholder agriculture will benefit much more from foundational and systemic improvements such as access to electricity, on-farm implements, extension services, and local processing facilities rather than using GMOs.
Human rights typically refer to a set of legal entitlements accorded by states that have signed and ratified specific international laws and protocols, usually translated into domestic legislation. They include civil and political rights, economic, social and cultural rights, protections for specific vulnerable populations, and restrictions of particular actions or weaponry in the context of conflict.

Adoption of the Universal Declaration of Human Rights and subsequent international legal instruments, have led to a marked improvement in the protection of human rights around the world. Still, universal respect for human rights is far from being a reality. Severe violations of the rights of individuals and communities are common at the hands of state or non-state actors. Interventions aimed at either preventing the abuse of human rights or ensuring ex-post accountability for perpetrators, tend to diminish in scope and effect especially when faced by the systemic absence of rule of law, real or perceived impunity, the lack of rapid-response preventative mechanisms, and the difficulty of collecting adequate evidence for prosecution.

In recent years, new information and communication tools—particularly digital photography and social media platforms—have played a very important role in increasing transparency and collecting and collating all types of evidence. Our analysis concludes that more progress can be achieved with the help of 3 technological breakthroughs.

- Low cost (under $50) wearable, or otherwise easily concealable, cameras with automatic geocoding and timestamps, capable of ‘SOS’ data preservation (e.g., via satellite)

- Low cost (under US$25,000) aerial vehicles—satellites or unmanned aerial vehicles—to capture high resolution imagery

- A simple point-of-use, low cost DNA-based rape kit capable of delivering rapid results
Human rights, as a standardized, broad, international construct, were developed formally after the Second World War. The Universal Declaration of Human Rights—embracing the notion that “All human beings are born free and equal in dignity and rights”—was adopted by the United Nations General Assembly in December 1948. The declaration, even today, remains the foundation of international human rights law.

CORE FACTS AND ANALYSIS

Since coming into effect, the Universal Declaration of Human Rights has inspired a multitude of instruments (over 80 declarations, treaties, covenants, conventions and bills), with various degrees of enforceability under national or international law. Some of the constructs within these instruments still remain aspirational. Table 1 summarizes the chief instruments that embody the broad set of human rights as codified into various legal instruments (Weissbrodt & de la Vega, 2007).

- The International Bill of Human Rights which is comprised of the Universal Declaration of Human Rights, the International Covenant on Civil and Political Rights, and the International Covenant on Economic, Social and Cultural Rights.

- Six core treaties which specify protections for specific vulnerable populations like children, migrants, the disabled, and the Convention Against Torture.

- A range of Humanitarian Laws governing the conduct of armed conflict including the Geneva and Hague Conventions.

- A number of topic-specific treaties, such as the ban on landmines and cluster bombs, and the Rome Statute, which created the International Criminal Court (ICC) to prosecute war crimes, crimes against humanity and genocide.
A summary of key human rights instruments

| International Bill of Human Rights | 1. Universal Declaration of Human Rights: equality, liberty, fair trial, privacy, nationality, marriage, religion, employment, clothing, medical care, free/compulsory elementary education, etc.  
2. Convention on Elimination of [...] Discrimination Against Women  
3. UN Convention Against Torture  
5. Convention on the Rights of Persons with Disabilities  
6. International Convention on the Protection of the Rights of all Migrant Workers and Members of their Families |
| Humanitarian Law (governing conflict) | 1. Geneva Conventions (on conduct of war)  
   - Four conventions (treatment of wounded & sick, prisoners of war, protection of civilians)  
   - Two amendment protocols (protection of victims of international armed conflict, non-international armed conflict and adoption of additional distinctive emblem (for medical services)  
2. Hague Conventions (prohibition of chemical & biological weapons, etc.) |
| Other topic-specific treaties | 1. Mine Ban Treaty  
2. Convention on Cluster Munitions  
3. Rome Statue of the International Criminal Court (for genocide, war crimes, crimes against humanity) |

**Table 1**: Human rights instruments can be roughly grouped into 4 categories. First, the International Bill of Human Rights which lays the foundation for a broad set of instruments. Second, 6 core treaties specific to the rights for various vulnerable groups (e.g., children, women, migrants). Third, international humanitarian laws governing the rights of combatants and non-combatants in armed conflict. Fourth, a number of topic-specific treaties, like the treaty against landmines.

Human rights violations involve a wide range of perpetrators and victims

Despite the formal presence of various human rights instruments, rights—of individuals or specific groups of individuals—are routinely violated by a wide range of actors, from representatives of the state like the military and law enforcement agencies, to non-state actors such as armed groups, corporations, citizenry, and organized crime groups. **Table 2** illustrates a typology of typical violations.
Typology of human rights violations

<table>
<thead>
<tr>
<th>PERPETRATORS</th>
<th>TYPICAL VICTIMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Workers</td>
</tr>
<tr>
<td>Military, Paramilitary &amp; non-state armed groups</td>
<td>Forced labor</td>
</tr>
<tr>
<td>Law enforcement agencies</td>
<td>Forced labor</td>
</tr>
<tr>
<td>Businesses</td>
<td>• Exploitative conditions or wages • Child labor</td>
</tr>
<tr>
<td>Citizenry</td>
<td>Abuse of domestic workers</td>
</tr>
<tr>
<td>Organized crime</td>
<td>Human trafficking</td>
</tr>
</tbody>
</table>

Table 2: Human rights violations can be committed by a range of perpetrators, against different types of victims. This is an indicative typology of what types of violations may occur at the hands of different types of perpetrators.

Military or paramilitary forces, and non-state armed groups

Armed groups—state or non-state—are often accused of using excessive force and violence on civilian populations, extra-judicial executions, and sexual violence in conflict settings. For example, after a pro-independence referendum in 1999, East Timor (occupied by Indonesia since 1975) was allegedly attacked by pro-Indonesia militia who killed over 1,400 civilians and displaced 90% of the population. Beginning the mid-nineties, the Democratic Republic of Congo witnessed heavy conflict involving state militia and rebel groups, with thousands of casualties and reports of widespread sexual violence (Human Rights Watch, 1999). In Colombia, both the FARC rebels and right-wing paramilitaries have been accused of large-scale violence and killings (Human Rights Watch, 2013). Similarly, armed forces representing Israel have been accused of causing excessive civilian casualties in Lebanon in 2006 (Human Rights Watch, 2007), as have Indian armed forces in Kashmir since the 1990s (Amnesty International, 1995). In many conflicts, rape has been used as a weapon of war (UN Human Rights, 2014).

¹The conflict involved the militaries of Congo, Rwanda, Uganda, Zimbabwe, and Namibia. Rebel groups include Rassemblement Congolais pour la Democratie, Movement for the Liberation of Congo, National Congress for the Defence of the People.
Law enforcement actors
Representatives of the police, judiciary, and other law enforcement agencies can commit violations against citizens through arbitrary detention, torture, denial of justice, and extrajudicial killings. Prominent examples of police brutality include the long-standing record of the Egyptian police, which eventually led to the 2011 popular uprisings (The Economist, 2013), and the Georgian police, where a majority of the force was fired after reforms were enacted in wake of the 2003 Rose Revolution (World Bank, 2012). Such allegations are not restricted to developing countries. The US, the UK and other OECD countries have been accused by several human rights groups of gross violations through acts of extraordinary rendition, and indefinite detention in prisons like the one in Guantanamo Bay, in the aftermath of 9/11 (Human Rights Watch, 2014).

Private businesses
Large international and national corporations are regularly accused of exploiting workers, subjecting them to hazardous working conditions, forced displacement of local populations, environmental pollution, and use of child labor. Prominent examples of allegations include the forced displacement of the Ogoni people (as well as complicity in the execution of Ken Saro-Wiwa, the noted human rights activist) by the Shell oil company in Nigeria in collusion with the Nigerian military regime (New York Times, 2009), heavy pollution of the rainforest in Ecuador by Chevron (New York Times, 2014), and use of ‘sweatshop’ labor by textiles, fashion and apparel (TFA) companies such as Nike, Reebok, Adidas, Gap and Disney (Harrison & Scorse, 2010). Such violations can be committed by multinational companies, their local suppliers (including sub-contractors), private security firms they hire, or other value chain partners. Four industries—extractives, retail & consumer goods, pharmaceuticals & chemicals, and infrastructure & utilities—account for the vast majority of documented violations by businesses (Wright, 2008).

Citizenry
Members of the citizenry can commit violations against their fellow citizens for a number of reasons. Traditional practices in many cultures around the world often discriminate against women and girls, through practices like child marriage, dowry-related abuse, female genital mutilation, and even ‘honor killings’ (WHO, 2013) (Human Rights Watch, 2014). In ethnically-driven or religious conflicts communities can turn on each other, as seen in the Rwandan genocide in 1994 (UN Human Rights Council, 2014), the wars in the former Yugoslavia from 1992-95 (International Criminal Tribunal for the former Yugoslavia, 2014), and the 2002 riots in Gujarat, India (Jaffrelot, 2003).

Organized crime groups
Groups such as the Juarez drug cartel in Mexico (Congressional Research Service, 2007), and the many gangs arising from the breakdown of law and order in Russia (Stoecker, 2000) have reportedly been responsible for widespread trafficking of illicit drugs, humans and weapons, and terrorizing populations. Gangs cause an estimated two-thirds of violent deaths worldwide (Small Arms Survey, 2013) (Lind & Mitchell, 2013).

The only metrics for assessing any country’s human rights record are subjective

While one measure of the rights of citizens is the number and types of international instruments their government has adopted, there is often a limited correlation between a country’s formal laws and the...
reality of their enforcement. Given the intrinsic subjectivity involved in characterizing the nature and severity of human rights violations, it is very difficult to objectively measure the strength of human rights protections in a country. However, there are some indicators which attempt to quantify subjective analyses, the most well-known being the World Bank’s Governance Indicator and the Freedom Score by Freedom House.

The World Bank Governance Indicator (World Bank, 2014) uses aggregated surveys of citizens, institutions and experts to score the quality of governance of countries along 6 dimensions: voice and accountability, political stability and absence of violence, government effectiveness, regulatory quality, rule of law, and control of corruption. This index measures issues beyond human rights; at the same time, it does not fully address human rights with the necessary level of specificity. Based on this indicator, the worst-ranked countries include Uzbekistan, Equatorial Guinea, Saudi Arabia, China and Iran, and the best-ranked countries include Norway, Sweden, Denmark, Switzerland, New Zealand and Costa Rica. Senegal, India, Indonesia and Mexico are in the middle of the rankings.

On the other hand, the Freedom in the World score (Freedom House, 2014) on political and civil liberties is based on expert analysis (from academic institutions, think tanks, and human rights organizations) based on news report, academic publications, NGO reports, etc. According to Freedom House, the political rights score evaluates the “electoral process, political pluralism and participation, and functioning of government”; the civil liberties score assesses “freedom of expression and belief, associational and organizational rights, rule of law, and personal autonomy and individual rights.” Interestingly, the scores according to this assessment roughly align with the World Bank Governance Indicator rankings.

There is a strong link between a country’s level of development, and the protection of the rights of its citizens

It is important to note that human rights violations are not exclusive to low income countries. Governments, militaries and corporations from high income countries are routinely implicated in major human rights abuses, usually against citizens of lower income countries without the wherewithal or national-level regulatory protection to prevent the abuses, or find recourse. There is also ample evidence that religious and ethnic minorities even in wealthy countries suffer systematic violations of their rights (Human Rights Watch, 2014). Still, it is natural that human rights protections accorded to citizens of a country are a function of the strength of the rule of law in that country. Exhibit 1 shows the World Bank Governance Index and the Freedom House score for countries grouped into quintiles along the UN’s Human Development Index, or HDI (UNDP, 2014), a composite index combining health, economic capacity and education. According to this analysis, the lower the HDI score of a country, the worse its human rights indices tend to be.
Exhibit 1: With some notable exceptions, the human rights protections given to citizens of a country tend to be a function of the level of human development in the country. This exhibit groups countries based on their Human Development Index score, and plots the average scores or ranks according the World Bank Governance Indicator (left axis), and the Freedom House index of civil and political rights (right axis; in which a lower score indicates better protection of human rights).

Human rights interventions fall into 5 broad categories

Advocacy campaigns are aimed at changing policies or legislation at the national or international level in order to protect vulnerable groups, or for engendering formal responses to violations. They can be overtly public, or entirely behind-the-scenes and completely out of the public eye. Recent high-profile examples of advocacy campaigns include the global multilateral effort to secure bans on the use of landmines and cluster bombs (UN, 1997) (UNODA, 2014), the ‘Bring back our girls’ social media campaign to urge the Nigerian government to rescue the more than 270 schoolgirls kidnapped by the Boko Haram militia group (The New York times, 2014), as well as the campaign to legalize same-sex marriage in the US (Becker, 2014).

Name-and-shame campaigns are the most common type of human rights intervention, involving public embarrassment of alleged violators, or actors who can influence them but seemingly are turning a blind eye, with the intention of provoking corrective action. These typically take the form of accusatory reports in popular or influential media, public protests, email chains or online petitions to their customers or constituents, or other forms of media campaigns to the same effect. One of the earliest and best known examples of name-and-shame campaigns is the one that led to the widespread boycott of Nestlé’s food products because of the company’s aggressive push for its breast milk substitutes in low
in income countries—and the alleged link to death and disease among affected babies (Muller, 1974). Arguably, name-and-shame campaigns can be considered a form of advocacy.

Criminal prosecution is usually the preferred mechanism for ex-post accountability, from the point of view of the victims. Given the broad range of violations, it is likely that most of the prosecuted cases are handled in routine criminal courts. In some cases, special local courts or other forums are created, like the Gacaca system for the Rwandan genocide (UN Outreach Programme on the Rwanda Genocide, 2007). In cases when it appears unlikely that the accused will be tried fairly in the home country, prosecutions are conducted at the ICC, or at other special international tribunals such as the one for the former Yugoslavia (International Criminal Tribunal for the former Yugoslavia, 2014).

Civil litigation, especially against large companies, is a more recent phenomenon in which victims or their families seek financial compensation from the accused company. For example, companies like Chevron and Shell have been sued in US courts under the auspices of the Alien Tort Claims Act, for their alleged violations in Ecuador and Nigeria, respectively (The New York Times, 2014) (The New York Times, 2009).

Standardization and certification of business practices, with compliance monitoring, has contributed to improvements in corporate responsibility in recent years. Examples include fair-trade certification of food and other farm-based products (Fair Trade USA, 2012), the ‘Voluntary Principles on Security and Human Rights’ for the extractive and energy industries (developed by a coalition of governments, NGOs and corporations), and the Kimberley Process Certification Scheme to monitor extraction and flow of diamonds across international borders to control the flow of conflict diamonds. Such mechanisms, to date, have been largely voluntary, and are too recent to have a long-term impact yet.

In recent years, new communication tools and social media platforms have significantly improved transparency

The recent proliferation of technologies like camera-enabled mobile phones and social content sharing platforms have dramatically increased the ability of affected communities to document and disseminate information about and evidence of violations, as well as create global awareness of events and issues that may have otherwise gone largely unnoticed. One prominent example is Ushahidi from Kenya (MIT, 2014), a crowd-sourced, SMS-based reporting tool which tracked incidents of violence in the aftermath of the 2007 elections in the country. Since then, it has been used in South Africa, Haiti, The Democratic Republic of Congo, and Gaza. Similarly, platforms like Twitter and Facebook are widely credited with having enabled the popular uprisings that together comprised the ‘Arab Spring’ (Howard, et al., 2011). Other examples include CGnet Swara, a mobile enabled network, which has helped tribal communities in India document police violence (International Center for Journalists, 2012), and HarassMap, a platform for crowd-sourcing and documenting cases of sexual harassment and abuse in Egypt (M. Chalabi, 2013).

In addition to increasing transparency, such technologies have had a disintermediating effect; vulnerable communities and groups can now make their voices heard globally, without relying on international NGOs or formal media channels as much as they did even at the turn of the century. The broader manifestations and benefits of information and communications (ICT) tools are discussed in the section on Digital Inclusion.

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3 Note that only citizens of countries which have adopted the Rome Statute of the International Criminal Court, can be prosecuted at the ICC. The US, Israel, China, India and number of other countries have not adopted the statute. In addition, recent controversies have led to the African Union, as a whole, opposing the ICC’s policies (Hickey 2013).
KEY CHALLENGES

Human rights violations occur, remain overlooked, or go unpunished for a host of reasons. Perhaps the most demoralizing and daunting of these is the willingness of people and communities to accept—and even inflict—abuse on individuals and communities who they perceive as ‘different’ from them. There are a number of challenges that prevent universal protection of human rights from being a reality.

Lower income countries tend to have weaker legal frameworks and enforcement mechanisms

As suggested in Exhibit 1, lower income countries tend have weaker laws and policy frameworks to protect and promote human rights. In some cases, the laws are deliberately exclusionary, or even outright discriminatory. Even if appropriate laws are on the books, many lower income countries lack the law enforcement and judicial capacity to enforce them. Corruption and a lack of incentives exacerbate capacity gaps, and cultural practices—especially when it comes to women and minorities—make matters worse. Recent examples include the spate of anti-gay laws in a number of African countries (Amnesty International, 2014) and in Russia (Amnesty International, 2014), the new polygamy law in Kenya (Africa Review, 2014), anti-blasphemy laws in Islamic countries like Pakistan (Chowdhry, 2013), and the Armed Forces Special Powers Act in India, which has been used to impose long-term military or paramilitary presence in areas with religious, ethnic and separatist conflicts (Asian Human Rights Commission, 2014).

Perpetrators in positions of power often feel real or perceived impunity

When laws or enforcement mechanisms are weak, individuals and corporations in positions of power feel a certain degree of immunity from prosecution. The same can apply to countries with powerful militaries and political alliances: the many American invasions of weaker countries (Human Rights Watch, 2006), Israel’s actions in Lebanon and the Occupied Palestinian Territories (Human Rights Watch, 2014), and Russia’s interventions in Georgia and Ukraine (Human Rights Watch, 2014), have all been documented by human rights organizations as examples of such aggression.

During ongoing conflicts, there are few early-warning signs that can alert appropriate authorities about imminent atrocities; even when there is adequate early warning, effective rapid-response preventive mechanisms are difficult

In the past three decades, there have been several major human rights atrocities against people ostensibly under the protection of UN Peacekeepers or other forces. In the case of the Rwandan Genocide of 1994, there is now clear evidence that the UN peacekeepers knew about the imminent threat to the Tutsi community. According to most accounts, however, the genocide went on partly because of political paralysis among institutions in a position to intervene (Dallaire, 2003). Similarly, the UN Protection Force for the former Yugoslavia (UNPROFOR) was seemingly aware of the impending massacre of civilians in Srebrenica in 1995, but for reasons similar to those in Rwanda, did not prevent the incident (Human Rights Watch, 1995). In the 2010 mass rapes in Luvungi in the Eastern Congo, on the other hand, there are conflicting reports on how much the local UN Peacekeeping troops knew about the imminent threat of large scale sexual violence (Heaton, 2013). In the Darfur genocide that began in 2003, many atrocities—especially during the early years—occurred when there was no legitimate protection force around. A UN Peacekeeping mission (UNAMID) was not authorized and deployed until 2007; even since then, UNAMID has been limited in its ability to fully prevent atrocities in Darfur (UN Security Council, 2014).
Often, there is lack of verifiable evidence to prosecute perpetrators

Timely, credible evidence is a prerequisite for holding violators legally accountable. Evidence can come in various forms: victim or witness accounts, photographs, video, aerial imagery, and biological or chemical residue. Obtaining and preserving verifiable evidence is, however, challenging.

Digital cameras, while increasingly ubiquitous, can be confiscated by violators and critical data destroyed. The proliferation of phone-based digital cameras has led to a dramatic increase in the ability of victims and witnesses to document violations, especially in conjunction with social networking tools. The obvious challenge is that perpetrators will attempt to confiscate all the cameras they can find. Even if imagery is presented in a court of law, its veracity (e.g., time and location of the photographed scenes) can be challenged. Importantly, there is no broadly available platform for preserving footage and imagery related to human rights on public or restricted archives. Mass commercial platforms can be unreliable with respect to security, validation, and digital chains-of-custody. Furthermore, the lack of reliable internet or phone network access in many conflict areas means that important data and recordings can be lost or destroyed before they can be saved or transmitted.

Aerial imagery is still expensive, and relatively low resolution. For some types of violations (e.g., large-scale destruction of entire villages, or tracking the movement of militia and vehicles, exodus of populations, mass burial sites), aerial imagery—rather than ground level photographs or video—is more useful. This can be collected via satellites, aircraft or drones. For example, satellite imagery was used to document the Sri Lankan military attack on the Tamil population in 2009, where civilians were trapped in no-fire zones. Similarly in 2010, Amnesty International’s Remote Sensing for Human Rights Program used satellite imagery to detect mass destruction of civilian housing in Kyrgyzstan (Amnesty International, 2014). The challenge is that the satellite imagery available to civilians is still of relatively low resolution and only useful for outdoor settings visible from the sky (without cloud cover). Satellites are also expensive, although low cost satellites are now being developed by some companies. While high resolution aircraft-based aerial imaging is available (e.g., through unmanned aerial vehicles, or UAVs), it is restricted to military use and very expensive for civil society to commission. Lower cost drones can only be deployed locally and for a limited amount of time, and must be flown to the point of interest from a nearby location. This makes it risky for users (Digital Globe, 2013) (Gertler, 2012) (Astrium, 2012).

Biological (DNA) evidence is still a nascent technology, especially in developing countries. Recent advances in DNA-based technologies have led to significant improvements in the ability of law enforcement agencies to conduct accurate forensic investigations. In the US, this has contributed to a number of exonerations of individuals wrongly convicted of serious crimes (The Innocence Project, 2014). The technology has also been used to develop rape kits to preserve the perpetrator’s tissue samples for prosecution. These kits, however, require a trained medical examiner, gathered evidence needs to be processed in a lab with sophisticated equipment, and the overall system is expensive—well over $100,000 per analyzer. Moreover, biological samples can disintegrate quickly or be tampered with, rendering them inadmissible in a court of law. While some preservation mechanisms exist, they may not be feasible at the location where samples are collected (RAINN, 2014) (Engadget, 2012).

As these examples show, war-related atrocities occur because there is no military protection of civilian populations, the legitimately appointed protection force does not have advance warning of an impending atrocity, or the ability of the force to intervene is frequently undermined by political or other considerations.
SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

The human rights of individuals and communities, especially those without power or voice, will only be adequately protected if attitudes about fairness and justice change, and strong institutions capable of protecting the rule of law are developed. Even as those fundamental improvements are achieved, a small number of technological breakthroughs can improve evidence collection, increase transparency, and thereby enhance the prospects for accountability.

Low cost (under $50) wearable, or otherwise easily concealable, cameras with automatic geocoding and timestamps, capable of ‘SOS’ data preservation (e.g., via satellite)

The proliferation of mobile-phone based digital cameras and cloud-based social media platforms has allowed citizens to make impromptu recordings of events of interest and post them online. This ability to instantly shoot-and-upload has led to an unprecedented level of citizen journalism and activism, and in turn, the documentation of human rights violations. While this steady march towards miniaturization of computing devices and sensors is eroding long-held notions of individual privacy, it has given an increasingly powerful tool to victims and witnesses of human rights violations to document incidents and push for accountability.

Crucially, any data stored in devices like mobile phones is dependent on phone networks and the internet for uploads or wider sharing. During emergencies and conflict situations, access to these is unreliable. Moreover, anyone with the intention of committing a violation will attempt to confiscate all phones, and any other visible recording device, before data can be shared. A particularly valuable feature for a wearable miniature camera would be the capability to preserve data (e.g., via one-time SOS satellite uplink), especially in a situation where the data may otherwise be destroyed. If such a device comes equipped with geocoding and timestamps, the imagery captured will be even more powerful with respect to legal admissibility.

Over the past 1-2 years, wearable cameras like Google Glass have begun appearing on the market. However, they are still quite conspicuous, and far too expensive (well in excess of $1,000) even for the average consumer in developed countries. Still, given the speed with which these technologies are developing, it is quite likely that inconspicuous wearable cameras will become common in high income countries within the next 3-5 years. It will likely take another 3-5 years for these devices to become affordable enough for low income populations.

Once they are available on the market at the right price point, there is reason to believe that adoption will not be difficult, especially judging by the example of mobile phone-based cameras. It is important to note, however, that much of citizen journalism today happens because people carry their mobile phones everywhere. It is not clear if consumers will find enough reason to carry a separate wearable device a routine basis, or if there will be a demand for such devices, except in higher income consumer segments (especially since mobile phones already have cameras). As such, we believe that the difficulty of deployment will be COMPLEX.
Low cost (under US$25,000) aerial vehicles—satellites or UAVs—to capture high resolution imagery

Aerial images (via satellites or UAVs) can provide crucial evidence for tracking movements of large groups of people, such as combatant units. The ideal mechanism to capture aerial imagery for protecting human rights will have the following characteristics:

- The images are of high enough resolution, to identify distinguishing features of vehicles or even individuals.
- The aerial vehicle should be deployable (in the case of UAVs) or usable (in the case of already deployed satellites) on demand, and capture images for sufficiently long periods, in diverse weather conditions and at sufficiently safe heights.
- Be affordable for human rights organizations to own, or use as a service.
- Have contingency transmission mechanisms, so that images are not lost due to disruptions in flight.

Over the past 2-3 years, low cost UAVs or drones have become increasingly available to the public. They can be deployed on-demand for capturing high resolution images, with in-flight transmission. However, the affordable drones (i.e., ones that cost less than $5,000) can only be used for relatively short periods of time (1-2 hours or less), and are vulnerable to bad weather. Also, a small number of companies (e.g., PlanetLabs) are beginning to develop low cost, low orbit satellites. However, the resolution of images captured from the altitudes they can be deployed at, is still low.

Still, these technologies are evolving rapidly, and are already being used in a wide range of applications. Therefore, there is reason to believe that an adequate combination of capabilities required for documenting human rights violations will become available within 3-5 years. Drones, in particular, will
likely be heavily regulated, and governments (and other actors) committing human rights abuses may attempt to deter their use. However, these hurdles will not be insurmountable given the difficulty of enforcing any regulatory restrictions. As such, usability and deployment is expected to increase dramatically over the next few years. The existing market, in the shape of human rights organizations and media outlets, is niche. Given these factors, we believe the difficulty of deployment is CHALLENGING.

A simple point-of-use, low cost DNA-based rape kit capable of delivering rapid results

Sexual violence occurs for a whole host of reasons, including gender discrimination, societal and interpersonal power dynamics, and impunity that comes from the lack of accountability. A major challenge is that even if a woman overcomes the stigma associated with being a victim of sexual violence and lodges a formal complaint, there is limited evidence to make a robust legal case. Rape kits—to preserve semen and other degradable biological tissue, and conduct DNA analysis on the samples to match against potential perpetrators—are becoming increasingly common in higher income countries. However, these require skilled technicians and a sophisticated, expensive laboratory to analyze the samples. To be useful in low resource or conflict settings, a rape kit would have to be very low cost (under $10 per test, with the processing equipment not more than a few hundred dollars), usable off-grid, and not require much clinical training to use. In addition, the analysis should be rapid, with the ability to digitize and transmit relevant data for secure (presumably cloud-based) storage. Similar low cost DNA-based technologies being prescribed—and developed—for medical diagnostics, seem to be 3-5 years from becoming available on the market. In principle, a DNA-based rape kit should not take more than 5 years beyond that.
However, once such a technology is developed, it will face significant challenges in deployment, along virtually every dimension. Enough facilities (e.g., health clinics) will need to have the device at hand, those administering the test will need some level of training, and financing will be necessary to cover the costs involved. Without financing it will also be very difficult to ensure a steady supply and maintenance of the kits and the processing equipment. Moreover, policy changes will be necessary to determine how the judicial systems of different countries can best use such evidence in their legal proceedings. But most importantly, the behaviors of victims and the community will still have to evolve considerably. Rape kits can be administered only if a victim seeks help immediately after the incident, while the biological evidence is still intact. In other words, deploying such a technology will be EXTREMELY CHALLENGING.

Breakthrough 3 - Difficulty of deployment

- Extremely Challenging
  - Policies: Highly regulated and controversial changes required
  - Infrastructure: Requires national-scale training programs
  - Human capital: Requires moderate improvements to infrastructure
  - Access to user finance: Significant financing required, limited mechanisms available
  - Behavior change: Significant behavior change needed on daily basis, changes contrary to cultural norms
  - Existing demand: Low demand, needs to be built
  - Market fragmentation/Distribution channels: Highly fragmented, challenging to reach customers
  - Business model innovation: No identified deployment model, major hurdles identified

- Challenging
- Complex
- Feasible
- Simple
Across the three main levels of education—primary, secondary, and tertiary—there are a number of recurring themes that reduce access to education and/or diminish the quality of education. These include, but are not limited to, low government budgets that lead to a dearth of adequately equipped schools and qualified teachers, a lack of accountability to meaningful outcomes and readiness for the job market, potential discrimination against segments of the population based on either gender or religion (e.g., in many cultures adolescent girls and women are discouraged from seeking an education), and the high opportunity cost of enrolling and staying in school for individuals of secondary school age, or older, instead of earning a living. Fundamental solutions to the problem will require systemic improvements in infrastructure, better teacher training and certification, and ensuring accountability. However, one particular technology can play a powerful role.

‘Smart’ electronic textbooks, customized for various age groups and educational levels, with curated and up-to-date content, ‘wiki’ interfaces for vernacular and other locally relevant and gender-inclusive material, visual and dynamic learning tools for students, interfaces and tools for teachers, student-teacher interaction and peer-to-peer collaboration. These smart e-textbooks can be delivered on tablet devices or on smartphones, the prices of which are steadily falling.
Education is the foundation of long-term development. A well-educated population, trained in technical topics such as the sciences, medicine, engineering and jurisprudence, is essential for advancing a country’s industries, institutions and laws, without prolonged external assistance. A workforce skilled in running businesses can serve as the engine of a strong private sector economy. A populace educated in the arts and humanities contributes to the society’s cultural wellbeing. Unfortunately, educating a country’s population takes, quite literally, a generation. Building the necessary infrastructure and systems can take even longer. As a result, it can be very difficult to design effective and sustainable education programs, and even harder to measure their long term impact. This chapter examines the design of education programs across the age continuum: primary (age 6-14 years), secondary or youth (15-19 years), and post-secondary (focused on readiness for the job market).

### Core Facts and Analysis

#### Primary Education

The target of the 2nd Millennium Development Goal (MDG) is to “Ensure that, by 2015, children everywhere, boys and girls alike, will be able to complete a full course of primary schooling” (UN, 2012). Since this declaration, primary enrollment has increased dramatically in developing countries (UNESCO Institute for Statistics, 2012), and out of the 8 MDGs, the 2nd MDG has shown the strongest progress.

Despite enrollment gains, more than 57 million children of primary school age remain out of school

As shown in Exhibit 1, primary school enrollment in sub-Saharan Africa has increased from 58% in 1999, to 78% in 2012. In South Asia it increased from 75% to 90% during the same period. Notwithstanding this seeming progress, several major challenges remain. As of 2011, more than 57 million children around the world, out of the approximately 655 million children of primary school age, remained out of school (Exhibit 2). These children are concentrated in Nigeria (8.7 million), the Democratic Republic of Congo (about 5.5 million), Pakistan (5.4 million), Philippines (1.5 million), India (1.4 million), Niger (1.2 million), Côte d’Ivoire (1.1 million), and Burkina Faso (0.9 million). In addition, a number of smaller countries have a very high prevalence of out-of-school children (OOSC); these include Eritrea (65%), Afghanistan (63%), Mali (34%), and the Central African Republic (29%). Of the total number of out-of-school children globally, 51% are expected to never enter school, 30% are...
expected to enter school in the future, and the remaining 19% were in school but have left. It is also worth noting that after very strong gains in the early part of the millennium, the reduction in the overall number of out-of-school children appears to have stalled at 57-60 million. This is likely because these out-of-school children either live in extremely remote areas that are difficult to reach, or are from very vulnerable populations and face extremely challenging hurdles in attending school.

Primary school enrollment by region

Exhibit 1: Primary school net enrollment has increased dramatically in sub-Saharan Africa and South (and West) Asia since 1999.

Out-of-school children of primary school age

Exhibit 2: Despite the increase in primary school enrollment rates, around the world over 57 million primary school age children remain out of school. Most of these children are in sub-Saharan Africa and South and West Asia.
At least 123 million enrolled primary school children receive education of subpar quality

Quality of education is difficult to measure. Not only is there limited agreement on appropriate metrics for determining quality, but most developing countries do not collect standardized data on student performance. Based on the little data that is available, both sub-Saharan Africa and South Asia have major gaps along the key drivers of education quality.

Attendance

In addition to the children who are out of school, a very large number of students in developing countries, despite being nominally enrolled, do not regularly attend school. Exhibit 3 shows that 30% of enrolled primary school students in sub-Saharan Africa and 23% in South Asia do not regularly attend school (UNICEF, 2012). Around the world, about 138 million children enrolled in primary schools do not attend regularly, mostly in the developing world.

Primary school absentee rates

Exhibit 3: According to a 2011 UNICEF study, 30% of enrolled primary school students in sub-Saharan Africa and 23% in South Asia do not attend school regularly.

Student-to-teacher ratios

The more students there are in a class, the less attention the teacher can give to each student. As Exhibit 4 shows, the average student-to-teacher ratio in sub-Saharan Africa is 44.7, and 39.1 in South Asia. In comparison, the average ratio in North America and Western Europe is 13.9 (UNESCO Institute for Statistics, 2012).
Teacher qualifications and training

Teachers’ qualifications and training determine their teaching ability, and are hence an integral contributor to overall education quality. Exhibit 5 shows findings from a UNESCO study of teacher qualifications from 100 countries (UNESCO, 2006), categorizing them according to the minimum education level required for teaching in primary schools. These qualifications are characterized in terms of the International Standard Classification of Education (ISCED) levels; ISCED 2 refers to 9 years of schooling, ISCED 3 refers to 12-13 years, ISCED 4 to 13-15 years, and ISCED 5 refers to advanced degrees. According to the survey, almost half the countries in sub-Saharan Africa require only ISCED levels 2 or 3 (i.e., a secondary-level education, or less), and only 8% require an advanced degree. In some South Asian countries, the requirements are even less stringent. Despite the less stringent requirements in these regions, only 63% of primary school teachers in South Asia, and 75% in sub-Saharan Africa, meet the basic required qualifications. Further, only an average of 10% of teachers across the range of surveyed African countries receive any form of on-the-job training (UNESCO, 2006) (Exhibit 6).

Please note that the UNESCO survey on teacher qualifications (UNESCO, 2006) does not include data for India and Pakistan (the two largest South Asian countries), and is therefore not representative of the entire region.
Minimum training requirements for primary schools by HDI decile

Percent of countries in each region, with minimum required training at ISCED levels 2-5

Exhibit 5: The minimum qualifications for primary school teachers varies across countries and regions. The qualifications are according to ISCED levels. ISCED 2 refers to 9 years of schooling, ISCED 3 to 12-13 years, ISCED 4 to 13-15 years, and ISCED 5 to advanced degrees. In sub-Saharan Africa, only 8% of countries require ISCED 5. The requirements in most South Asian countries are, likewise, low. Please note that this UNESCO study does not include India and Pakistan, South Asia’s two largest countries.

Primary school teachers who have received specific training in teaching

Exhibit 6: New data from UNESCO (which is still sparse) shows that across several African countries, only 10% of teachers receive education-specific training.
One of the more contentious debates in international development is the role of government versus the private sector in providing education to the poor, especially at the primary level (Colclough, 1996). Proponents of public (i.e., government-run) education believe that it is the only meaningful way to provide free (or affordable), universal, and equitable education for the poor. Detractors argue that public systems lack accountability for quality or financial management and that private schools are much more accountable (Tooley & Dixon, 2005) (Tooley, 2009) (Lutyens, 2011). Our study does not take a stance on that debate, nor do we believe that the two approaches are mutually exclusive. Across all income groups in sub-Saharan Africa and South Asia, 16% and 18% of primary school students, respectively, are enrolled in private schools (UNESCO Institute for Statistics, 2012) (Exhibit 7). More interestingly, a targeted study of the urban poor in India, Nigeria and Ghana found that 72% of low income students go to private schools, of which 68% do not receive any financial aid (Tooley & Dixon, 2005) (Exhibit 8).

A number of low income parents send their children to private schools, especially in urban areas

One of the more contentious debates in international development is the role of government versus the private sector in providing education to the poor, especially at the primary level (Colclough, 1996). Proponents of public (i.e., government-run) education believe that it is the only meaningful way to provide free (or affordable), universal, and equitable education for the poor. Detractors argue that public systems lack accountability for quality or financial management and that private schools are much more accountable (Tooley & Dixon, 2005) (Tooley, 2009) (Lutyens, 2011). Our study does not take a stance on that debate, nor do we believe that the two approaches are mutually exclusive. Across all income groups in sub-Saharan Africa and South Asia, 16% and 18% of primary school students, respectively, are enrolled in private schools (UNESCO Institute for Statistics, 2012) (Exhibit 7). More interestingly, a targeted study of the urban poor in India, Nigeria and Ghana found that 72% of low income students go to private schools, of which 68% do not receive any financial aid (Tooley & Dixon, 2005) (Exhibit 8).

Percent of primary school students attending private school

Exhibit 7: In general, there appears to be no correlation between the poverty level in a country, and overall enrollment in private schools; 16% of primary school students in sub-Saharan Africa and 18% in South Asia attend private schools.

\[\text{Exhibit 7: In general, there appears to be no correlation between the poverty level in a country, and overall enrollment in private schools; 16% of primary school students in sub-Saharan Africa and 18% in South Asia attend private schools.}\]
Public vs. private school enrollment of low income students in urban areas of India, Ghana and Nigeria

Exhibit 8: Targeted studies in India, Ghana and Nigeria show that 72% of surveyed households among the urban poor rely on private schools.
Secondary schooling—or other formal education—for youth, has not received global priority at the same level and scale as primary education has. Also, there is no standard age group which formally defines youth. Some institutions start their definitions as early as 12 years and others begin at 15 years; some end at 19 years, and others extend the definition to include individuals as old as 24 years. This section uses the age range typically associated with the secondary school years: ages between 15 to 19 years. The global population of individuals in that age range is about 606 million (Exhibit 9). Of these, 88.4 million live in sub-Saharan Africa, and another 167.1 million live in South Asia (UN Department of Economic and Social Affairs, 2014).

The opportunity cost of going to school at this stage increases. Low income students who enroll in secondary school are of an age at which it is not uncommon for them to start working to support their families. Students often have to forego immediate income-earning opportunities for an education that may not position them for improving their livelihoods or income, especially in the near term. Consequently, the relevance of secondary education—and how it can help these students increase their immediate and long term income potential—is extremely important.

Public expenditure on secondary education, relative to primary education, differs vastly between countries and between regions. The data shows that there is significant variability in the ratio of primary to secondary expenditure between countries within a low income region, and between different low income regions. For instance, in South Asia, average government expenditure on secondary education is 79% of that on primary education; in sub-Saharan Africa, it is 188%. It is therefore difficult to draw a general conclusion about the overall quality of secondary education based simply on expenditure levels. However, metrics like student-to-teacher ratios suggest significant quality gaps (Exhibit 10).

**Global youth population**

<table>
<thead>
<tr>
<th>Region</th>
<th>Youth population in sub-Saharan Africa</th>
<th>South Asia</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Asia &amp; the Pacific</td>
<td>25.2</td>
<td>24.3</td>
<td>49.5</td>
</tr>
<tr>
<td>Middle East &amp; North Africa</td>
<td>24.8</td>
<td>41.7</td>
<td>66.5</td>
</tr>
<tr>
<td>Latin America &amp; the Caribbean</td>
<td>54.7</td>
<td>54.9</td>
<td>109.6</td>
</tr>
<tr>
<td>Europe</td>
<td>25.2</td>
<td>24.3</td>
<td>49.5</td>
</tr>
<tr>
<td>North America</td>
<td>24.3</td>
<td>24.3</td>
<td>48.6</td>
</tr>
<tr>
<td>East/Central Europe and Central Asia</td>
<td>125.1</td>
<td>125.1</td>
<td>250.2</td>
</tr>
<tr>
<td>Total</td>
<td>606.1</td>
<td>88.4</td>
<td>694.5</td>
</tr>
</tbody>
</table>

Exhibit 9: Globally, there are 606 million youth in the 15-19 year age group. About 256 million of them live in South Asia and sub-Saharan Africa.
Student-to-teacher ratios in secondary schools

<table>
<thead>
<tr>
<th>Region</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Asia &amp; Pacific</td>
<td>16.7</td>
</tr>
<tr>
<td>East/Central Europe and Central Asia</td>
<td>10.8</td>
</tr>
<tr>
<td>European Union</td>
<td>10.1</td>
</tr>
<tr>
<td>Latin America &amp; the Caribbean</td>
<td>15.4</td>
</tr>
<tr>
<td>Middle East &amp; North Africa</td>
<td>13.3</td>
</tr>
<tr>
<td>North America</td>
<td>13.8</td>
</tr>
<tr>
<td>Southeast Asia</td>
<td>22.8</td>
</tr>
<tr>
<td>South Asia</td>
<td>31.6</td>
</tr>
<tr>
<td>sub-Saharan Africa</td>
<td>27.0</td>
</tr>
</tbody>
</table>

Exhibit 10: Secondary school student-to-teacher ratios in South Asia and sub-Saharan Africa are much higher than in other parts of the world, and likely reduces the overall quality of education.

Enrollment in secondary schools is significantly lower than that in primary schools

Perhaps the most significant and telling statistic about youth education in developing countries is the dropoff in enrollment rates between primary and secondary education, as shown in Exhibit 11. In sub-Saharan Africa, secondary enrollment is 29%, a drop of 46 percentage points compared to primary enrollment; in South Asia, it is 33%, a 36 percentage point drop from primary enrollment (UNESCO Institute for Statistics, 2012).

The gender gap is more pronounced at the secondary school level

As girls enter youth, many societal challenges begin manifesting themselves. These challenges have been discussed in detail in the section on Gender Equity. As Exhibit 12 shows, the percent of enrolled secondary students who are female drops to 43% in both South Asia and sub-Saharan Africa, from 46% and 47% respectively (UNESCO Institute for Statistics, 2012).
Dropoff in enrollment rates between primary and secondary school

Exhibit 11: A significant number of students in sub-Saharan Africa and South Asia, who get a primary education, do not start secondary school.

Percentage of female students in primary and secondary school

Exhibit 12: While the gender gap in primary education is minimal it begins to grow in secondary school, in both sub-Saharan Africa and South Asia.
The role of private schools is more prominent in secondary education

Middle and upper income students in developing countries often choose to pay higher fees and attend private secondary schools. What is interesting, however, is that a large number of students even at the lower end of the income spectrum, appear to prefer private schools (Tooley & Dixon, 2005) (Tooley, 2009). As Exhibit 13 shows, participation in private schools in sub-Saharan Africa and South Asia at the secondary level jumps dramatically compared with the primary school level (UNESCO Institute for Statistics, 2012).

### Percentage of secondary school students attending private schools

<table>
<thead>
<tr>
<th>Region</th>
<th>% of primary school students in private schools</th>
<th>% of secondary school students in private schools</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Asia &amp; the Pacific</td>
<td>20%</td>
<td>25%</td>
</tr>
<tr>
<td>East/Central Europe and Central Asia</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>European Union</td>
<td>10%</td>
<td>14%</td>
</tr>
<tr>
<td>Latin America &amp; the Caribbean</td>
<td>23%</td>
<td>24%</td>
</tr>
<tr>
<td>Middle East &amp; North Africa</td>
<td>20%</td>
<td>16%</td>
</tr>
<tr>
<td>North America</td>
<td>8%</td>
<td>7%</td>
</tr>
<tr>
<td>Southeast Asia</td>
<td>13%</td>
<td>18%</td>
</tr>
<tr>
<td>South Asia</td>
<td>18%</td>
<td>40%</td>
</tr>
<tr>
<td>sub-Saharan Africa</td>
<td>21%</td>
<td>21%</td>
</tr>
</tbody>
</table>

**Exhibit 13**: In sub-Saharan Africa and South Asia, there is a significant increase in the percent of students who go to a private school at the secondary level when compared with the primary level.

Technical Vocational Education and Training (TVET) programs are gaining momentum as an alternative—or a complement—to traditional secondary school education

Traditionally, secondary schooling curricula have emphasized preparation for higher education, focusing on topics like science, mathematics, and literature. Recently, there has been a trend towards improving the employment prospects of secondary school graduates, leading to noticeable growth in TVET programs. TVET programs typically have three components (UN Department of Economic and Social Affairs, 2011) (Leke, et al., 2010) (Alelu, 2012):

- General life and workplace skills, such as financial literacy and workplace etiquette.
Training for jobs in specific industries such as plumbing, furniture making, and various other trades.

Entrepreneurship training, so that individuals can build their own businesses.

Examples of programs which offer different flavors and combinations of these components, include: Junior Achievement Worldwide (which, through affiliates like INJAZ Al-Arab, relies on community volunteers from various professions to train and mentor youth using a standardized curriculum), Fundacion Paraguaya (which focuses on entrepreneurship, supported by microfinance), Go For Gold (a program in South Africa which prepares graduates for employment in the construction sector), Aflatoun (which helps teenagers learn financial literacy and entrepreneurship through a learning-by-doing model), and the African Leadership Academy (which incorporates aspects of African History, leadership development and entrepreneurship in a standard secondary school curriculum).

TVET is a new trend, however, and very few secondary schools in developing countries incorporate TVET into their formal secondary education curricula. In addition, only a small number of youth in developing countries enroll in formal TVET programs outside of secondary schools (Betcherman, et al., 2007). Note that TVET programs are not just for students of secondary school age, they can extend to students in older age groups, as well as to adults.

Out of the 256 million youth (ages 15-19 years) in sub-Saharan Africa and South Asia, about 62 million—based on an estimate of the percentage of students with access to trained teachers (UNESCO Institute for Statistics, 2012)—are enrolled in secondary schools of seemingly adequate (or superior) quality; 33 million are enrolled in schools of inadequate quality; about 5 million are enrolled in some formal TVET program, outside of the secondary school system (although data on TVET enrollment is sparse); 95 million are literate but get little to no formal TVET or secondary education, and the remaining 62 million are not literate enough to participate in any formal secondary level education even if it were accessible (UNESCO Institute for Statistics, 2012)\(^5\) (Exhibit 14). Of these 256 million youth, approximately 55% (141 million) are engaged in paid work (Betcherman, et al., 2007).

Youth across the education spectrum in South Asia and sub-Saharan Africa \(^1\)

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\(^1\) Note that statistics for education and literacy for youth 15-19 do not exist in any single source. These estimates are based on data available from multiple sources for different age ranges (chiefly the UNESCO Institute for Statistics), but normalized for the 15-19 age group.

\(^5\) LIGTT analysis based on different sets of data.
In order to become competitive in the global economic ecosystem, it is essential for countries to have a large workforce with advanced education in a broad range of areas such as engineering, the sciences, medicine, and business management. The most salient fact about post-secondary or tertiary education in developing countries is that a very small portion of the population participates in it. Furthermore, even those with advanced degrees are not guaranteed appropriate jobs (Exhibit 15). Tertiary enrollment in both South Asia and sub-Saharan Africa is extremely low. The enrollment rate among women and men in sub-Saharan Africa is 5% and 7% respectively, and in South Asia it is 10% for both men and women (Exhibit 16).

**Education levels of the unemployed population in South Asia and sub-Saharan Africa**

Exhibit 15: In South Asia and sub-Saharan Africa, education does not guarantee employment; 23% of unemployed individuals in these regions have a secondary education, and another 12% have a tertiary education. The data is not significantly different across gender lines. Note that the data does not discuss underemployment, which can also be a major issue.
Tertiary level education enrollment rates

Average gross enrollment ratio, 2006-11

Exhibit 16: Tertiary enrollment in sub-Saharan Africa and South Asia is a fraction of that in industrialized countries, across both genders.

The majority of college students in developing countries are enrolled in public institutions

In most developing countries, youth with secondary schooling generally have two educational tracks to follow: a 3 or 4 year undergraduate program, provided at colleges and universities, or a post-secondary TVET program. The latter are typically small and fragmented, can vary in duration from a few months to 2 years, and provide education at a level somewhere between undergraduate degrees and secondary-level TVET. Currently, the majority of students receiving undergraduate education in developing countries are enrolled in public universities (World Bank: Task Force on Higher Education and Society, 2000). Higher education programs in developing countries face a number of challenges: limited resources, curricula that are not aligned with the demands of the job market, lack of accountability, and incentives that are not aligned with outcomes. Unlike primary or secondary education, there are limited opportunities for NGOs to make a significant difference in undergraduate-level education; the depth and breadth of expertise and resources required to create a university-level institution is beyond the means of most NGOs. Notable exceptions include Aga Khan University, which operates in several countries in Asia and Africa, and BRAC University in Bangladesh; both are part of two of the world’s largest NGOs.
The focus of tertiary education in Africa is on humanities and social sciences, more than on technical areas like engineering and medicine; this is at odds with employment prospects.

Over the past two decades, South Asia’s largest country and economy, India, has witnessed considerable economic growth. By many accounts, this has been powered by the large technically trained workforce and a dramatic increase in the number of institutions providing relevant tertiary education (Dinakar, 2007) (CLSA, 2008). This phenomenon, however, is not uniform across income groups in South Asia; it is even less promising in sub-Saharan Africa (Chynoweth, 2012).

*Exhibit 17* shows the academic disciplines in which college students in sub-Saharan Africa typically enroll. The social sciences (including business and law) and humanities (including the arts) account for 48% of all enrollment, education for 14%, and the pure sciences for another 10%. Only 6% study engineering, manufacturing and construction, another 7% are in health and medicine, and only 3% are in agriculture (UNESCO Institute for Statistics, 2012). In order to be relevant to students and help them gain meaningful employment, the academic coursework offered will need to closely match the industrial sectors and functional areas with the greatest opportunity. *Exhibit 18* shows an illustrative analysis of these industries in Africa, based on the intersection of the share of national economic growth and the multiplier factor. According to this analysis, the most attractive sectors are: agriculture and agribusiness, wholesale and retail, transport and telecom, and financial services.

Cross-referencing the tertiary enrollment data (*Exhibit 17*) against the industries which offer the best opportunities for employment (*Exhibit 18*) in Africa, shows that fewer than half of the students who invest in tertiary education in sub-Saharan Africa get the education they need to meet the human capital needs of the industries that offer the best job prospects (*Exhibit 19*). Not surprisingly, many multinational corporations in Africa have trouble finding local talent to fill executive roles and seek expatriates from other countries (typically from the US or from the EU) to fill such roles (Chynoweth, 2012).

**Academic disciplines of tertiary level students in sub-Saharan Africa**

*Exhibit 17*: Almost 75% of students enrolled in tertiary education in sub-Saharan Africa focus on social sciences, business & law (36%), humanities & arts (12%), education (14%), and the pure sciences (10%). Only 6% are in engineering and related fields, 7% in health, and 3% in agriculture.
Industries in Africa with the greatest opportunity for future job placements

Ranked by share of recent economic growth (2002-07) vs. employment multiplier

Exhibit 18: Illustrative analysis mapping industries based on their potential for creating local jobs, along two dimensions. The agriculture & agribusiness and the wholesale & retail sectors offer the best opportunity, while the natural resources and manufacturing sectors are growing strongly without creating many local jobs.

Cross-reference of current tertiary enrollment in sub-Saharan Africa against needs of high-potential industries

Assessment of how well the tertiary education system meets industry human capital needs

<table>
<thead>
<tr>
<th>HIGH-POTENTIAL INDUSTRIES</th>
<th>ACADEMIC DISCIPLINE OF ENROLLED STUDENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Education</td>
</tr>
<tr>
<td>Ecology &amp; Agriculture</td>
<td>Low</td>
</tr>
<tr>
<td>Wholesale &amp; Retail</td>
<td>Low</td>
</tr>
<tr>
<td>Transport &amp; Telecom</td>
<td>Low</td>
</tr>
<tr>
<td>Financial Services</td>
<td>Low</td>
</tr>
<tr>
<td>Construction</td>
<td>Low</td>
</tr>
<tr>
<td>Public Administration</td>
<td>Low</td>
</tr>
<tr>
<td>Natural Resources</td>
<td>Low</td>
</tr>
<tr>
<td>Tourism</td>
<td>Low</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>Low</td>
</tr>
<tr>
<td>Utilities</td>
<td>Low</td>
</tr>
</tbody>
</table>

Exhibit 19: Tertiary education systems in sub-Saharan Africa do not appear to be geared toward the human capital needs of the industries which offer the highest opportunities for employment.

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7 This illustrative analysis uses incomplete data from multiple sources, and is not meant to be the kind of rigorous assessment required for a thoughtful education policy.
KEY CHALLENGES

PRIMARY EDUCATION

There are a number of reasons why such a large number of children in lower income countries do not receive adequate education at the primary school level. The entire spectrum of challenges can be split across two overarching issues. First, the lack of access to an education. Second, the quality of education.

Lack of access to education is driven by 7 factors

Access to schools is the first step toward an appropriate education. Lack of access—even of inadequate quality—is caused by several, sometimes overlapping, factors.

There simply aren’t enough schools

Many remote, sparsely populated, and isolated areas simply do not have schools within reasonable reach. Public school systems in poorer countries are not adequately funded, leading to an overall lack of infrastructure. Annual public spending per student in sub-Saharan Africa and South Asia is $331 and $396, respectively, a small fraction of that in higher income regions (Exhibit 20). Furthermore, only a portion of that budget actually goes to directly educating children while the rest of it goes toward paying for system overhead (e.g., the education ministry, administrators, etc.). Even as there is limited data to show the actual distribution of funding between direct instruction-related activities and system overhead, the dismal condition of many schools is indicative of the allocation and distribution of funds. Many schools across Africa do not even have basic amenities such as electricity (only 24%), potable water (50%) and toilets (61%) (UNESCO Institute for Statistics, 2012) (Exhibit 21). In addition, there is a severe lack of textbooks; 2.6 and 2.3 students, respectively, have to share a single textbook for Mathematics and Reading. It is important to note that in these lower income countries, there are also examples of school systems, which appear to provide quality education for $100 or less per year per student (Kristoff, 2010).

Public expenditure on primary education

<table>
<thead>
<tr>
<th>Region</th>
<th>Per capita</th>
</tr>
</thead>
<tbody>
<tr>
<td>sub-Saharan Africa</td>
<td>$331</td>
</tr>
<tr>
<td>South Asia</td>
<td>$396</td>
</tr>
<tr>
<td>Southeast Asia</td>
<td>$786</td>
</tr>
<tr>
<td>Latin America &amp; the Caribbean</td>
<td>$1,306</td>
</tr>
<tr>
<td>East/Central Europe and Central Asia</td>
<td>$2,887</td>
</tr>
<tr>
<td>Middle East &amp; North Africa</td>
<td>$3,134</td>
</tr>
<tr>
<td>East Asia &amp; the Pacific</td>
<td>$4,266</td>
</tr>
<tr>
<td>European Union</td>
<td>$7,300</td>
</tr>
<tr>
<td>North America</td>
<td>$9,673</td>
</tr>
</tbody>
</table>

Exhibit 20: Government expenditure on primary education in sub-Saharan Africa and South Asia is a small fraction of that in wealthier countries.

---

The data represents schools from Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Congo, Côte d’Ivoire, the Democratic Republic of Congo, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Madagascar, Malawi, Mali, Mauritius, Mozambique, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Tanzania, Togo, and Uganda.
There is a low (perceived or actual) value of education, especially compared with the opportunity cost of attending. The relatively low levels of financing notwithstanding, there is strong evidence suggesting that even the available funds are not spent efficiently or effectively in many countries (Lutyens, 2011) (Tooley, 2009) leading to schools of very poor quality. As a result, many parents do not find schooling attractive or useful in any way and simply pull their children out of the schools.

A large number of children cannot afford school, and are engaged in child labor. Globally, over 300 million children between the ages of 5 and 17 years are engaged in employment (Diallo, et al., 2010), most of whom work to financially support their families. Child labor is a significant contributor to children being out of school. A study conducted by UNICEF across a number of African countries (Gibbons, et al., 2005) found that an average of 21% of out-of-school children are engaged in labor (Exhibit 22).

Minority groups are often excluded, intentionally or through neglect. In many countries with high ethnolinguistic fragmentation, many minority groups can find themselves disenfranchised, and their children deprived of opportunities for education. This can happen either because of passive underinvestment by the government in particular geographies where the ethnic minorities are concentrated, or because of active discrimination (IRIN, 2011).

Some cultures traditionally have not valued education. Some communities have traditionally not considered participation in formal education a priority. For example, throughout South Asia, which has one of the highest out-of-school populations in the world, formal education of girls is discouraged (Latif, 2000). In addition, nomadic populations across the world have also tended to deprioritize formal education (Carr-Hill, 2005).

Poor health and nutrition can prevent children from going to school. While there is limited data on how many children stay out of school because of ill health, a number of programs (NUEPA, 2008) (Chege, 2012) have found that providing hot, nutritious meals to children on school-days markedly increases their participation in schooling.

Exhibit 21: Most schools across Africa (according to new, somewhat sparse, data collected by UNESCO), do not have even the basic amenities.
Exhibit 22: A large number of out-of-school children—approximately 21% in a study across a number of African countries—are engaged in child labor.

There are a number of hurdles specific to some population segments
The challenges described above tend to affect children living in different contexts, and from different population segments, in different ways.

Remote and hard-to-reach areas: For children who live in remote or hard-to-reach rural areas, access is a core concern. The majority of people in sub-Saharan Africa and South Asia live in rural areas, and less than 20% of the roadways in these areas are paved (World Bank, 2011). These areas typically have a low density of schools, few qualified teachers (with limited incentives for qualified teachers from urban areas to relocate), little in the way of transportation to help students reach schools in nearby towns, and poor local governance to oversee the quality of education. There is also a high incidence of child labor in rural areas. More than 60% of all children work in agriculture, two-thirds of whom work, unpaid, for their family (Diallo, et al., 2010).

Urban slums: The situation is markedly different for children living in urban slums. Urbanization is a growing phenomenon in sub-Saharan Africa and South Asia. Children in poor, urban settings face a range of issues which are different from issues poor children face in rural settings (Mander, 2009). People living in urban slums are often separated from their communities and (typically informal but traditional) social safety nets. The physical environments in which the urban poor are forced to live in are more vulnerable (with few assets, and little security for the assets they do own) and degraded than those in rural areas. Because urban economies tend to be more monetized than rural economies, the urban poor find themselves needing to pay cash for many more things than their rural counterparts. The urban poor also tend to be subject to far greater levels of violence from state actors (e.g., the police) as well as criminals. Children are often also subjected to many forms of exploitation or violence, with many of them being forced to beg. Children of first generation migrants to urban...
areas can be even worse off, since they do not have a permanent place of residence, or necessary documentation. This indirectly excludes them from being able to access whatever little they otherwise can in the form of state-provided education and healthcare facilities. All of this put together, creates a very precarious environment for children to live and grow in, let alone seek an education.

Refugee and displaced populations: Even more vulnerable are children among refugee and internally displaced populations. Refugees and displaced people living in refugee-like situations do not have access to many services provided to populations living under more normal conditions. They are far removed from their own homes and assets, and often do not have a clear legal status where they live (whether in camps or urban settings). As of 2009, 31% children of primary school age were out of school in the major refugee camps around the world. The out-of-school rate was 37% among urban refugees. In total, more than 450,000 refugee children of primary school age are out of school (UNHCR, 2009). Since refugees usually do not have a steady source of income, most of the services they (and their children) receive, are provided by charitable agencies, and basics like shelter and food take precedence over education.

Quality of education remains poor and there is limited emphasis on outcomes

The gains made through the increasing rates of access and enrollment are undermined if the quality of teaching is subpar, schools are mismanaged, and learning outcomes achieved by children fall below minimum required age-appropriate benchmarks. A few factors play a central role in the overall quality of education that children receive.

There aren’t enough well-trained teachers

As Exhibit 5 and Exhibit 6 illustrate, the required minimum qualifications for primary school teachers in most developing countries are low, and there is very limited on-the-job training once they begin teaching.

Accountability and incentives are often not aligned with actual education outcomes

A commonly cited problem, especially in government-run school systems, is that neither the school systems nor the teachers are accountable for actual education outcomes. Studies have found that the root causes for this lack of accountability are the excessive power of teachers’ unions, and the general bureaucratic challenges that any large public system faces (Tooley, 2009) (Lutyens, 2011). In addition, low income parents are often not in a position to evaluate the quality of education, and rely on external indicators such as cleanliness of the buildings and toilets.

Teachers do not have adequate tools for instruction

Teachers need a range of tools—building blocks, maps, a variety of books, photographs, and ideally, computers—to offer children the breadth and depth of knowledge they require to be competitive in the long run. As Exhibit 21 shows, many schools across Africa do not even have basic amenities such as electricity, potable water, and toilets (UNESCO Institute for Statistics, 2012). There are also severe shortages of textbooks and other school supplies. Tools such as computers are available only to students attending the most elite of schools.
Globally, most hurdles that make primary education for the poor challenging, also apply to secondary education. In addition, there are 4 hurdles specific to secondary education.

3. There can be a high opportunity cost to secondary schooling. 152 million youth are from households below the poverty line of $1.25 per day (International Labour Organization, 2010). For youth living in such or even somewhat better conditions, there can be a significant opportunity cost to attending school. Income generated by these youth often constitutes a significant portion of their families’ aggregate income. Not surprisingly then, 43% and 54% of youth in South Asia and sub-Saharan Africa, respectively, work to support themselves and their families (Betcherman, et al., 2007).

4. Secondary education is often not perceived as adding value. Almost by definition, the job market in low income countries is meager. Almost a quarter of unemployed people in sub-Saharan Africa and South Asia have a secondary education (International Labour Organization, 2010) (Exhibit 15). This creates a disincentive for investing time in secondary education, especially considering the opportunity cost of forgone income. For most of these youth, formal secondary level education is not viewed as relevant for dramatically increasing incomes.

5. In the past, the global community has not emphasized youth education. There has not been as much emphasis—in global or national agendas—on youth education, as on primary schooling. For example, there is no Millennium Development Goal to promote youth education, nor any other concerted global effort.

6. Gender discrimination grows, as girls enter youth. Gender-based discrimination begins to play an increasingly major role as girls enter adolescence and early youth. Traditional practices force many young women from low income families to marry or take on other household responsibilities including caring for younger siblings or the elderly.
The challenges of providing affordable, quality and relevant tertiary education to low income populations in developing countries, are an extension of the challenges in secondary education.

There is a very high opportunity cost to higher education. Low income individuals older than 19 years face an extremely high opportunity cost of spending years in school rather than earning a living.

Curricula are not aligned with employment opportunities. The majority of colleges and universities do not prepare students for the demands of the job market, with respect to growth industries, or functional specialization. As a result, many of the most attractive roles in the private and NGO sectors are occupied by expatriates from industrialized countries.

There are not enough jobs. The economies in most countries in sub-Saharan Africa are not strong enough to absorb a large number of graduates with advanced degrees. Consequently, there are few clear incentives for individuals to invest in higher education. This, in turn, creates a vicious cycle with the two aforementioned challenges.
SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

Solving the broad problem of education requires fundamental, systemic improvements on three key fronts. First, infrastructure—construction of a large numbers of schools with appropriate amenities. Second, human capital—training and certification of all teachers. And third, policy changes—to ensure the system is accountable to students and parents, and the curricula are relevant. In all likelihood, achieving this will require a combination of both private and public systems, with the former leading the charge in innovation, and the latter, to ensure universal and equitable access. While the role of technology may not be central here, 1 breakthrough can play a powerful part in achieving dramatic improvements in overall access to quality education and learning outcomes.

‘Smart’ electronic textbooks, customized for various age groups and educational levels, with curated and up-to-date content, ‘wiki’ interfaces for vernacular and other locally relevant and gender-inclusive material, visual and dynamic learning tools for students, interfaces and tools for teachers, student-teacher interaction and peer-to-peer collaboration. These smart e-textbooks can be delivered on tablet devices or on smartphones, the prices of which are steadily falling.

While ‘smart’ devices like touchscreen phones and increasingly powerful tablets are well on the path to becoming as ubiquitous as the basic mobile phone, digital educational content has not kept pace. There are isolated pockets of exceptional content (e.g., videos by the Khan Academy), but there is very little in the way of curated and structured material which is suited to country-specific curricula for various stages of education, and ready for use off-the-shelf. Grade-specific ‘smart’ electronic textbooks with the following features can be a very powerful way of compensating for systemic gaps in infrastructure, human capital, and policy. Potential features include:

- Digitized textbooks across all disciplines, based on the curricular standards established by existing school systems (e.g., international standards like A-level/O-level and International Baccalaureate, and national standards like ICSE or CBSE in India).
- A repository of regularly refreshed supplementary material that may be curated from ‘best of’ writings, recordings of experiments, instructional videos, research papers, recordings of historical or public events.
- A dynamic, interactive, customized, intelligent and adaptive learning mechanism in which students’ performance on problem sets determines the pace of content and learning, using a rules engine which inserts introductory material and remedial problem sets, as required.
- A peer-to-peer ‘wiki’ collaboration platform, which allows students and teachers to exchange ideas, engage in virtual Q&A, and share relevant curated or created content, including local language and gender-inclusive content and videos.

In principle, all ecosystem ingredients are already present to create such e-textbooks, and various versions are available in industrialized markets. However, the control exerted by publishers and local school boards in markets like the US, appears to have contributed to the relatively slow emergence of disruptive innovations in content delivery. As a result, there are few platforms that can be immediately transplanted.
to a developing country context. Still, with targeted investment and collaboration we believe something like this should be market-ready within 2-3 years.

Meanwhile, tablet computers are becoming increasingly affordable and readily available. Tablets—and to a somewhat smaller extent, smartphones with touchscreens—offer the perfect platform through which such a breakthrough can be deployed on a large scale. Both devices have significant advantages over traditional keyboard-based computers, especially for children. Not only are they light, portable, and very easy to carry (even by small children), their touchscreen interface makes them more intuitive to use. Compared to keyboards, which require a certain literacy level and can be very cumbersome for children or other users who are unfamiliar with them, tablets are easy to interact with and handle. Already existing, standard applications make it possible to access visually rich and dynamic content on the web and easily share it. Utilizing in-built tools, applications and other programs, children can easily customize pictures they take or content they create and share it as well. This creates a rich, highly personalized and empowering experience for children. As technology advances, tablets will come with higher storage capacities, making them conducive for processing large amounts of data and content, and—like personal computers and laptops—capable of storing individual and customized usage histories. Although there is still a long way to go before tablets and smartphones can be considered affordable to the very poor, they are close to being affordable at a community level, so that they can be shared by groups of students in a school. The section on Digital Inclusion discusses the prospects for truly affordable devices, and what it will take to get there.

Despite the momentum in the global information and communication technology revolution, there will be a number of challenges such smart textbooks will have to overcome, once they are introduced to the market:

- Educational ministries and school systems will need to recognize the value of such a technology and its compatibility with existing curricula.
- Demand needs to be built with teachers and students, who will need to change daily behavior, and learn to use them effectively. Rapid adoption of mobile technologies suggests this is possible.
- Some effort will be required to ensure the availability of power (to charge the devices), and wireless connection.
- Despite the falling costs of tablet devices, some financing will be necessary for lower income students.
- Even though schools systems—especially public schools—operate through some form of centralized control, the market is still highly fragmented.
- There is no business model precedent; deployment models will need to very innovative to address all aforementioned hurdles.

Considering all of the above factors, we believe that deployment will be CHALLENGING.
Breakthrough 1 – Difficulty of deployment

- **Extremely Challenging**
  - Policies
  - Infrastructure
  - Human capital
  - Access to user finance
  - Behavior change
  - Existing demand
  - Market fragmentation/Distribution channels
  - Business model innovation

- **Challenging**
  - Requires high level of training for large numbers of people
  - Requires some improvements to existing infrastructure
  - Moderate financing needed, viable mechanisms identified
  - Major behavior change required, potentially on daily basis
  - Low demand, needs to be built
  - Fragmented market, weak distribution channels
  - Deployment model(s) being tested; major hurdles outstanding

- **Complex**
  - Requires high level of training for large numbers of people
  - Requires some improvements to existing infrastructure
  - Moderate financing needed, viable mechanisms identified
  - Major behavior change required, potentially on daily basis
  - Low demand, needs to be built
  - Fragmented market, weak distribution channels
  - Deployment model(s) being tested; major hurdles outstanding

- **Feasible**
  - Requires high level of training for large numbers of people
  - Requires some improvements to existing infrastructure
  - Moderate financing needed, viable mechanisms identified
  - Major behavior change required, potentially on daily basis
  - Low demand, needs to be built
  - Fragmented market, weak distribution channels
  - Deployment model(s) being tested; major hurdles outstanding

- **Simple**
  - Requires high level of training for large numbers of people
  - Requires some improvements to existing infrastructure
  - Moderate financing needed, viable mechanisms identified
  - Major behavior change required, potentially on daily basis
  - Low demand, needs to be built
  - Fragmented market, weak distribution channels
  - Deployment model(s) being tested; major hurdles outstanding
The ‘digital divide’ (the converse of ‘digital inclusion’) has traditionally been defined as the gap in access to the Internet, mobile phones, and other types of information and communication technologies (ICT), between wealthier societies and their less wealthy counterparts. Digital divides exist between economic strata within an individual country, as well as between countries. However, the nature of these two types of digital divide vary dramatically. While the traditional definition may be very appropriate for a wealthy country, a different definition is needed for characterizing the digital divide between industrialized countries and developing countries.

In the developing country context, ICT enabled services have to compensate major gaps in physical infrastructure, public and private institutions, and technical human capital. For example, telemedicine is proving to be a valuable ICT enabled service for connecting rural clinics (which typically do not have qualified clinicians) to physicians in urban areas, for remote consultation. Hence, the definition of digital inclusion, especially in context of developing countries, needs to go beyond merely access to the Internet and mobile phones, and include access to a broad range of ICT enabled services and tools required for human development.

The proliferation of mobile technology has laid a strong platform for the adoption of an increasing array of ICT enabled services. However, to achieve true digital inclusion, a number of gaps need to be addressed. These include the cost of smartphones that are currently on the market, very sparse
last-mile broadband connectivity in rural and remote areas, a lack of data about—and ID systems for—citizens and businesses, and an absence of ‘Internet of Things’ (IoT) devices. We believe that 4 specific breakthroughs will be critical for achieving digital inclusion, especially for low income populations.

- A new generation of wireless broadband network technologies that radically cut the cost of expanding coverage to rural areas

- Affordable (under $50) smartphones that support full-fledged Internet services, and need limited electricity to charge

- Biometric ID systems, linking birth registry, land title registry, financial services, education history, medical history, and other information critical for ICT enabled services

- A new generation of ‘Internet of Things’ (IoT) devices, which enable newer types of services, and compensate for gaps in infrastructure, effective institutions, and human capital
Recent years have witnessed a truly remarkable digital revolution in developing countries. However, low income populations in the developing world need a much broader range of ICT enabled services than their counterparts in industrialized countries, to compensate for the lack of strong institutions, physical infrastructure, and human capital deficits. Until devices to enable these services are developed (and the corresponding ICT enabled services actually provided) these populations cannot be considered ‘digitally included’. By this expanded definition, there is a long way to go before we achieve broad, global digital inclusion.

**CORE FACTS AND ANALYSIS**

‘Digital inclusion’, or conversely, ‘the digital divide’ has a number of definitions in common and institutional parlance. For example, The Oxford English Dictionary defines it as, “The gulf between those who have ready access to current digital technology (especially computers and the Internet) and those who do not; also, the social or educational inequality resulting from this.” Stanford University uses a US country-specific definition: “The growing gap between the underprivileged members of society, especially the poor, rural, elderly, and handicapped portion of the population who do not have access to computers or the internet; and the wealthy, middle-class, and young Americans living in urban and suburban areas who have access.” And the OECD defines it as, “The gap between individuals, households, businesses and geographic areas at different socio-economic levels with regard to both their opportunities to access information and communication technologies (ICTs) and to their use of the Internet for a wide variety of activities.” Others have simply used measures like mobile phone penetration or Internet access.

Within this context, a population can be considered ‘digitally included’ if they have affordable access to the same ICT products and ICT enabled services as their wealthier counterparts in their own country, or in other countries. In industrialized countries, dramatic changes and innovations in information and communication technologies in the last 30 years have revolutionized the way people live, work, and access services. In developing countries too, recent years have seen a remarkable increase in ICT penetration, and in particular, mobile phones. Today, even very poor individuals can speak with relatives who may have migrated long distances, and get targeted bits of information hitherto completely unavailable to them. Examples like M-Pesa, Kenya’s by-now famous ‘mobile money’ service, have leapfrogged western modes of financial transaction for a vast majority of unbanked people.

However, such access—being able to own a mobile phone or another ICT device and use a few successful ICT enabled platforms like M-Pesa—is an insufficient measure of digital inclusion.
Digital inclusion needs to be defined differently for the developing country context, to account for the critical role of ICT in compensating for gaps in institutions, infrastructure, and human capital.

Most definitions of digital inclusion focus on the relative gap between the digital haves and the have-nots, rather than on the specific ICT needs of low income populations, and whether or not those needs have been met. While it is clear that long-term sustainable development is unlikely without fundamental structural improvements, new ICT enabled tools are a critical interim bridge.

Low income countries are that way because they lack the essential pillars of development: strong institutions, robust infrastructure, and a depth and breadth of human capital. In healthcare, for example, these gaps manifest themselves as the absence of physicians and nurses, and a dearth of equipped and functioning clinics. In high income countries, there is a doctor for every 300 people on average, whereas in sub-Saharan Africa there is 1 for every 5,000 people. Similarly, when it comes to education in lower income countries, there are significant gaps in the number of trained teachers, adequately equipped school buildings, suitable tools for instruction, and accountability to outcomes. In the face of such structural gaps, telemedicine tools can help patients in rural areas remotely consult with trained physicians, and online education videos (e.g., the Khan Academy) can provide quality instruction to those who can access them. Such examples are beginning to demonstrate the ability of ICT to compensate for structural gaps, at least partially.

Any meaningful definition of ‘digital inclusion’, therefore needs to be in terms of whether the full range of such devices, and tools and services that help alleviate key human development challenges, are available to those who need them. Table 1 describes some of the major structural gaps developing countries face, and promising ICT enabled levers that constitute digital inclusion.
Examples of ICT enabled services to improve human development in low income countries

<table>
<thead>
<tr>
<th>Area of human development</th>
<th>Key gaps for low income populations and countries (current or historical)</th>
<th>Examples of ICT devices, and ICT enabled tools and services required for digital inclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Health</td>
<td>Acute lack of adequately trained physicians, nurses and other clinicians, especially in rural areas</td>
<td>Telemedicine tools for remote consultation with better trained physicians in urban areas</td>
</tr>
<tr>
<td></td>
<td>Sparse lab infrastructure for conducting reliable diagnostics</td>
<td>Point-of-care diagnostic devices enabled by smartphones and other ICT devices, to reduce reliance on high levels of clinical expertise</td>
</tr>
<tr>
<td></td>
<td>Weak patient-clinician linkages and entrenched behavior patterns, which limits treatment compliance</td>
<td>SMS-based reminder apps</td>
</tr>
<tr>
<td></td>
<td>Limited accurate data on patient health and epidemiological trends</td>
<td>Biometric patient IDs for tracking health metrics at the individual, community and population levels</td>
</tr>
<tr>
<td>Agricultural development</td>
<td>Smallholder farmers do not have access to true market prices, weather forecasts, and other critical information</td>
<td>Mobile phone-based services for weather forecasts market prices, contact information for dealers and other value chain partners, etc.</td>
</tr>
<tr>
<td></td>
<td>Agriculture ministries have limited capacity for quality extension services</td>
<td>Video-based extension services, delivered to farmer groups, with call-in for Q&amp;A</td>
</tr>
<tr>
<td>Financial services</td>
<td>Acute lack of brick-and-mortar banks in rural areas</td>
<td>Mobile money services like remittances</td>
</tr>
<tr>
<td></td>
<td>Limited mechanisms for remittances, or other forms of money transfer to distant locations</td>
<td></td>
</tr>
<tr>
<td>Education</td>
<td>Teachers have very limited training</td>
<td>Remote video content and instruction</td>
</tr>
<tr>
<td></td>
<td>Most schools are not adequately equipped with instruction tools</td>
<td>Digital textbooks, with interactive content, customized for local context</td>
</tr>
<tr>
<td></td>
<td>Limited access to up-to-date books</td>
<td></td>
</tr>
<tr>
<td>Electricity, water, and other utilities</td>
<td>High cost and complexity of managing small-scale utilities for rural populations</td>
<td>Distributed utility management tools</td>
</tr>
<tr>
<td></td>
<td>Limited mechanisms for billing and collection of payments</td>
<td>Mobile phone-based billing/payment systems</td>
</tr>
<tr>
<td>Miscellaneous public services</td>
<td>Limited accountability to citizens, and limited citizen voice in providing feedback</td>
<td>Digital reporting platforms to name-and-shame unresponsive public servants</td>
</tr>
<tr>
<td></td>
<td>Limited access to critical public services (e.g., rapid response police, or protection/rescue)</td>
<td>Citizen reporting for disaster response</td>
</tr>
</tbody>
</table>

Table1: Current definitions of digital inclusion do not focus on the specific needs of low income populations. While long-term sustainable development cannot happen without structural changes, ICT devices and ICT enabled services are a critical interim bridge.

The structural foundation for ICT connectivity is the Public Switched Telephone Network (PSTN), originally built for fixed line phones, and gradually expanding to become a ‘network of networks’.

The infrastructure for ICT connectivity is based on a global ‘network of networks’ called the Public Switched Telephone Network (PSTN). The network began in industrialized countries, many decades ago, with a plumbing of copper wires used for the early generation of fixed line telephones, carrying only analog signals. The PSTN has since evolved into a ‘network of networks,’ with new types and layers of
cables added with each passing generation of technologies. Today, it combines the old copper wires with coaxial cables (the original delivery mechanism for cable TV), extremely fast underground and undersea fiber-optic cables, wireless cellular towers, and even satellites. The combined network delivers information and media streams—now digitized—over long distances, seamlessly bridging one kind of networking mechanism (copper, coaxial, fiber-optic, wireless or satellite) with another (Kushnick, 2013).

Exhibit 1 shows the schema for the PSTN. Core or backbone networks typically have high bandwidth and interconnect distant regions (e.g., between cities or countries), edge networks provide last-mile access (e.g., to individual homes within a residential area), and the backhaul connects edge and backbone networks. In the evolution of the PSTN, two major inflection points have dramatically increased information flow and access, the range and quality of ICT enabled services, the ease of accessing them, and the scale at which they are used.
Exhibit 1: A simplified schema that shows the organization of the Public Switched Telephone Network (PSTN) today, as a conglomeration of diverse networks. Edge networks are closer to clusters of habitation, while backbone networks connect edge networks across cities, countries and continents.

The Internet and Worldwide Web, as the primary vehicles for data exchange around the world
Till the 1980s, various precursors of the Internet (e.g., the ARPANET) were used exclusively by a small number of government and research institutions, over the PSTN. The advent of the Internet protocol suite (TCP/IP)\(^1\) allowed consumers and businesses to engage in email and other limited transactions. In the 1990s, the introduction of the Worldwide Web (WWW)\(^2\) allowed users to freely publish—and make accessible to everyone else on the Internet—information about themselves and their services, using rich media. Conversely, it also allowed any Internet user to access content published by other Internet users. This caused a true explosion in how information is shared and consumed, which was difficult to imagine earlier. Eventually cloud computing made it possible to provide services remotely, in a distributed, seamless fashion to deliver feature-rich applications and Software As A Service (SAAS).

Along the way, the advent of search engines led to the phenomenon that became Google. The Internet, as we know it today, is not run by any one company. It is managed by all its participants to collectively self-regulate via non-profit organizations like ICANN (the Internet Corporation for Assigned Names and Numbers), which oversees assignment of unique identifiers on the Internet (The Internet Society, 2014) (A.M. Turing Award, 2014) (PC Magazine, 2014).

A key feature of the Internet is its resilience. Information can be re-routed across multiple paths (over the various member networks, which collectively enable strong redundancies) until it reaches its destination. In effect, the Internet is never ‘down’. The Internet is now the primary vehicle for data

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1. TCP/IP together allow information to be routed repeatedly across multiple paths until it reaches the destination anywhere on the PSTN. The Internet Protocol (IP) is a standard, simple and open protocol which allows any computing device to send messages over the network. Service providers can use the Transmission Control Protocol (TCP) for end-to-end transmission reliability. This, combined with the redundancy afforded by the large number of member networks, makes the Internet highly resilient.

2. The Worldwide Web is based on a system of globally unique identifiers for digital resources on the Internet (UDI, URL, and URI), an easy-to-use publishing language (HTML) and a protocol to allow for links to dynamic content (HTTP). Together, these make it easy for people to publish content on the Internet using a standard web browser.
exchange around the world, and a platform for an infinite range and number of services, with very low
barriers to entry. Anybody can provide or use services with relative ease. This makes the Internet a
tremendous equalizer, and an unmatched platform for development.

The development of mobile telephony, to obviate the need for dense networks of underground cables
at the last mile
Until recently, telephone networks, especially in developing countries, were controlled by public sector
monopolies. Installation of land-line phones often took several months (sometimes years), and their
reliability after installation was questionable at best. Only a small portion of the population in the
developing world had these telephones. Market liberalization eroded stifling monopolies, brought
competition and large injections of capital, and resulted in massive tariff reductions. Quick, cost-
effective deployment of cellular networks, combined with newer, cheaper backhaul and backbone
technologies, drove the leapfrog effect in developing countries from fixed line to cellular services. The
pre-paid business model innovation combined with cheap handsets made mobile telephony ubiquitous
and accessible to a wide swath of users who could not have dreamt of owning a fixed landline before.
Over the last decade dramatic advances in mobile phone technology—with respect to bandwidth,
reliability and cost—have made communication a reality for populations hitherto cut off from the rest
of the world.

The 1st generation networks or 1G, developed in the 1980s, used analog signals for voice calls
with bulky and expensive ‘brick’ phones. Wireless radio channels were restricted to one call at a time,
limiting the calls each cell could support. Signals could be intercepted by anyone with a radio scanner
tuned in to the right frequency. By the 1990s, digital signals and improved networking protocols to
enable multiple channels of communication led to 2G systems, with radically better network utilization,
more security, and data services (e.g., SMS, multimedia messaging, mobile Internet, international and
satellite roaming). Later, 2G improvements such as EDGE and GPRS increased data speeds even more.
The early part of the new millennium saw the introduction of 3G networks, with even higher data
speeds, better spectral efficiency, energy efficient transmissions, and data encryption. This allowed
sophisticated, secure and data-intensive services such as Voice over IP (VoIP), video conferencing, and
financial transactions. As of 2014, advanced 3G and 4G networks are achieving faster transmission
speeds than most high-speed cable Internet services (Telcoantennas, 2014).

Through the combination of Internet and mobile enabled services, the move to information-
based economies and widespread liberalization of telecom has allowed information to flow freely and
cheaply between different types of networks, as well as between distant networks. The same service
can thus be provided in a network-agnostic manner in the PSTN (e.g., the Internet can be accessed via
mobile phones, and phone calls can be made using the Internet and computers). This is a result of the
digitalization of all kinds of information, where both voice and video is sent as data, using the Internet
Protocol as the universal lingua franca for connecting disparate networks.

In every region of the world, mobile phones are outstripping fixed line phones as the default.
As Exhibit 2 shows, there are 92.6 mobile phone subscriptions per 100 people around the world,
compared to 16.2 fixed phone lines. In developing regions, this difference is more pronounced (World
Bank, 2014). It is estimated that 130 million new mobile subscribers will come on board year after year
until 2017, with South Asia and sub-Saharan Africa experiencing annual growth rates of almost 20%. Of
course, businesses in data-intensive industries will still require fiber cables for reliable, high bandwidth
access.
Exhibit 2: Mobile networks are much more ubiquitous than fixed phone networks, reaching close to universal coverage in some developing countries.

Despite the overall increase in mobile subscriptions, low income rural populations still lack access to both mobile and broadband services.

The promising statistics on the growth of mobile phone subscriptions can inspire misplaced confidence. To begin with, it is important to acknowledge that subscriptions in South Asia and sub-Saharan Africa are still significantly lower than other parts of the world (Exhibit 2). Second, phone subscriptions are much more expensive to users in developing countries than in wealthier countries, relative to incomes (Exhibit 3). Third, rural populations don’t have the same access as their urban counterparts, partly due to lower network coverage, and partly because they are poorer. Exhibit 4 shows coverage rates for India, Ghana and South Africa; it also shows that rural users are much more likely to share a phone than urban users. Similarly, Malawi has a coverage rate of 94%, but only 21% of the population has a mobile phone (GSMA, 2014) (GSMA, 2013) (Indexmundi, 2014). Finally, most of the networks in developing countries are 2G, especially in rural areas; broadband (3G or better) networks are usually restricted to urban areas. Hence, mobile broadband penetration is only 22% in Asia, and 11% in sub-Saharan Africa (Exhibit 5) (ITU, 2013).
The price of mobile broadband services

Price as a % of GNI per capita

<table>
<thead>
<tr>
<th></th>
<th>Industrialized countries</th>
<th>World average</th>
<th>Developing countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-paid handset</td>
<td>1%</td>
<td>8%</td>
<td>11%</td>
</tr>
<tr>
<td>Pre-paid handset</td>
<td>1%</td>
<td>11%</td>
<td>16%</td>
</tr>
</tbody>
</table>

Exhibit 3: The price of mobile broadband as a proportion of Gross National Income per capita is higher in developing countries, which makes it less affordable to low income populations.

Mobile coverage and use in rural vs. urban areas

Population with access to GSM coverage

<table>
<thead>
<tr>
<th>Country</th>
<th>Urban</th>
<th>Rural</th>
</tr>
</thead>
<tbody>
<tr>
<td>India</td>
<td>32%</td>
<td>20%</td>
</tr>
<tr>
<td>Ghana</td>
<td>62%</td>
<td>30%</td>
</tr>
<tr>
<td>South Africa</td>
<td>63%</td>
<td>40%</td>
</tr>
</tbody>
</table>

Active subscriber penetration in South Africa

<table>
<thead>
<tr>
<th>Category</th>
<th>Urban</th>
<th>Rural</th>
</tr>
</thead>
<tbody>
<tr>
<td>No phone</td>
<td>14%</td>
<td>22%</td>
</tr>
<tr>
<td>Share a phone</td>
<td>25%</td>
<td>39%</td>
</tr>
<tr>
<td>Own a phone</td>
<td>61%</td>
<td>39%</td>
</tr>
</tbody>
</table>

Exhibit 4: Rural mobile coverage and use of cell phones is disproportionately low, especially in developing countries. Also, a significant number of people in rural areas share phones.
Global mobile broadband penetration

Exhibit 5: Mobile broadband penetration is very low in Africa, particularly sub-Saharan Africa. It is also low in South Asia. Broadband (3G or better) networks are usually restricted to urban areas. Please note that this map combines data for Asia and Oceania, which is dominated by the statistics from larger countries like India, China, etc.

Only smartphones (and tablets) have the necessary capabilities to support the services and applications needed for true digital inclusion

Just as computers evolved from bulky desktops to laptops, and eventually tablets, mobile phones have simultaneously evolved to become smaller, lighter and more like computers in their capabilities. There are several categories of mobile phones: at one end of the spectrum are inexpensive and simple basic phones; at the other end are smartphones, essentially pocket-sized computers with touchscreens, designed to support full-fledged Internet services by exploiting the broadband capacity of 3G+ networks. In between the two ends of the spectrum, are feature phones. Smartphones offer a fundamentally different set of capabilities than basic phones and feature phones. There are 3 essential dimensions along which the capabilities of these devices are different.

User and data collection interface
These interfaces determine how the user interacts with the device. Basic phones typically have a number pad, on which the number buttons can be used—with some inconvenience—to enter letters of the alphabet when texting. Most of today’s basic phones also have a still camera. Feature phones have keypads (which incorporate the full range of alphanumeric characters), or touchscreens to allow users to select which application they wish to launch. Many feature phones also have video cameras. Smartphones have a range of interfaces: touchscreens, voice-activated control and ports for freely exchanging data with other computing devices. Some even have inbuilt thumbprint and face scanners for security.
Processing power, storage capacity, and a platform for installing new applications (‘apps’)
These capabilities collectively determine a device’s breadth of functionality. Basic phones do not really have a processor and cannot support data-rich applications, being limited to only voice or SMS. Feature phones typically come with a number of essential functions (such as address book, calendar, calculator, and alarm clock), and users can download only limited additional applications, if any. Smartphones, on the other hand, have processors, operating systems and storage capacities comparable to computers of the recent past. These phones work quite like small, general purpose computers which a broad range of powerful functions including email, music and videos playback, GPS-enabled maps, document and image processing, and can support any of the thousands of applications developed by a whole ecosystems of app developers, which the user can download at will. Indeed, beyond the basic functions like voice calls, texting and email, it is possible that the same brand of smartphone is used so differently by two users that they might as well be two different devices altogether. This capability of smartphones to be programmed and hyper-customized to the needs or whims of each user, sets them apart from any handheld consumer device ever developed in the past.

Modes of wireless communication
These modes determine the ways in which the device can transmit and receive wireless data. All mobile phones use ultra high frequency (UHF) radio signals (also used for over-the-air TV broadcasting) for communication with phone towers. Whereas basic phones are limited to a single mode of communication in that range, smartphones use a number of other modes, such as Bluetooth (for bilateral communication with another Bluetooth-enabled device, for distances up to 150-200 feet) and Wi-Fi (for connecting to Internet hubs within a distance of 50-100 feet). Many smartphones are also equipped with RFID (radio frequency identification, for communication with uniquely tagged objects or devices), and near-field communication (NFC, a variant of RFID) also used in ‘smartcards’ at shopping checkout stations within a few inches from the user. Feature phones tend be closer to basic phones in their modes of communication.

Recently, affordable high-end feature phones have been introduced to the market, with many features hitherto supported only by smartphones. This has led some to conclude that feature phones can spearhead digital inclusion (GSMA, 2013). However, feature phones by definition still have one fundamental design constraint relative to smartphones. Their operating logic—firmware—is burnt into the hardware, and can therefore vary from one model to another even with the same brand. This makes it harder for developers to make the same app work with different types of phones. On the other hand, the operating logic of smartphones is software (i.e., an operating system like in computers), and virtually all the smartphones in the world operate on a very small number of operating systems—Google’s open-platform Android and Apple’s proprietary iOS. This means that as long as software developers can write apps compatible with those operating systems, they will be usable on virtually all smartphones.

Referring back to Table 1, the types of ICT-enabled services low income populations need in order to be truly digitally included, simply cannot be provided through basic or feature phones. Only smartphones (and tablets, which for all practical purposes, are large smartphones) have the required capabilities, especially the ability to support a broad range of apps custom-developed for the needs and demands of specific communities and market segments. Therefore, even as the explosive growth of mobile, SMS- and voice-based services are being celebrated as milestones, we believe real digital inclusion cannot be achieved without smartphones. Currently, because of the prices of even the least expensive smartphones, basic phones and feature phones comprise the majority of devices low income populations use to access ICT in developing countries (Exhibit 6 and Exhibit 7).
Penetration of ICT devices in the developing world

Exhibit 6: Fewer than 50% of people in the developing world use phones and computers. Of them, most use basic phones and feature phones.

Cost of smartphones vs. feature phones and basic phones

Exhibit 7: Smartphones are 2 to 10 times more expensive than high-end feature phones, and significantly more expensive than basic phones.
A citizen ID system is a critical enabler of accountable services, and of broader digital inclusion

In industrialized countries, governments and businesses alike collect an extraordinary amount of information about individuals: birth, educational history, income, financial transactions, residential history, ownership of property, taxes, a myriad of other aspects of life, and even death. The ID validates that an individual, in fact, exists, and people are who they claim to be. The information linked to IDs is used to provide a range of public and private services, and for participation in the broader social and economic system. Indeed, in the typical industrialized country, it is hard to imagine any citizen or business functioning without a primary or derivative ID for even a day, and the importance of individual IDs cannot be overstated. With the ever-increasing volume of data collected, services are promising to become hyper-customized to an individual’s very particular needs and wants. (Of course, recent revelations like the Snowden leaks and the various hacking scandals have demonstrated the risks of having that much data collected and digitized).

The need for some form of ID has been recognized by the governments of developing countries as well (where, as discussed later in this section, formal ID systems are weak, if present at all), and have led to a range of Know Your Customer (KYC) requirements. In India, for example, recognizing the challenges faced by the very poor in verifying their identity, the Reserve Bank of India began allowing alternative methods of verification. Similarly, Kenya’s national ID system helped significantly with KYC requirements, believed to have been critical to the rapid growth of M-Pesa (Oyebode, 2013) (Jentzsch, 2009). Exhibit 8 illustrates the correlation between the existence of a national ID system and population with bank accounts.

While ID systems can be a key enabler of many of the services identified in Table 1, the lack of robust ID systems can have devastating consequences for the poor, and considerably impact a country’s economy. For example, India’s public distribution system (PDS), one of the largest food distribution programs in the world is reportedly laden with fraud and corruption. According to the 2008 Planning Commission report, more than 36% of food grains intended for poor households were sold to non-poor households, and 58% of subsidized grains did not reach beneficiaries. The primary reason is thought to be corruption, perpetuated by the lack of identification of real beneficiaries. The economic costs of such fraud and corruption is massive, given that all of India’s subsidy programs together amount to 14% of India’s GDP (Zelazny, 2012).

In the broader context of global development, the absence of insightful information about particular population segments can lead to uninformed decisions based on broad generalizations about ‘the global poor’. It would then become a case of assuming that the 2 billion low income people in developing countries constitute one monolithic population, rather than an amalgam of many complex and different population segments.

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3 Know Your Customer (KYC) requirements are mandated by the Central Bank of a country, and include information that must be collected and authenticated to validate an individual’s ID before bringing them on board as customers with a bank account for using financial services. In India, KYC-verified customers who had been with a bank for more than 6 months could recommend another person to become a customer by certifying their photograph and address.
Example of the relationship between national ID systems and population with bank accounts

Unidentified population (% of total population)  Bank account holders (% of adult population)

- **Tanzania**: Did not have national ID card system until 2013
  - Unidentified population: 97%
  - Bank account holders: 5%

- **Pakistan**: Had national ID card system since the 1950s
  - Unidentified population: 42%
  - Bank account holders: 12%

- **Cameroon**: Had national ID card system since the 1990s
  - Unidentified population: 31%
  - Bank account holders: 24%

**Exhibit 8**: Having a national ID appears to significantly improve access to financial services (Jentzsch, 2009).

The ‘Internet of Things’ paradigm is enlarging the scope of ICT enabled services

The new paradigm of the Internet of Things (IoT) has led to a plethora of applications in industrialized countries, where remote and traditionally disconnected objects like thermostats, coffee makers, cars, and even light bulbs and animals, are integrated through wireless sensors into internet-based applications running on phones, tablets and computers. Not all such applications are lifestyle oriented though. Examples of current and proposed IoT solutions that help address specific critical needs include: remote monitoring of patient cardiac activity via real-time data transmitted by implanted pacemakers and stints (Govindrajan, 2011); accelerometers (already used in smartphones to adjust screen display orientation) to detect when elderly people fall, and remotely warn relatives or caregivers (Livescience, 2013); satellites and ground sensors that can send information about crops, weather and soil conditions to farmers, to refine fertilizer application and other agronomic activities; making irrigation more efficient by monitoring leaks (McKinsey, 2010). By enabling the use of large volumes of wide-ranging, highly specific, accurate and real-time data in ICT solutions in an automated and radically less expensive manner, IoT solutions can also address the seemingly intractable challenge of collecting information in resource-constrained environments.
KEY CHALLENGES

Digital inclusion in the context of global development is still far from being a reality. Given the full potential of existing ICT tools and what needs to happen to further human development, the ‘Mobile for Development’ (M4D) movement has had negligible impact. Most existing solutions are bespoke, designed for specific user segments, rather than scaled across markets. This has led to a proliferation of incremental, duplicated services (GSMA, 2013). Additionally, even these few existing solutions are typically developed by individuals and companies from industrialized markets, who have limited insights into user needs and constraints in low income settings. There is clearly a stark lack of local ICT capacity in most developing countries. Unfortunately, there are a number of other major hurdles as well.

The cost of expanding coverage of wireless networks to rural areas is very high

Despite the explosion of mobile networks, a sharp urban-rural divide remains. Even when they are within the network, coverage in rural areas remains spotty and is typically not broadband. To provide sufficient bandwidth to a last mile channel for end users, transmission needs to support high throughput of traffic. This requires high-efficiency modulation i.e., high signal-to-noise ratios in conveying a message signal such as a bit stream, inside another signal that can be physically transmitted. Distance is a significant limiting factor for this. The farther the transmitting node from the end user, the lower its effective bandwidth will be. Since rural areas are less densely populated than urban areas, they need a larger number of base stations to serve the same number of people. This requires more equipment (towers, servers, telephony switches) and longer backhaul connections, which leads to higher capital and operating costs. Another challenge is the need for electricity. Rural areas in developing countries are typically off-grid, and diesel and batteries are more expensive than grid power. These factors increase the cost of expanding network coverage to rural areas (where economics are weaker to begin with), and exacerbate the rural-urban digital divide (GSMA, 2013) (Scientific American, 2013).

Not surprisingly then, network sites are concentrated in areas that are on-grid, and mobile penetration in developing countries is almost double in urban areas compared to rural areas (Exhibit 9).

Network coverage in on-grid vs. off-grid areas

Exhibit 9: Mobile networks sites are very sparse in areas that are off-grid and where mobile towers are powered mostly by diesel generators and batteries. Renewable energy solutions are yet to take off.
Smartphones are not affordable for low income consumers (although prices appear to be dropping rapidly)

Many factors contribute to the retail price of smartphones. The cost of manufacturing is only one. Still, examining the bill-of-materials (BOM) is instructive on the challenges involved in making them affordable. As Exhibit 10 shows, the BOM for a hypothetical average smartphone (Nomura Equity Research, 2012) is highly fragmented: of the total BOM of $130, no single component costs over $20, and most cost less than $10. Hence, it will be difficult to dramatically reduce the overall manufacturing cost.

Please note that this data is from 2012, and will soon be out-of-date considering the ever-falling cost of IT components. For example, the price of the 16GB internal flash memory, the most expensive component cited in Exhibit 10, dropped from $19.20 in 2011 to $10.40 in 2012 (IHS Technology, 2012). Modularization in manufacturing (e.g., off-the-shelf chipsets and turn-key systems including phone designs and chips preloaded with Android and other software, offered by large chip makers like MediaTek and Spreadtrum) has significantly reduced costs. Tradeoffs in components like cameras, LCD screens and batteries have reduced costs further. Finally Google’s free Android operating system has been a significant driver of the proliferation of less expensive smartphones across brands. As of early 2014, there have been some media reports of Chinese vendors manufacturing low-end smartphones for $40 (MIT Technology Review, 2013); around the same time, Mozilla announced a $25 smartphone for emerging markets, seemingly the same model which retails for $70 in the US (BBC, 2014). However, the functionality and usability of these lower cost smartphones is yet to be seen.

Illustrative bill-of-materials for an average smartphone

Exhibit 10: Components for processing applications (processors and memory chips), and for display (glass and touchscreen parts) are the most expensive parts of the average smartphone.

Note that the most advanced smartphones on the market likely use much more sophisticated and expensive components.
Institutions to develop and oversee reliable ID systems are weak or non-existent in developing countries.

In a country like the US, a consortium of agencies—the Department of Motor Vehicles, the municipal birth registry, the passport agency, the Social Security Administration, and others—collectively ensure that citizens are part of the formal state system. The first official ID—a birth certificate—is issued shortly after a child is born, on the strength of the parents’ ID. Such institutions are weak in developing countries, and usually do not reach low income or rural populations. As a result, only 44% of children in sub-Saharan Africa are registered today, with rates going as low as 3% in countries like Somalia. Globally, almost 50 million births are not registered (UNICEF, 2010).

While technology for expanding robust national ID systems exist, and are not a barrier per se, there are practical barriers such as the lack of funding or political will on part of the government, a lack of awareness or interest on the part of citizens, and the logistical complexity of bootstrapping such a system in which the majority of people do not have any proof of their identity.
Digital inclusion, by definition, is about access to technologies, and the services those technologies enable. In developing countries, ICT and ICT enabled services can go a long way in compensating for gaps in physical infrastructure, institutions and human capital. The proliferation of mobile phones and the Internet, and the services they have enabled, bodes well for the potential impact of true digital inclusion on broader human development. We believe that 4 breakthroughs—two of which are broad and systemic—can pave the way for true digital inclusion for low income populations.

A new generation of wireless broadband network technologies that radically cut the cost of expanding coverage to rural areas

In developing countries, networks—wired or wireless—are largely missing in rural areas, or are lacking the bandwidth to support the full breadth of essential ICT enabled services. The network economics of conventional cellular technologies that work for urban areas—typically densely populated—do not translate well to rural areas. With existing technologies, setting up adequate infrastructure requires more towers, base stations, backhaul, and electricity (through the grid or off-grid options like diesel generators) for people living in rural areas, than for the same number of people in an urban area. Network technologies that allow greater spans of the network, and can operate wirelessly over large distances (with equipment that costs less and is less energy-intensive), can radically improve the economics of rural broadband coverage.

Instead of the current mobile network paradigm (i.e., blanket coverage with many small, adjacent cells, each supported by a base station), one approach is to use a tiered networking model with inexpensive, low-power and limited-range devices. In such a system, smartphones connect via Wi-Fi or cellular radio to nearby network access points powered by off-grid electricity. These access points can then connect to a macro station (directly or via intermediate repeater sites) over frequencies from unlicensed/unused portions of the radio spectrum (i.e., ‘white space’), such as the frequencies usually reserved for TV or ISM (industrial, scientific and medical) communication (Pietrosemoli & Zennaro, 2013). The macro cell station, in turn, can connect via broadband to the nearest available PSTN node. Recent trials in Cape Town have demonstrated that such technology can successfully deliver broadband access. Similar trials have now been launched in Tanzania and Kenya (Google, 2013) (Microsoft, 2013). However, the technology for operating networks using this backhaul is in early stages, and the necessary equipment is still sub-scale. In addition, very few countries allow the legal use of ‘white space’ for commercial use.

An alternative for the backhaul is to use low and medium altitude (LEO and MEO) non-geostationary satellites that constantly move in fixed orbits around the earth. However, a large number of such satellites will be required to provide continuous coverage. Although LEO and MEO services are increasingly becoming commercially available, they are still too expensive to be feasible at scale. Yet another approach is to use aerial equipment in the stratosphere—such as the Google ‘loons’, which use balloons—at altitudes of 18-27 km to provide Internet to rural areas via radio links. Facebook is also experimenting with solar-powered drones at altitudes of 20 km to provide data at speeds at par with fiber optic cables using infrared lasers (MIT Technology Review, 2014).

The various technologies that can make wireless broadband a reality in low income rural areas, are in different stages of development: modified Wi-Fi is already commercially available; LEO and MEO satellite services are rapidly emerging but still 3-5 years from becoming a realistic option; and aerial backhaul systems could be ready in 1-3 years.

Even as such technologies are becoming market-ready, there will be a number of deployment
challenges. Many countries have regulatory constraints on the use of the radio frequency spectrum. Commercial wireless services providers need operating licenses from the country’s regulatory authority, unless they use unlicensed bands, on which there is no protection from interference from other users. Acquiring licenses to use a particular band needs significant technical expertise, time and money, and leasing spectrum from existing carriers can be cumbersome. Regardless of which technology is used, there is clear need for developing enough infrastructure. In addition, even as the technologies are being developed, there are no proven business models. Therefore, deployment will be CHALLENGING.

**Breakthrough 1 - Difficulty of deployment**

<table>
<thead>
<tr>
<th>Difficulty</th>
<th>Policies</th>
<th>Infrastructure</th>
<th>Human capital</th>
<th>Access to user finance</th>
<th>Behavior change</th>
<th>Existing demand</th>
<th>Market fragmentation/Distribution channels</th>
<th>Business model innovation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extremely</td>
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<td>Challenging</td>
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<td>Feasible</td>
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**Affordable (under $50) smartphones that support full-fledged Internet services and need limited electricity to charge**

To be ‘digitally included’, low income populations in developing countries need a fundamentally different set of ICT tools and services, compared with their counterparts in industrialized countries. These services will vary from one user segment to the next, as will language and other aspects of information sharing and service delivery. The ideal device (i.e., a mobile phone) needs to accommodate a high degree of customizability, and should be able to access services and rich information which can be delivered only over the Internet. Only smartphones—rather than basic or feature phones—have the platform capabilities to accommodate this. Access to affordable smartphones will create a virtuous cycle in developing countries—much like the creation of the Worldwide Web did in industrialized countries—by dramatically increasing users’ access to many different types of services. This, in turn, will lead to a jump in the sources and types of available applications and information.

Low income users often cannot afford even basic phones. For example, even in South Africa, a middle income country, fewer than 40% of rural consumers own phones. Smartphones, currently costing anywhere from 3 to 20 times as much, are not a realistic option. It stands to reason, therefore, that smartphones will have to cost considerably less than $50 (the current retail price of the average basic phone) to be affordable. The biggest challenge in reducing the cost of smartphones is that there are many components and the cost—
Biometric ID systems, linking birth registry, land title registry, financial services, education history, medical history, and other information critical for ICT enabled services

Individuals born in industrialized countries have formal IDs, which are linked to a range of services vital to their wellbeing and empowerment, and are an intrinsic part of their day-to-day lives. This system ensures that all citizens are counted, that their voices are heard, and that they receive the public services they are entitled to.

While some developing countries have some systems for issuing IDs for their citizens, these are not mandatory. As a result, these IDs are neither issued until applied for nor used widely, especially in rural areas. In the absence of IDs for individuals and businesses, and in the absence of a system of services linked to IDs, citizens of those countries continue to live in informal economies. They cannot easily establish citizenship or legal title of land or property, cannot access loans and other formal mechanisms of finance, and if repressive...
governments so wish, the fact that they ever even existed can be denied. In addition, few small businesses have any legal standing, independent of their owner. Investing in business growth then becomes either a personal risk for the owner or depends solely on trust between the owner and an investor. In other words, the absence of IDs is a fundamental barrier to economic and human development.

Industrialized countries have a network of functioning institutions—birth registries, passport agencies, national ID etc.—which rely on each other’s validation to grant IDs. Such an institutional framework is missing in developing countries, especially for the rural poor. With only a minority of the citizens holding any form of valid ID, developing countries have to ‘bootstrap’ systems. India’s recently launched Aadhar—a unique identification system—is an example of one such large-scale program, in which virtually the entire population of the country is being registered with unique IDs (UIDAI, 2014). Similarly, Rwanda has also embarked on an ambitious national ID program. There appears to be a growing chorus of voices in favor of such systems (World Economic Forum, 2012) (Yudhoyono, et al., 2013).

ID is established using a combination of three (or more) modes: something one can carry (e.g., a plastic card), something one knows (e.g., a password), or something physically intrinsic and unique to each individual (i.e., a biometric such as fingerprints, iris, or face). The more the modes of identification, the more robust the authentication will be, but it also increases the complexity and cost of enrollment and authentication. A key factor in scaling the Aadhar system is its fingerprint biometric. Biometric-based ID systems are generally accurate, scalable and relatively fraud-proof, they can be digitized, and individuals no longer have to carry any documents which can be lost, stolen, damaged or forged. There are, however, differences in the various types of biometrics with respect to cost and accuracy. Fingerprints, for example, have higher false positive rates than iris scans but are less expensive and less intrusive. Facial recognition, on the other hand, has not proved reliable yet under imperfect lighting and other complicated conditions.

While biometric sensors and data management systems for health records, land registry etc. exist, there are no integrated systems that tie, for example, a unique biometric identifier to a GPS-mapped land parceling and registry system, nor are there systems that tie someone’s educational or health histories to their ID. While all the components are already available, creating robust integrated systems will take considerable work. Given the initiatives underway in countries like India and Rwanda, it is likely that a reasonably integrated system will be in place within the next 2-3 years. The challenge will be in creating a system of software components that can be replicated by other countries.

It is important to note that there are serious and legitimate concerns about mandatory ID systems, and about biometric IDs in particular. Digitized systems make it possible for governments and other powerful parties to easily access large volumes of information about citizens and communities. This opens the door for easy abuse of this information. By enabling surveillance of targeted individuals and communities, biometric ID systems can aid the creation of police states. The more integrated the ID systems are with other aspects of life, the easier surveillance becomes. One can imagine the dangers of a system which has facial recognition, GPS-based tracking of mobile phones, and any data on ethnic or religious identity. Integration of personal information also exposes people to hacking and theft of personal information. It will be very important that stringent international standards—with respect to protection of privacy and civil rights, as well as for data security—are in place before such systems are deployed. As of early 2014, most industrialized countries lacked comprehensive laws about biometric data, and most African and Asian countries did not meet international criteria that are considered to be adequate for hosting and protecting data (Scientific American, 2013) (ITU, 2012). In fact, as of early 2014, India’s Aadhar system was not formally recognized by its laws or courts, and remained a parastatal effort.

Beyond the significant regulatory constraints, a national biometric ID system will require the installation of large numbers of biometric sensors, other hardware, and related software, which will link the various system components. It will also take considerable behavior change to implement. Finally, the logistical challenges involved in reaching remote populations will be daunting. Considering these hurdles, deployment will be EXTREMELY CHALLENGING.
A new generation of ‘Internet of Things’ (IoT) devices, which enable newer types of services, and compensate for gaps in infrastructure, effective institutions, and human capital

The Internet of Things (IoT) paradigm is about a vast array of distributed actuators, devices and sensors embedded into objects used in day-to-day life, to monitor the performance of people and objects, improve the performance of appliances, and provide a range of new services to individuals and institutions. In developing countries, the absence robust infrastructure, effective institutions and reliable human capital, increases the dependence on IoT devices and corresponding ICT enabled services. Examples of such services include:

- **Health**: Point-of-care diagnostic devices that can use cloud computing and smartphones for rapid analysis, and access a patient’s medical records using biometric systems.

- **Agriculture**: Location-based agronomy and extension tools for activities like determining soil condition and identifying pests and pathogens.

In these early years of the IoT paradigm, there is a yawning gap between what is technically possible and what is commercially available, even in industrialized countries, and more so in developing countries. Specific timelines for market readiness will vary by the type of device; some are already on the market, some could be a decade away.

Deployment challenges will also vary by the type of solution and service. Some common challenges are:

- Technology fragmentation, lack of standards and interoperability, lack of standardized hardware and software components that are optimized for specific uses and easy to integrate.
- Availability of supporting infrastructure and devices.
- Availability of complementary products and services.
Considering the above, deployment will be EXTREMELY CHALLENGING.

**Breakthrough 4 - Difficulty of deployment**

- Need for behavior change and imperfect understanding of behaviors, needs and incentives.
- Complexity and cost of operations and maintenance.
- First entry cost and need for and availability of consumer financing.
- Regulations, which are still evolving even in industrialized countries.
- Need for—and ease of—customization and configurability.
- Absent or underdeveloped distribution channels.
- Weak market institutions that increase the cost and complexity of doing business, as well as weak public institutions for security and privacy protection.

Considering the above, deployment will be EXTREMELY CHALLENGING.
WATER
Water is one of the world’s most critical natural resources. Essential for virtually every form of life on the planet, it is also a key input for producing food and energy. By all accounts, the world is facing a multi-faceted water crisis: depletion of groundwater, shrinking bodies of surface freshwater, pollution of sources of drinking water for humans and animals alike, rising sea levels, acidification of ocean water; and the list goes on. While there are many specific issues constituting this global ‘water crisis,’ our study focuses narrowly on the issues impacting the health, lives, and livelihoods of the global poor in developing countries. As such, this study does not discuss other important water-related challenges, such as damage to the environment and ecosystems, and water scarcity in industrialized countries.

The challenges related to water for developing countries are different from those facing industrialized countries. Not surprisingly, there are also some significant differences between the challenges in South Asia and those in sub-Saharan Africa, due to population density, the relative differences in development, and the impact of intensified agriculture launched by the Green Revolution in South Asia (Spielman and Pandya-Lorch 2009).

Usage of water varies significantly between industrialized and developing countries, and even between different developing regions of the world. Exhibit 1 and Exhibit 2 show how much water different regions of the world use, and for what purposes (FAO 2014). Around the world, a total of 3.9 trillion cubic meters of water is consumed each year. This is roughly equal to 8 times the volume of Lake Michigan, one of the world’s Great Lakes, which covers an area of 22,300 square miles, with an average depth of about 280 feet (US Environmental Protection Agency 2014). Among the various regions around the world, South Asia is the largest consumer (26%), followed by East Asia and the Pacific (19%), and North America (13%). However, on a per capita basis, North America is the largest consumer of water, using almost 1,600 cubic meters per year. South Asia uses one-third of that, and sub-Saharan Africa uses less than 10% of what North America consumes per capita. In high-income regions (e.g., EU and North America), 45-50% of water is used for industrial purposes, particularly energy production. In sub-Saharan Africa and South Asia, on the other hand, agricultural irrigation accounts for the largest use of water.
Exhibit 1: On a per capita basis, citizens of North America use the most water in the world, people in sub-Saharan Africa use less than 10% of that, and usage in South Asia and other regions is in between. In aggregate, however, South Asia consumes the most water, followed by East Asia and the Pacific, and North America. Sub-Saharan Africa uses only 6% of the global water supply.

Exhibit 2: Globally, about 70% of water is used for agriculture, driven heavily by developing countries. In developed countries, industrial applications (particularly energy production) account for the largest use.

The primary sources of water vary between regions, based on both geophysical and economic constraints. Populations draw water from the sources that are most easily accessible in the near term. The two main sources for fresh water are under the ground (known as groundwater), or on the surface (lakes, rivers and other reservoirs, known as surface water). The easiest way to access water is from nearby surface sources.
As a result, 75% of water used around the world is from surface sources (Exhibit 3). The rest comes mostly from underground aquifers, and a negligible amount (0.2%) is drawn from desalination of brackish or saline seawater. Industrialized countries rely on surface sources for 70-80% of their water, largely on the strength of extensive infrastructure involving dams, reservoirs, canals and pipes for distribution.

In South Asia, the Green Revolution (Spielman and Pandya-Lorch 2009) and the subsequent intensified agricultural practices have led to a heavy reliance on groundwater, with mechanized pumps being used to draw the water to farms. In sub-Saharan Africa, on the other hand, the absence of comprehensive agricultural development programs has limited construction of wells and access to irrigation systems, thereby restricting local groundwater consumption. As a result, more than 90% of what little water is consumed in sub-Saharan Africa, is from surface sources (FAO 2014).

Sources of water in different regions of the world

Exhibit 3: Globally, 75% of water used for various human activities is from surface sources (rivers, lakes, dams). Surface sources account for 91% of all water used in sub-Saharan Africa, but a relatively lower share (66%) in South Asia.

Different regions of the world face a combination of different water-related stresses: physical scarcity, unsustainable use, economic scarcity, and quality

Over the past few decades, population growth, agricultural development, and broader economic development have led to a significant increase in water consumption. Consequently, there has also been a shrinkage of renewable water sources. South Asia is facing a particularly dire shortfall. The per capita renewable water supply in the region is a fraction that of other areas that depend primarily on agriculture (Exhibit 4). Only the Middle East and North Africa region—largely a desert region—has less water per
capita. Exhibit 5 shows the per capita fresh water shrinkage between 1962 and 2012 (FAO 2014). Globally, there has been a reduction of 59% in per capita renewable water over the past five decades. A number of large countries in sub-Saharan Africa and South Asia have witnessed greater declines than the global average, including Pakistan (73%), India (62%), Nigeria (72%), Kenya (80%), and Uganda (80%). It is important to note that due to its large population, South Asia began with an already low base of per capita supply.

Renewable water sources available per capita

Exhibit 4: South Asia is currently facing a severe water shortage. Only the predominantly arid Middle East & North Africa region has less renewable water than South Asia.
Exhibit 5: A number of large countries (with population over 20 million) are facing dramatic reductions in water supply on a per capita basis, due to population growth and dwindling supplies. In Kenya, for example, per capita renewable water has shrunk by 80% over the past 50 years. In Pakistan, it has shrunk by 73% in the same period, while India has witnessed a 62% reduction (from an already low base). By comparison, the global average reduction between 1962 and 2012 is about 59%.

Exhibit 6 shows the parts of the world that are experiencing physical water scarcity due to intrinsic geographic constraints (e.g., desert countries in the MENA region), or as a consequence of heavy consumption (e.g., India and Pakistan). A number of analyses have concluded that the situation is grave enough that even within the next decade water scarcity in these regions can destabilize countries, threaten food security, and lead to water being used as a ‘weapon’ in cross-border negotiations (US Intelligence Community Assessment 2012) (Goldenberg 2014). In addition, there appears to be a continued increase in the frequency and severity of ‘water wars’ between pastoral communities in the Horn of Africa (Pavanello 2009) (Yale University 2010).

Exhibit 6 also shows regions facing economic scarcity. These are areas where the population cannot access water—which may be available in abundance—due to the lack of infrastructure (dams, canals, large-scale pumps, and piping systems), and because most households are too poor to invest in small-scale boreholes and pumps. As a result of economic water scarcity in sub-Saharan Africa, the vast majority of smallholder farmers do not have access to adequate irrigation. Not surprisingly then, agricultural yields in the region are a fraction of that in other food producing parts of the world, and food insecurity has been an ongoing crisis on the African continent for decades. Only 6% of cultivated land in Africa is irrigated, compared with 37% in Asia. Most importantly, of the total irrigated land in Africa, more than two-thirds is concentrated in 5 countries—Egypt, Madagascar, Morocco, South Africa, and Sudan. Only 2 of these countries are in sub-Saharan Africa (IFPRI 2010).
Causes of water scarcity across the world

Exhibit 6: Water scarcity can be due to physical reasons (i.e., there is no water in the area), or for economic reasons (i.e., the water is physically present, but the majority of the population cannot access it). Most of sub-Saharan Africa faces economic scarcity. South Asia faces a combination of both types of scarcity (IWMI 2007).

Yet another type of water problem has to do with the quality of drinking water. The majority of people in many developing countries lack access to adequate sanitation facilities, as a result of which there is a high prevalence of open defecation. Human fecal matter carries a range of bacteria, viruses, parasites and helminthes, which can enter drinking water sources that are not adequately protected. The WHO defines water sources protected from such fecal pathogens (e.g., due to appropriate construction or piping) as “improved” (WHO/UNICEF Joint Monitoring Programme 2008). As Exhibit 7 shows, 28% of the population in sub-Saharan Africa lacks access to an improved water source. South Asia is slightly better off, with 12% lacking access. Exposure to fecal pathogens causes widespread diarrheal disease, which is among the leading causes of mortality among children under 5 in sub-Saharan Africa and South Asia (Exhibit 8).
Exhibit 8: Diarrheal disease is the 3rd leading cause of mortality (along with malaria) among children under 5, in aggregate across sub-Saharan Africa and South Asia.

Exhibit 7: The WHO defines ‘improved water sources’ as those protected from contamination by fecal matter. Across sub-Saharan Africa, 28% of the population does not have access to such sources. South Asia, with 12% of the population lacking access to an improved water source, is on par with other developing regions like Southeast Asia. In high income countries, virtually 100% of the population has access to improved sources of water. It is important to note that merely having access to improved water sources does not mean that people are fully protected from polluted water.
Only 13% of the world’s population lives in countries not significantly impacted by 1 or more of the 3 water-related problems.

Exhibit 9 shows the percent of the global population facing each of the aforementioned problems: physical scarcity, economic scarcity, and poor quality. This is based on LIGTT’s analysis, combining definitions and data from multiple sources. We categorize a country as facing a water quality problem, if the annual disability adjusted life years (DALYs) lost from water-related diarrheal diseases exceed 1,000 per 100,000 people, according to the WHO. For physical scarcity we use UN-Water’s definition from its water scarcity analysis (UN-Water 2013). We use the UN Environmental Programme’s definition of water-stress (which is based on the ratio of water withdrawal to available water) to categorize countries as facing a problem with unsustainable use (UNEP 2008). We categorize a country as facing economic scarcity, also using the UN-Water definition (UN-Water 2013).

Based on these definitions, only 13% of the world’s population lives in countries without any major water-related problems; these countries include Brazil, Russia and Japan. The remaining 87% of the world’s population lives in countries that face at least 1 of the 3 problems.

- Sub-Saharan Africa and South Asia primarily bear the brunt of economic scarcity. Ironically, these regions are also dominated by agriculture and smallholder farming.
- 26% of the world’s population, including countries like India, Kenya and Sudan, faces all 3 problems simultaneously.
- Bangladesh, Nigeria and Ethiopia are among the countries facing poor quality and economic scarcity; these countries constitute 10% of the world’s population.
- 45% of the global population, living in countries like the US, China, Mexico and Germany, is facing shortages due to physical scarcity or unsustainable use. Of these, China and Mexico (along with Egypt, Turkey and others), currently face physical water scarcity, while the US, Germany and others are using their water unsustainably.
- Pakistan and South Africa (4% of global population) are the main countries at the intersection of quality and physical scarcity/unsustainable use.
- A very small number of countries face the challenges of quality or economic scarcity, in exclusion of the other problems.

1 DALYs are discussed in greater detail in the Global Health section. Note that Bangladesh is slightly below the 1,000 DALYs lost per 100,000 people threshold even though it is included in the list of countries facing water quality problems.
How different countries are affected by the 3 major water-related problems

Exhibit 9: The world’s ‘water problem’ can be characterized as the intersection of three challenges—physical scarcity and/or unsustainable consumption (i.e., areas with intrinsically limited water, or where it is being overdrawn), economic scarcity (where water is present, but the population does not have the economic means to access it), and quality (due to contamination of drinking water by biological or chemical pathogens). Different countries, based on their geography, population, level of development, economic activity, and management practices, face different combinations of these challenges. According to our analysis, 87% of the world’s population lives in countries that face at least 1 of these 3 problems; 40% lives in countries facing at least 2 of the 3 problems, and 26% lives in places facing all 3 problems at the same time. The exhibit also lists some of the countries in each category.
OBSERVATIONS AND RECENT TRENDS IN WATER ACCESS, QUALITY AND SUSTAINABILITY

Our analysis should be considered in light of the observations and trends outlined below.

Water scarcity is, at once, a truly global issue as well as a hyper-local issue. On one hand, severe water problems can lead to major geopolitical challenges due to interstate competition over water sources, food insecurity, famine, and large-scale human displacement. On the other hand, even within regions or countries that otherwise have sufficient water, without a means to transport water, abundance in one locality does not guarantee an adequate supply in a nearby locality even a few miles away. Hence, the latter locality may need to find its own source, or encroach on its neighbor.

There is a serious dearth of data on water at the local level. Much of the data about water—especially about groundwater supply levels—is very sparse, and data at district or municipal levels is absent (or unreliable) in most developing countries. As a result, it has proven very difficult for national or regional level decision-makers to make informed judgments about water policy and infrastructure development.

A water scarcity problem can lead to a water quality problem. Major reductions in water supply in low income countries can cause the poorest population segments to settle for water of poor quality. Similarly, people who have to travel a long distance to collect clean water are likely to settle for water of lower quality from a nearby source.

In developing countries, it is more appropriate to think of water as part of the water-food-health-conflict nexus. Water is often discussed as a part of the water-food-energy nexus (World Economic Forum 2011). It is important to note that this construct applies primarily to industrialized countries where water is heavily used for energy production. We need to think of water-related problems as part of a more complex nexus in the developing world context, where the lack of access to water is leading to food shortages and conflict over control of water, and poor quality of drinking water is causing many millions of deaths each year.
As the discussion so far demonstrates, the water problem has multiple facets—access, quality, sustainability—and affects many facets of global development. Having recognized the intersection of these issues in this section, we conduct deeper analyses of the specific issues in other sections. Each of the above water-related problems is discussed in a separate section of this study, as explained below.

1. **We analyze economic water scarcity in the chapter on irrigation, in the section on Agricultural Development and Food Security.**
   
   This is primarily because economic scarcity largely affects countries with large rural populations dominated by smallholder farming. We identify 5 breakthroughs in that chapter.
   
   - Low cost drilling technologies for shallow groundwater, which reduce the cost to under $100 per farmer
   - Low cost, easy-to-construct rainwater storage repositories where harvested rainwater can be stored for several months without contamination
   - Affordable (under $50), lightweight, fuel efficient solar-powered irrigation pumps
   - Low cost precision irrigation application system, ideally combining fertilizers with irrigation
   - Portable sensors for estimating depth of shallow groundwater

2. **Water quality is addressed in the chapter on diarrheal diseases, as a part of the section on Global Health.**

   We identified 5 technological breakthroughs for improving access to sanitation and clean water.
   
   - Resource recovery systems for fecal waste, in order to enable financially sustainable solutions for sanitation.
   - Next generation toilets or homes with in-home toilets, especially for the urban poor
   - Additives to facilitate the breakdown and/or disinfection of fecal sludge in pit latrines
   - Water pumps that automatically purify with chlorine
   - Extremely simple and affordable point-of-use water treatment systems

3. **Solutions for sustainable water use (and to smaller extent, intrinsic physical scarcity) are discussed in the section on Resilience Against Climate Change and Environmental Damage.**

   The section also discusses the effects of climate change (such as uncertainty of precipitation, and extreme weather events like floods and drought), chemical pollutants like arsenic, overfishing, and increasing salinity levels. Of the 6 breakthroughs identified in this section, 4 are relevant to sustainable water use.
   
   - A scalable, low cost method to desalinate water using renewable energy
   - Low cost system for precision application of agricultural inputs, ideally combining fertilizers and water
   - A scalable method for sustainable integrated aquaculture production
   - Low cost, distributed monitoring sensors to identify environmental toxins and their concentrations

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2 Note that this breakthrough is highlighted in a number of other topics as well, including irrigation.
The lack of proper irrigation is a critical constraint to increasing agricultural productivity for smallholder farmers in sub-Saharan Africa. With proper irrigation, not only can farmers improve their crop yields, but diversify their crop portfolio toward higher income crops and increase the total number of harvests in a given year. However, smallholder agriculture in sub-Saharan Africa is largely rain-fed, which results in a limited window for farmers to irrigate their fields.

There are a number of reasons why African farmers do not have access to irrigation systems: there is limited awareness of the value of irrigation; diesel pumps are currently too expensive, and diesel supply is both sparse and expensive; even most manual pumps are too expensive, in addition to being very strenuous to use (especially for women); lastly, digging wells is also a prohibitively expensive proposition.

Current data suggests that there is an adequate supply of shallow groundwater (rechargeable by rain) across much of sub-Saharan Africa. However, the experience from intensified agriculture in South Asia demonstrates that groundwater can easily be depleted if not sustainably used. Our analysis concludes that 5 technological breakthroughs can lead to significant improvements in the overall agricultural productivity of smallholder farmers in sub-Saharan Africa.

- Low cost drilling technologies for shallow groundwater, which reduce the cost to under $100 per farmer
- Low cost, easy-to-construct rainwater storage repositories where harvested rainwater can be stored for several months without contamination
- Affordable (under $50), lightweight, fuel efficient solar-powered irrigation pumps
- Low cost precision irrigation application system, ideally combining fertilizers with irrigation
- Portable sensors for estimating depth of shallow groundwater
Soil moisture, usually enabled by irrigation, is one of the key drivers of agricultural productivity. Studies have found that irrigation can lead to substantial increases in productivity from 50% (IFPRI, 2010) to over 100% (Molden, 2007).

CORE FACTS AND ANALYSIS

Irrigation offers several critical benefits for smallholder farmers including increased crop yields, the possibility of cultivation even during dry seasons and droughts, and the opportunity to grow high value, high nutrition crops. Since the Green Revolution, even as intensified agricultural practices in other parts of the developing world have led to greater adoption of irrigation, sub-Saharan Africa has lagged far behind. Most smallholder farmers in Africa have historically relied on rainfall as the sole source of water and still do. Irrigation technologies remain largely out of their economic means. Currently, only about 6% of farmland in the region is irrigated (Exhibit 1). As a result, cereal production closely follows the amount of rainfall in any given year (Exhibit 2) (McIntyre, Herren, Wakhungu, & Watson, 2009) (Molden, 2007).

It is important to note that South Asia and sub-Saharan Africa face different challenges with regard to irrigation: much of South Asia\(^1\) is struggling with major long-term water scarcity due to overuse and population pressures, while sub-Saharan Africa is facing the problem of inadequate access to seemingly available water.

**Share of rain-fed vs. irrigated arable land in developing countries**

![Graph showing share of rain-fed vs. irrigated arable land in different regions](#)

**Exhibit 1:** Most of the agricultural land in most developing countries is rain-fed. This is especially true for sub-Saharan Africa.

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\(^1\) With the exception of Bangladesh and Indian states like Orissa, which were not deeply involved in the Green Revolution.
Rainfall and cereal yields in Burkina Faso

Exhibit 2: Cereal production in Africa is closely linked to rainfall, as shown in this study from Burkina Faso (Molden, 2007).

There appears to be abundant shallow groundwater in sub-Saharan Africa; however most farmers cannot access it because they cannot afford pumps.

Exhibit 3 shows a hydrological map of Africa, according to which there appears to be abundant shallow groundwater (at a depth of 7 meters or above) through much of sub-Saharan Africa. It is important to note that water is a highly localized resource; availability at a certain depth in one area does not necessarily imply availability at the same depth in an adjacent area. As things stand, the only available data is in the form of large-scale surveys and maps, which is an imprecise method of estimating local water availability. Still, several studies have found that there is groundwater at shallow depths across most of sub-Saharan Africa. In Ethiopia, for example, it is estimated that roughly 1.9 million hectares of arable land can be irrigated using household-level irrigation systems. This is 5 times the total area currently irrigated (Ethiopia ATA, 2014).

Despite the availability of groundwater, most African smallholder farmers do not have the economic wherewithal to access the water because pumps and other irrigation equipment are too expensive. As such, sub-Saharan Africa is considered to be a region of ‘economic water scarcity’ (FAO, 2012) (Exhibit 4).
**Hydrological map of groundwater in Africa**

*Exhibit 3:* Current data suggests that there is substantial unutilized groundwater through much of sub-Saharan Africa (British Geological Survey, 2014).

**Water scarcity around the world**

*Exhibit 4:* Most of sub-Saharan Africa is considered to be facing ‘economic water scarcity’ because the majority of the population cannot afford the pumps and other equipment to access available water. By contrast, parts of the world that do not have adequate water present, are considered to be facing ‘physical water scarcity’ (IWMI, 2007).
Irrigation involves several steps, all of which are currently under-developed for smallholder farmers in sub-Saharan Africa

There are 5 separate steps involved in the process of getting the water from the source, all the way to crops on the farm, as outlined below.

- **Capturing** the water in an artificial central reservoir at the community level. This can take the form of small hand-dug wells, to borehole wells, all the way to dams. A small number of farmers live near natural bodies of surface freshwater, and do not need artificial reservoirs.

- **Lifting** the water from the central reservoir to a local (e.g., on farm) reservoir or tank. This can range from carrying buckets manually, to manual pumps and motorized pumps. As discussed later in this section, manual pumps have severe limitations on the depth from which they can lift water, while motorized pumps are very expensive.

- **Storage** at a local (e.g., on-farm) reservoir or tank. This can range from small drums, to overhead tanks, ponds, and large tanks equipped with their own pumps.

- **Distribution** from the local reservoir to the plant. This can range from furrows in the field (which are flooded by the farmer), to hoses/pipes, and elaborate canals. Most smallholder farmers depend on rainfall, and even those who use irrigation systems do not have access to anything beyond the most rudimentary hoses.

- **Application** of the water to the crops. In the case of simple methods like furrows, there is no additional application mechanism. For piped systems, application systems range from regular hoses, to drip hoses, small sprinklers, and large-scale systems like mobile sprinklers and pivots which can cover considerable acreage. Not surprisingly, smallholder farmers typically do not use anything beyond basic hoses for application.

Table 1 illustrates the irrigation ‘technology staircase’, showing the various levels of sophistication for each of the above five steps, along with the approximate cost of technologies and installations at each level of sophistication (Interview, 2014).
The irrigation technology staircase

<table>
<thead>
<tr>
<th>Steps</th>
<th>Levels of sophistication</th>
<th>Basic</th>
<th>Limited</th>
<th>Medium-scale</th>
<th>Large-scale, sophisticated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capture</td>
<td></td>
<td>Small hand-dug well ($50-$200)</td>
<td>Borehole ($300-$1,000)</td>
<td>Deep borehole or small dam ($1,000-$3,000)</td>
<td>Community dam (&gt; $0.5 million)</td>
</tr>
<tr>
<td>Lift</td>
<td></td>
<td>Hand-carried by bucket ($0)</td>
<td>Treadle pump, hand pump or rope pump ($50-$100)</td>
<td>Small motorized pump, or animal drawn pump ($100-$150)</td>
<td>Large motorized pump (&gt; $1,000)</td>
</tr>
<tr>
<td>Storage</td>
<td></td>
<td>Drum or small pond ($50-$200)</td>
<td>Artificial pond ($300-$1,000)</td>
<td>Small reservoir or groundwater recharge ($1,000-$3,000)</td>
<td>Large reservoir or community dam (&gt; $0.5 million). Note: this can be the same as the reservoir used for capture.</td>
</tr>
<tr>
<td>Distribution</td>
<td></td>
<td>Furrow ($0)</td>
<td>Ditch, small canal, or basic hose ($10)</td>
<td>Small network of pipes or canals ($500-$2,000)</td>
<td>Extensive network of pipes or canals (&gt; $2,500)</td>
</tr>
<tr>
<td>Application</td>
<td></td>
<td>Pour/furrow ($0)</td>
<td>Hose, or drip/trickle kit ($10-$25)</td>
<td>Automated drip, single sprinkler, or sprinkler system ($500-$2,000)</td>
<td>Pivots or large mobile sprinklers (&gt; $2,500)</td>
</tr>
</tbody>
</table>

**Table 1:** The irrigation ‘technology staircase’, shows the various levels of sophistication for each of the 5 steps involved in irrigation. Most smallholder farmers in sub-Saharan Africa have access only to the ‘basic’ level of equipment and tools.
KEY CHALLENGES

In developed agricultural ecosystems, water is captured either by a dam or deep boreholes. Lift is achieved with large electric or diesel pumps, and water is then stored in large reservoirs, and/or distributed directly to the points of usage via extensive canal networks. Finally, it is applied to the crops via large pivot sprinklers for broad application on large farms, or intricate drip systems for more targeted application. Such irrigation infrastructure and technologies are neither available, nor affordable for smallholder African farmers. The following are some of the major hurdles.

1. There is a lack of demand for irrigation among African smallholder farmers

Irrigation is a relatively new practice in much of sub-Saharan Africa, and few farmers have witnessed the tangible economic benefits they can derive from irrigation. Most farmers in the region are subsistence farmers, and are understandably wary of investing their already scarce resources into expensive, and seemingly unproven, irrigation systems. As a result, they have been unwilling to change traditional practices and still depend on rainfall as the primary source water for their crops. While irrigation system costs could theoretically be shared among farmers within a community, such models have not shown the ability to scale yet.

2. Drilling wells is expensive, and unaffordable for subsistence farmers

The cost of drilling is driven by capital equipment, fuel and labor. High competition in emerging economies like India has historically pushed down the overall costs of drilling a bore. Such competition does not exist in Africa, and hence the cost of equipment is generally higher. The difficulty and cost of digging wells is a direct function of the depth of the water table.

- When water is available at fewer than 4 meters of depth, manual digging is adequate. Hand-dug wells are inexpensive, with the primary cost being the farmer’s time.
- When water is between 4 and 7 meters deep, a drill is usually required. This can be a human-powered drill, especially for soft soils. In Kenya, drilling a 7 meter well in soft soils costs about $300-$400 (Kickstart, 2013).
- For water tables of 7-20 meters, more sophisticated equipment like a motorized percussion drill is required. These wells are much more expensive to dig, and the risk of hitting rock increases as the bore goes deeper. Twenty meters is roughly the upper limit for which manually operated pumps are practical. Tube wells for that depth cost roughly $1,000 in Kenya.
- Deep boreholes greater than 20 meters are very expensive, often costing more than $10,000. A case study in Ethiopia analyzed a 150 meters borehole (Rural Water Supply Network, 2006) worth $18,000 (Exhibit 5), and found that the cost per meter is roughly $130, with about 75% of this cost being expense for capital equipment, fuel, and labor.
Exhibit 5: Digging a 150 meter borehole costs roughly $130 per meter. About 75% of this is expense for capital equipment, fuel, and labor (Rural Water Supply Network, 2006).

There is no easy way to detect groundwater and its depth

There generally appears to be abundant shallow groundwater through much of sub-Saharan Africa. However, availability and depth of groundwater can vary dramatically over relatively short distances. While water may be just 5 meters below the surface in one location, it may be 20 meters below the surface just a few yards away. Currently, there is no practical mechanism to identify shallow groundwater depth at specific points in order to choose an optimum digging location. Soil composition and depth are major determinants of drilling costs. While soft soil can be dug with simple, manual drills, rock requires motorized equipment that is more expensive. Igneous rock, prevalent across much of Africa, is particularly challenging to dig through. The risk of not finding water at the chosen location or hitting rock once the digging starts further increases the expected cost of drilling for smallholder farmers.

Pumps available on the market today are too expensive for smallholder farmers

Once a well is dug, the type of pump required to lift water similarly varies in cost and functionality, depending on water depth. Treadle suction pumps that cost between $30 and $150 can draw water from up to a depth of 7 meters and can irrigate 0.25 hectares per 4 hours of labor (Kickstart, 2013) (ATA, 2013). These pumps are easy to service as the entire pumping mechanism is above the surface. In recent years treadle pumps have achieved some adoption in a few regions, which indicates this core technology is feasible. IDE has sold 1.4 million treadle pumps in South Asia since 1985, and Kickstart sells about 25,000 pumps each year in East Africa. A portion of the Kickstart pumps are bought by NGOs, who then handle distribution to farmers (Kickstart, 2013) (ATA, 2013). Despite some success, treadle pumps are still relatively expensive for smallholder farmers and labor-intensive, especially for women.
Manual rope pulleys that cost around $100, can draw water from up to 18 meters below surface and can irrigate roughly 0.1 hectare per 4 hours of labor (ATA, 2013) (Kickstart, 2013). These are low cost, and easy to service. Hand pumps on the other hand cost upwards of $500 (McKenzie & Ray, 2009). Like treadle pumps, hand pumps are manual but require much more physical effort to operate since they do not use the entire body weight of the person operating it. 

The cost of motorized pumps ranges from $100-$3,000 and depends on the mechanism they use: suction (drawing water from 7 meters or shallower depths), displacement, or pressure (drawing water from 12 meters or more). Motorized pumps can irrigate 3 hectares per hour on average (Kickstart, 2013) (ATA, 2013). While some types of motorized pumps are now becoming available in markets such as Kenya for as little as $150-$200, they have been prone to damage after 2-3 years of use. Moreover, the cost of diesel—roughly $120 per hectare per year in East Africa—necessary to run these pumps, increases the overall operating cost for farmers.

There are few methods for storing rainwater for long periods

There are almost no highly efficient structures for holding rainwater in large volumes. Typical storage ponds used to capture and store rainwater tend to have high losses due to evaporation and seepage. These are also costly to construct. As a result, there is little storage of water for anything more than a few weeks. So far, structures that can store water efficiently and can be built at a low cost, do not exist.

There are few private sector suppliers and after-sale-service operators in sub-Saharan Africa

A major challenge with any irrigation system is maintenance. Pumps, in particular, are prone to breakdown. The low demand for irrigation systems has made it unattractive for the private sector to enter markets with suppliers and after-sale-service providers. This further weakens the broader ecosystem for irrigation equipment. Without sufficient industry competition, equipment prices in sub-Saharan Africa are higher than in countries like India.
Making irrigation affordable, desirable and sustainable will require a combination of technologies, along with innovative business models for sales, distribution and maintenance. A core assumption about the irrigation context in sub-Saharan Africa—which may be disproven as more data becomes available—is that there is an abundant supply of shallow groundwater, which can be sustainably tapped without endangering long-term water security. Under this assumption, there are 5 potential breakthrough technologies that can drive the adoption of irrigation across sub-Saharan Africa.

**Low cost drilling technologies for shallow groundwater, which reduce the cost to under $100 per farmer**

An affordable method to reach shallow (e.g., <10 meters) groundwater will allow farmers to utilize the seemingly large renewable water sources across sub-Saharan Africa. While shallow groundwater resources are rechargeable by rain, and hence sustainable under moderate use, there is a risk of overuse. Any low cost solution will have to be accompanied by some form of community-level metering and monitoring to ensure sustainability of the available water resource.

Wells are currently drilled using a standard mechanism, which requires heavy equipment and power (usually diesel) to operate. It is not clear what types of mechanical improvements will make the physical process for burrowing significantly less cumbersome or less expensive (or whether such an improvement is even physically possible). However, in principle, it should be possible to have a drill actuated by the engine of a motorcycle, which is very common form of transport across much of Africa. Hence, we believe such a technology is about 5 years from becoming a reality.

Currently, there is extremely low demand among African smallholder farmers for irrigation. Depending on the cost of the technology that is developed, farmers may require financing to pay for construction and usage of wells (even for community-level wells). Such a technology will also have to overcome many of the typical challenges faced by products and services in this market: fragmentation, and the lack of an ecosystem of suppliers and after-sale-service providers. However, based on the agricultural development experience in South Asia, and what can be seen in areas of Africa that have access to irrigation services, there is reason to believe that appreciation of the benefits of irrigation can become apparent within a short period of time. Overall, we believe deployment will be CHALLENGING.
Low cost, easy-to-construct rainwater storage repositories where harvested rainwater can be stored for several months without contamination

A feasible mechanism to capture and store rainwater for several months at a time, can prevent runoff-related losses, and create shallow groundwater reserves. There is considerable research on the artificial recharging of groundwater (Government of India, 2007), but most techniques (e.g., percolation tanks) require intensive construction and technical expertise. Some type of material or structure, which can easily be laid or constructed underground to store several months’ worth of water, can serve as an easily accessible, low maintenance, and environmentally sustainable source for irrigation.

Different types of materials are currently used for capturing rainwater in developed markets, as well as in some emerging markets like India. However, the lack of infrastructure in Africa makes it difficult to transport any type of material to rural areas. Technically, it is feasible to adapt these materials (e.g., making them lighter) for the rural African context. We believe it will take 3-5 years for such a technology to become a reality, at least at a small scale.

However, it is not clear that the market will prefer such a system over simply digging for groundwater. Even with innovative and low cost technologies, capturing a meaningful volume of rainwater, which can be used by a large number of local farmers, will require constructing what will essentially be a series of shallow wells. Building this infrastructure will need a large number of trained workers. Moreover, it will require some form of financial commitment from farmers and their communities, and a large number of trained workers to build these repositories. Overall, the deployment of such a technology in Africa will be EXTREMELY CHALLENGING.

Note that in South Asia, where water scarcity is reaching critical levels, the demand for a technology like this is likely to be higher. That prospect, combined with the market density and strength of the private sector, likely means that it will be significantly more feasible in countries like India.
Affordable (under $50), lightweight, fuel efficient solar-powered irrigation pumps

Irrigation is one of the most significant levers for increasing on-farm yield. The manual (e.g., treadle) pumps currently available are quite labor intensive, and often not suited for the needs of women farmers. Motorized pumps currently on the market require diesel, the cumulative costs of which are high (even though incremental costs might be low). In remote areas, the paucity of distribution networks for diesel is an additional constraint. Affordable, solar-powered pumps can be an ideal solution to this problem. A number of organizations are developing solar pumps, and a small number of them are already being used in India. The biggest hurdle appears to be throughput: the more the volume of water pumped, the larger and more expensive the solar panel needs to be.

Considering the effort being dedicated to this problem and the pace with which this market is developing, it is likely that market-ready pumps will become available within the next 2-3 years. However, even if solar pumps become available, there are a number of deployment hurdles: the majority of African farmers are still extremely poor, live in remote areas, and are used to rain-fed farming. Considerable effort will need to go into creating demand, providing finance, and training. A critical lesson from the decades of agricultural development in South Asia, is that water can easily be overused, and groundwater easily depleted. As such, it will be important to consider regulating water use, so that it is used sustainably. Enforcing any such regulations will be very challenging. Hence, we believe that deployment will be COMPLEX.
Low cost system for precision application of agricultural inputs, ideally combining water and fertilizers

The lessons from the Green Revolution in Asia, also discussed in other sections of this study, show that a few decades of overuse can devastate groundwater reserves for the long term. The additional stress of climate change and the consequent change in rainfall patterns increases the need for efficient use of water.

As discussed in other sections of this report, fertilizer overuse is a major problem, with overall efficiency of about 50% for nitrogen, less than 10% for phosphorous, and about 40% for potassium (Baligar, Fageria, & He, 2001). The rest of the applied fertilizer is unavailable to the plants and is wasted as runoff. The mismatched timing between availability of nitrogen and crop need for nitrogen is likely the single greatest contributor to excess nitrogen loss in annual cropping systems (Robertson & Vitousek, 2009). Ideally, nutrients should be applied in multiple small doses when plant demand for them is greatest. A low cost, robust, scalable technology is needed to precisely meter and distribute plant water and nutrients, based on soil and plant type.

In principle, variations of existing programmable irrigation systems used in industrialized countries can be downscaled and adapted to the needs of smallholder farmers. Already, small scale drip and sprinkler systems—along with other methods for increasing water usage efficiency—are beginning to emerge in markets like India. Their costs will continue to drop through the use of less expensive material, and manufacturing moving to lower cost geographies. With some attention, such technologies can be developed in 5 years.

However, there is limited evidence to suggest that users—farmers or otherwise—will be interested in spending money on technologies to conserve water, when the resource itself is available free of cost. The potential for saving fertilizer can prove to be a positive incentive, although the current demand for fertilizers is also very low. That, combined with the all the other structural barriers surrounding the
African smallholder farmer market—fragmentation and the absence of an ecosystem for distribution and maintenance—means deployment will be CHALLENGING.

### Breakthrough 4 – Difficulty of deployment

<table>
<thead>
<tr>
<th>Complexity</th>
<th>Policies</th>
<th>Infrastructure</th>
<th>Human capital</th>
<th>Access to user finance</th>
<th>Behavior change</th>
<th>Existing demand</th>
<th>Market fragmentation/Distribution channels</th>
<th>Business model innovation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Feasible</td>
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<td></td>
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</tr>
<tr>
<td>Complex</td>
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<td></td>
</tr>
<tr>
<td>Challenging</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extremely Challenging</td>
<td>Policies</td>
<td>Infrastructure</td>
<td>Human capital</td>
<td>Access to user finance</td>
<td>Behavior change</td>
<td>Existing demand</td>
<td>Market fragmentation/Distribution channels</td>
<td>Business model innovation</td>
</tr>
<tr>
<td></td>
<td>Low role of policy/regulations</td>
<td>Requires some improvements to existing infrastructure</td>
<td>Moderate need to train a limited number of people</td>
<td>Moderate financing needed, viable mechanisms identified</td>
<td>Major behavior change required, potentially on daily basis</td>
<td>Extremely low demand or not a perceived need</td>
<td>Fragmented market, weak distribution channels</td>
<td>Deployment model(s) being tested; major hurdles outstanding</td>
</tr>
</tbody>
</table>

**Low cost, portable sensors for accurately estimating local shallow groundwater depth** (reducing, in conjunction with drilling technologies, the cost of wells to <$100 per farmer)

Knowing exactly where to drill, is a process of trial-and-error: water can be 4 meters under the ground in one place, and 20 meters under just a short distance away. The ability to rapidly and inexpensively identify the optimal location for digging can dramatically increase access to shallow groundwater. While technologies exist for exploring deep water reserves, these are extremely expensive (costs in millions of dollars), and have not been adapted for shallow water. Our research found very few efforts underway to address this problem. We believe it will take at least 6-8 years before a technology like this becomes a reality.

When it does become available, such a technology could help individual farmers and well-diggers reduce cost considerably. This can make irrigation affordable for farmers, and help well-drilling become a profitable and scalable business proposition too. At a more macro level, such a technology can be used to obtain crucial data on groundwater depth, and contribute to the construction of up-to-date water maps, which can help policymakers make more informed decisions on water management at the micro level. Assuming it is affordable, such a technology can have significant demand if it successfully overcomes the structural challenges associated with market fragmentation, distribution and maintenance. Deployment of such a technology will be COMPLEX.
Breakthrough 5 – Difficulty of deployment

- Policies: Minimal role of policy/regulation
- Infrastructure: Minimal need for infrastructure
- Human capital: Moderate need to train a limited number of people
- Access to user finance: Moderate financing needed, viable mechanisms identified
- Behavior change: Moderate behavior change required with evidence of behavior change being viable
- Existing demand: Moderate demand
- Market fragmentation/Distribution channels: Moderate fragmentation of customers, under-developed channels
- Business model innovation: Deployment models being tested
Diarrheal disease is responsible for 710,000 childhood deaths while soil-transmitted helminths (STH) affect roughly 1.5 billion people globally. In addition to mortality, the indirect burden of diarrheal disease and STHs is significant; they are a major contributor to malnutrition, which in turn is believed to underlie 45% of all childhood deaths.

Diarrheal disease is transmitted through the fecal-oral pathway, which is traditionally addressed through interventions targeting water quality, water supply, sanitation, hand hygiene, and food hygiene. Diarrheal disease burden can also be reduced through vaccination, nutritional interventions and oral rehydration therapy. Mortality from diarrheal disease has decreased dramatically over the past two decades. Over the same time, access to improved water, improved sanitation, vaccines, and oral rehydration therapy, all increased, and malnutrition decreased. However, the extent to which reduction in mortality can be attributed to specific interventions or demographic trends is a subject of debate. Despite these gains, factors such as high population growth and decreasing water supplies are expected to exacerbate diarrheal disease in the future.

Sustainability of interventions and adherence of beneficiaries (e.g. are people consistently washing their hands), have remained major challenges in diarrheal disease prevention. Behaviors around practices such as eating and defecation have deep cultural roots and can be hard to influence. There is no shortage of failed interventions and technologies in addressing this issue. While there have been demonstrated reductions in diarrheal disease from small-scale interventions, there has been limited success in bringing these interventions to scale. There are 5 technological breakthroughs for reducing mortality and morbidity from diarrheal disease.

- Resource recovery systems for fecal waste
- Next generation toilets or homes with in-home toilets, especially for the urban poor
- Additives to facilitate the breakdown and/or disinfection of fecal sludge in pit latrines
- Water pumps that automatically purify with chlorine
- Extremely simple point-of-use water treatment systems
Diarrheal disease is the 3rd leading cause of childhood mortality worldwide, behind only neonatal conditions and pneumonia (Liu, et al., 2012). It is responsible for 710,000 childhood deaths, almost all in developing countries (Liu, et al., 2011) (Exhibit 1).

**CORE FACTS AND ANALYSIS**

Defined as passage of three or more loose or watery stools per day, diarrhea is usually caused by an intestinal tract infection, which can be caused by many different pathogens including bacteria, viruses and protozoa. These are generally spread through contaminated food, drinking water or person-to-person contact (WHO, 2013).

Soil-transmitted helminths (STHs) are parasitic nematodes (worms) that feed on the host tissue or compete with the host for nutrition. Many STHs are contracted when children ingest eggs that were excreted in fecal matter of infected individuals. STHs are estimated to infect some 1.5 billion people globally (WHO, 2013). The most common and important STHs are roundworm, whipworm, and hookworm. While these infections are rarely fatal, STHs can cause intestinal distress, malaise or weakness, and impaired cognitive and physical development. The severity of symptoms is directly related to the number of worms an individual harbors.

Both diarrheal disease and STHs lead to malnutrition in the host (Table 1). Diarrheal disease can reduce an individual’s ability to absorb nutrients in the intestines and the effects of the disease last well beyond the diarrheal episode. STHs feed on host tissue, including blood, or compete with the host for nutrients. This leads to a loss of iron and protein and, similar to diarrheal disease, also causes malabsorption of nutrients. Recently, a condition known as environmental enteropathy has been proposed to explain, in part, malnutrition that results from sustained exposure to fecal pathogens, even in the absence of diarrheal episodes. A 2008 WHO study concluded that as much as 50% of childhood underweight and malnutrition could be associated with repeated diarrhea or soil-transmitted helminth infections (Prüss-Üstün, et al., 2008).

**Exhibit 1:** Diarrheal disease is the 3rd leading cause of childhood mortality in sub-Saharan Africa and South/ Southeast Asia (Liu, et al., 2012).
Key diarrheal pathogens and soil-transmitted helminths

<table>
<thead>
<tr>
<th>Pathogen class</th>
<th>Important pathogens</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diarrheal pathogens</td>
<td>Globally important pathogens:</td>
<td>- Diarrhea, which causes dehydration and can lead to mortality</td>
</tr>
<tr>
<td></td>
<td>Rotavirus, <em>Cryptosporidium parvum</em>, Shigella,</td>
<td>- Reduction in ability to absorb nutrients (lasting beyond the diarrheal episode)</td>
</tr>
<tr>
<td></td>
<td>ST-enterotoxigenic E. coli (ST-ETEC)</td>
<td>- Environmental enteropathy (prolonged reduction in ability to absorb nutrients, can occur without diarrhea)</td>
</tr>
<tr>
<td></td>
<td>Additional pathogens important in some specific regions:</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Aeromonas</em>, <em>V. cholera</em>, <em>C. jejuni</em></td>
<td></td>
</tr>
<tr>
<td>Soil-transmitted</td>
<td>Roundworm (<em>Ascaris lumbricoides</em>), whipworm (<em>Trichuris trichiura</em>), hookworm (<em>Necator americanus</em> and <em>Ancylostoma duodenale</em>) and certain types of tapeworm (<em>Taenia</em>)</td>
<td>- Enteric inflammation, general malaise and weakness, and impaired cognitive and physical development</td>
</tr>
<tr>
<td>Helminths</td>
<td></td>
<td>- Anemia (hookworm only)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Increased malabsorption of nutrients</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Loss of appetite</td>
</tr>
</tbody>
</table>

Table 1: A handful of pathogens are responsible for the majority of severe diarrhea and STH infections. Rotavirus, *Cryptosporidium parvum*, *Shigella*, and ST-ETEC are the four most important diarrheal pathogens globally (Kotloff, et al., 2013).

Diarrheal disease and malnutrition share a complex link

The relationship between diarrheal disease, soil-transmitted helminths and malnutrition is recognized, but not entirely understood. Focusing specifically on diarrheal pathogens, the common belief for decades was that diarrhea itself caused a reduced ability for the body, specifically the small intestine, to absorb nutrients, and this effect could last significantly longer than the diarrheal episode itself. One meta analysis found that probability of stunting at age 2 increased by 2.5% per diarrheal episode, and 25% of all stunting was attributable to having 5 or more episodes of diarrhea (Checkley, et al., 2008).

Recently, the scientific community has begun to propose a more complex explanation, which is not related to diarrhea per se, but exposure to high levels of fecal pathogens. This condition is often referred to as ‘environmental enteropathy’ or ‘environmental enteric dysfunction’. Environmental enteropathy is a poorly defined condition, but is generally characterized by “villous atrophy, crypt hyperplasia, increased permeability, inflammatory cell infiltrate, and modest malabsorption” of nutrients (Humphrey, 2009). The underlying causal mechanism has not been specified yet. One proposed model is that high enteric pathogenic bacterial exposure in the small intestines creates an immune response, which in turn causes the common characteristics of enteropathy such as atrophy of intestinal villi (small finger-like structures on the surface of the intestines that increase surface area for absorption of nutrients). The effects are twofold. First, as a result of reduced surface area in the intestine, the small intestines have a reduced ability to absorb nutrients. Second, nutrients are repartitioned away from growth to support the immune system. This is an ongoing area of research.

Enteropathy could help explain why sanitation has stronger associations with achieving gains in infant and child growth, rather than reduction in diarrhea (Brown, et al., 2013).
While many experts have come to take these positive associations between WASH interventions and health as conventional knowledge, some skeptics have noted the risk of confounding in this type of analysis, and a recent Cochrane review did not, in fact, include this particular study due to questionable methodological quality (See: Dangour, et al., 2013. The effect of interventions to improve water quality and supply, provide sanitation and promote handwashing with soap on physical growth in children).

Peru found that diarrhea could explain 16% of stunting, while access to sanitation and water services could explain 40% (Brown, et al., 2013).

STHs do not trigger the same immune response as diarrheal disease. It is believed that they affect nutrition by feeding directly on intestinal contents or blood, leading to nutrient loss and anemia (WHO, 2013). STHs and their effects on nutrition and growth have increasingly become a debated topic. In 2007 and 2012, The Cochrane Collaboration reviewed evidence for mass deworming initiatives and found that the evidence linking deworming programs to gains in nutrition and growth indicators was weak. Leaders from evaluation groups including Innovations for Poverty Action (IPA), the Center for Effective Global Action (CEGA), and the Abdul Latif Jameel Poverty Action Lab (J-PAL), have criticized these studies for excluding important randomized trials and ignoring the effect of deworming on improvements in education outcomes.

Diarrheal disease is primarily a childhood disease

Children under 5 represent 68% of the diarrheal disease burden (IHME, 2012). Children are generally more susceptible to diarrheal disease, due to their developing immune systems, and a high rate of malnutrition or other immune-suppressant risk factors. Children are also at higher risk for life-threatening diarrheal disease due to the higher composition of water in a child’s body relative to adults, relatively higher metabolic rates and lower capacity of their kidneys to conserve water (WHO-UNICEF, 2009).

The past two decades have seen a large drop in childhood mortality caused by diarrheal disease (Exhibit 2). The Child Health Epidemiology Reference Group (CHERG) estimates that childhood mortality fell by 31% between 2000 and 2010 (Liu, et al., 2012). The WHO and UNICEF estimate that in 1990 mortality was as high as 5 million (WHO-UNICEF, 2009). While it is widely accepted that the global burden has dropped significantly over the past two decades, the specific reasons for this decline are not well understood. The primary drivers are believed to be improvements in nutrition, improved case management, particularly the widespread use of oral rehydration therapy, increased coverage of immunization for measles and rotavirus, and increased access to clean water and sanitation.

<table>
<thead>
<tr>
<th>Year</th>
<th>Deaths (millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>1.2</td>
</tr>
<tr>
<td>2005</td>
<td>1.0</td>
</tr>
<tr>
<td>2010</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Exhibit 2: Global mortality from diarrheal disease has decreased from nearly 1.1 million to less than 0.75 million per year, since 2000. However specific causes of this reduction remain unclear (Liu, et al., 2012).
While mortality from diarrheal disease has decreased, morbidity has remained more or less constant (Kosek, et al., 2003). This implies that the global health community has made major strides in case management and control of at least some pathogens that are responsible for moderate to severe diarrhea, but relatively little progress has been made in controlling the general transmission of diarrheal pathogens.

Diarrheal disease burden is highly concentrated in a small number of countries (Exhibit 3), with 10 countries representing 78% of deaths. Even within these countries, variability in the rate of diarrheal disease mortality is high (Exhibit 4).

### Contribution to global childhood mortality by country

Exhibit 3: 10 countries account for 78% of childhood deaths from diarrheal disease.

### Childhood mortality rates across high burden countries

Exhibit 4: Mortality per 100,000 people varies greatly, even across high burden countries.

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1. This opinion is not universally held, and some experts note that cross-sectional surveys used to gather this data are unreliable (Luby, 2011).
2. These estimates are based on childhood mortality rates from 2010 CHERG data and population data from the CIA World Factbook, which contains data from various years. Note that deaths are for children only, while population figures are national. Thus, mortality rate for children specifically would be higher in all cases.
Diarrheal disease and intestinal nematodes are caused by 4 types of pathogens

The various pathogens causing diarrheal disease and intestinal nematodes behave in different ways. Some bacteria, for example, are believed to be seasonal. There are major spikes in bacterial infections during the wet seasons, which highlights the importance of water as a transmission pathway. In contrast, viruses, particularly rotavirus, show seasonal spikes in the drier, colder seasons. This indicates that person-to-person transmission is an equally or more important transmission pathway (Levy, et al., 2009). Unlike viruses, bacteria can also reproduce outside of the human body (e.g., on food left at room temperature), thus becoming more likely to produce disease after ingestion. STHs on the other hand must mature in soil, eliminating person-to-person transmission as a major pathway. Further description of the different types of pathogens can be found in Table 2.

The Global Enteric Multicenter Study (GEMS) identified 4 important specific pathogens that represent a disproportionate percentage of disease burden in developing countries: Rotavirus, Shigella, ST-ETEC, Cryptosporidium (Kotloff, et al., 2013).

### Major classes of pathogens and their characteristics

<table>
<thead>
<tr>
<th>Pathogen type</th>
<th>Important pathogens</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viruses</td>
<td>Rotavirus</td>
<td>Viruses are infectious pathogens that can only replicate after infecting other living cells. Rotavirus is the single most important pathogen associated with diarrheal disease.</td>
</tr>
<tr>
<td>Bacteria</td>
<td>ST-Enterotoxigenic E. coli, Shigella, Aeromonas, V. cholera, C. jejuni</td>
<td>Bacteria can grow on food and in water and sewage under the right conditions. Some bacteria are seasonal, with major spikes in the wet season.</td>
</tr>
<tr>
<td>Protozoa</td>
<td>Cryptosporidium Parvum</td>
<td>Protozoa are advanced organisms that are transmitted through cysts that are extremely robust, able to survive for long periods outside of the body and resistant to chlorine purification.</td>
</tr>
<tr>
<td>Soil-transmitted Helminths</td>
<td>Roundworm (Ascaris lumbricoides), whipworm (Trichuris trichiura), hookworm (Necator americanus and Ancylostoma duodenale) and certain types of tapeworm (Taenia)</td>
<td>Soil-transmitted helminths (STH) are parasites that do not cause diarrhea, but rather live in the body, generally the intestines, and cause enteric inflammation. Eggs must mature in soil before becoming infectious to humans, however, they are extremely persistent and can survive for weeks to months on crops and soil, and years in fecal matter.</td>
</tr>
</tbody>
</table>

Table 2: Each of the different types of pathogens travels along the fecal-oral pathway, but have different characteristics affecting their transmission and susceptibility to different interventions.
Traditionally, the flow of pathogens has been described through the F-diagram. Diarrheal disease and STHs are transmitted from person-to-person along the fecal-oral pathway, in which individuals ingest pathogens that have been excreted in fecal waste by other infected individuals and sometimes animals. The pathway is complex and can follow many routes, which vary in importance from location to location. This pathway has historically been represented with the F-diagram, which describes the flow of pathogens from fecal matter to new hosts (Exhibit 5).

The F-Diagram representing the Fecal-Oral Pathway.

Exhibit 5: The F-diagram has historically been used to describe the fecal-oral pathway (Brown, et al., 2013).

While this diagram is useful as a descriptive tool, it is limited in its usefulness for informing interventions. Drinking water or fluids, for example, can be contaminated in a number of ways including contamination at the source, either from flooding or direct runoff from inadequate sanitation systems, contamination in transit through water pipes with intermittent supply, or contamination in the household from poor storage practices.

A more nuanced fecal-oral pathogen flow model

In order to provide a more nuanced conceptual framework for problem and intervention analysis, we have developed the Pathogen Flow Model (Exhibit 6). This five-stage model maps major transmission pathways, allows identification of major breakpoints, and provides a view of which challenges must be solved in unison. Each stage of a pathway presents unique challenges, which are responsive to different types of interventions.

Stage 1 - Pathogen hosting

The transmission of fecal pathogens begins with individuals who are carrying diarrheal disease causing pathogens in their gut. These individuals may be suffering from diarrheal disease, or they may be asymptomatic carriers. In both cases, but particularly for individuals suffering from diarrheal disease, the disease-causing pathogens grow and replicate. This can also occur with asymptomatic carriers who carry potentially disease-causing organisms, but do not suffer from diarrhea. While humans can be infected by pathogens that come from animal hosts, the majority of infections responsible for the overall diarrheal and STH disease burden in children are likely acquired from other human hosts.4

4 One notable exception is *Taenia* which is often carried in cows or pigs.
Following infection and the replication of pathogens in the body, pathogens are then excreted into the environment at defecation points. These defecation points, such as open fields, sewers, and pit latrines represent high-density sources of persistent diarrheal pathogens. The challenges associated with defecation points vary from urban to rural locations but generally revolve around the lack of sustainable and scalable sanitation systems. It is often taken as common knowledge that sanitation interventions are positively correlated with reduction in diarrheal disease and childhood growth. A meta analysis of sanitation interventions found an average relative risk reduction in diarrheal disease of 37% (Waddington, et al., 2009). A recent Cochrane review, however, found there was insufficient evidence to link sanitation interventions to childhood growth (Dangour, et al., 2013).

When there are insufficient sanitation systems, diarrheal pathogens spread through transmission pathways such as crops and water sources. There are many possible transmission pathways, and targeting any single pathway in isolation is unlikely to create major improvements in health. Interventions at this stage have generally displayed less effectiveness than interventions at earlier or later points in the pathway. For example, water quality interventions at the source—a transfer point—are associated with an 11% reduction in diarrheal disease, while interventions at the household lead to a 35% reduction (Fewtrell, et al., 2005).
Stage 4 - Exposure

Pathogens enter the body in three ways: through drinking water, through food, and directly from hands.

Drinking water
Drinking water is generally contaminated at three main points—at the source, in transit (such as through pipes), and in the home (through improper storage). Major interventions focusing on drinking water are generally source protection (prior to the exposure stage), water purification, and safe household storage.

Food
Food can be contaminated in fields when farmers use wastewater for irrigation, when feces are deposited in fields due to open defecation or as fertilizer, in markets due to unhygienic conditions, or in the home through a mother’s hands while preparing food, a child’s hands while eating, or by flies that land on food and deposit pathogens. The ability of bacteria to reproduce rapidly on food has led to food, and particularly complementary (weaning) food, gaining increased importance in reduction of diarrheal disease. Food hygiene generally focuses on hand washing before preparing food and eating, appropriate food preparation practices including washing or disinfecting and then properly cooking food, appropriate storage of leftover food, and reheating food that had been previously prepared.

Hands and fingers
Hands and fingers can be contaminated during defecation, caring for an infant, and through contact with the soil and environment. Hand hygiene is focused primarily on hand washing with soap.

Interventions at the exposure stage tend to be moderately effective. Studies have found a 31% reduction in diarrheal disease from hygiene interventions and a 42% reduction from water quality interventions (Waddington, et al., 2009).

Stage 5 - Infection

Exposure does not necessarily lead to disease. Rather, children who are malnourished, not optimally breastfed, or are HIV positive are more likely to develop diarrhea after exposure to pathogens. Vaccination is also effective in reducing the risk of diarrhea following exposure to some pathogens.
KEY CHALLENGES

Diarrheal disease is a condition that is driven by some of the most fundamental human activities—eating, drinking, preparing food, and defecating. In the absence of adequate sanitation systems, fecal pathogens contaminate the environment, food, and water both through environmental mechanisms and through human activities. Pathogens are then ingested, and in individuals who are susceptible, produce disease, at which point lack of adequate care becomes a major driver of mortality.

Key challenges in breaking the fecal-oral pathway, reducing susceptibility to disease through improved nutrition and health care, and improving care for those who fall sick are outlined below.

1. High rates of infection amongst the population lead to a constantly replenishing and growing supply of diarrheal pathogens and STHs in the environment

Rates of infection in many developing countries are extremely high. There are 1.7 billion cases of diarrhea globally per year, with an average of 2.9 episodes per child per year (Brown, et al., 2013), indicating that diarrheal pathogens are constantly being excreted into the environment and in massive quantities.

2. Lack of adequate, sustainable sanitation systems enables wide-scale environmental contamination with fecal pathogens

There are a number of systemic, multifaceted problems which expose low income populations to fecal pathogens. These include poor infrastructure, lack of public sanitation services, and the absence of sustainable business models for private sanitation.

Lack of sanitation infrastructure
Sanitation infrastructure such as sewerage and treatment facilities, the most common approach to clean environments in developed countries, is severely underdeveloped in most developing countries. The gold standard of closed sewage systems where wastewater is treated before being returned to the environment is highly uncommon. Sanitation systems generally only reach small portions of the population and are underdeveloped or in disrepair, leaving most individuals using alternative sanitation systems or practicing open defecation.

Lack of sustainable, scalable models for community or household sanitation systems
One of the key challenges with sanitation systems is maintenance—keeping the toilets at an acceptable level of cleanliness while removing waste—which is dependent on an effective business or public utility model. In most developing countries, government-funded sanitation systems have limited reach, often excluding the poor. In the absence of public models, private or hybrid models are being developed, although none have yet been fully proven. In the absence of an effective model which generates revenue, either from usage of the toilet or through sale of the fecal sludge, sanitation systems inevitably become unsanitary and go into disuse.

Existing urban and rural systems have major shortcomings, which lead to environmental contamination
In urban areas, particularly for the poor, sanitation systems are generally pit latrines and open sewers, which have several major shortcomings. First, both are prone to flooding which leads to widespread contamination. Second, open sewers in particular are often located in areas with high population density where they cause extensive contamination. Third, pit latrines often fill up faster than the waste decomposes, which means that they must be emptied. Often pit latrines are emptied by private parties who dispose of the fecal sludge improperly, usually very close to urban populations, where the diarrheal pathogens can contaminate water sources or soil, and come in easy contact with children. In rural areas, sanitation
Environmental conditions are conducive to the persistence and spread of pathogens

Bacterial pathogens can survive in water over 10-60 days and in soil for many months, and STH eggs can survive in soil for 27-35 days in summers, and up to half a dozen months during the winter season in temperate zones (Ensink & Fletcher, 2009). Both can survive significantly longer than their average lifespan in fecal waste.

In the absence of sanitation systems, there are a large number of ways in which food and water can become contaminated, or children can be exposed to pathogens directly

When there are insufficient sanitation systems, diarrheal pathogens flow through multiple transmission pathways, which brings them in direct contact with potential human hosts. There are many possible transmission points, and therefore many breakpoints in the transmission pathway to consider.

Distributed water sources including surface water, shallow wells and boreholes
Surface and shallow water sources, especially in rural areas, can be contaminated through flooding and runoff of fecal matter and pathogens. Deeper groundwater, in both urban and rural areas, can be similarly contaminated through episodic flooding, particularly when boreholes are constructed poorly (without a concrete block at the surface to prevent fecal matter from reaching the aquifer through and around the pipe).

Centralized water sources (water pipes)
In urban settings, water distribution pipes and sewage pipes or ditches are often constructed near each other. Pipes are inherently leaky, with even well maintained western systems losing roughly 15% of system water. Piping systems in developing countries are dramatically worse and often have only intermittent water supply. When the water supply is shut off, it creates reverse pressure, and if there is fecal matter around the pipes it can leach into the water pipes. This re-contaminates water even if it has already been purified.

Crops
It is estimated that 10% of the world’s food supply is irrigated with wastewater (Jimenez, 2006). Use of untreated wastewater for irrigation deposits pathogens, particularly on vegetables, which can then be ingested if the produce is not cleaned and cooked properly before eating.

Flies
Some flies are born and breed in fecal matter and carry pathogens on their exoskeleton or through their gastrointestinal system. Flies also tend to proliferate in hot and humid conditions, especially the rainy season, when there are more pathogens in the ecosystem.

Soil and environment
Soil and the broader environment are contaminated from open defecation, disposal of fecal sludge, runoff from inadequate sanitation systems, from wastewater that is used for irrigation, and from episodic flooding.
Diminishing water availability leads to utilization of lower quality water sources
As water sources become over-abstracted or are replenished at slower rates due to changes in hydrological patterns, the quality at these sources tends to degrade. Individuals then have to use lower quality water sources. This exacerbates existing challenges with nearly all water sources in water-poor areas, including most of South Asia and sub-Saharan Africa. This is also expected to become increasingly critical as the global population grows and hydrological patterns continue to change.

Children are exposed to diarrheal pathogens either directly from pathogens on their hands or through consumption of contaminated food or water

Exposure to diarrheal pathogens is enabled by food and personal hygiene habits as well as insufficient water purification systems.

Hand hygiene
Mothers and children do not wash hands with soap after contact with fecal matter, either through defecation or care for a child or infant who has defecated.

Food hygiene
Mothers often do not wash their hands with soap before preparing food and children do not wash their hands prior to eating. Weaning foods are prepared under unhygienic conditions and stored at room temperature. Several studies have found that the second 6 months of life are the period with the highest rate of diarrheal disease (Motarjemi, et al., 1993). One study found that 41% of weaning food items were contaminated with E. coli (Black, et al., 1982). Weaning foods have been found to be more contaminated than food prepared for adults, due to storage of weaning foods at high ambient temperatures (Black, et al., 1982). Apart from weaning food, previously cooked food is often not reheated before consumption later. Storage at room temperature can lead to exponential bacterial growth in cooked food. Studies have found that bacterial contamination on food greatly exceeds that found in drinking water (Black, et al., 1982).

Water quality and supply
There are several challenges in providing safe water to children. First, water delivery infrastructure is often poorly developed and in some cases absent in developing countries, particularly in rural areas. While most individuals in urban areas have access to water, access in rural areas, particularly in sub-Saharan Africa and India remains low. In both regions, only about half of the population has access to an improved water source. When there is no national level water infrastructure, community level systems are often employed; however, these systems need ongoing maintenance models and require an adequate service model to be sustainable.

There are various models, which have proven effective, but most proven community-level water distribution systems exist in rural areas with relatively high population densities. New models that can serve communities with lower population densities are required. For the household level, there are an abundance of point-of-use water purification systems; however these tend to have low compliance, due to the complexity and time involved when using them. Numerous studies have found point-of-use purification systems effective at reducing microbial contamination at the household level as well as diarrheal disease in children under 5 by up to 42% (Clasen, 2003).

However, studies have found significant heterogeneity in results from point-of-use water treatment systems, which is likely related to compliance (Clasen, et al., 2007). In one study of the poor in urban Bangladesh, even with bi-monthly visits to educate families about the dangers of untreated drinking water, only 30% of families used the most popular treatment system they tested, with lower rates of compliance for other systems (Luoto, et al., 2011). The low rate of adequate water treatment is also greatest
Increased susceptibility due to poor nutrition

Diarrheal pathogens are opportunistic. Development of active infection following exposure, like with many diseases, is driven by the strength of an individual's immune system. Malnourished children, in particular, have higher susceptibility. Children who are stunted are 1.6 times more likely to die from diarrheal disease than those who are not stunted (Black, et al., 2008); Vitamin A deficiency causes a 60-70% increase in diarrhea prevalence (el Bushra, et al., 1992), and zinc deficiency has been found to increase diarrhea prevalence by 15-24% (Bhutta, et al., 2008). Suboptimal breastfeeding also contributes to childhood susceptibility to diarrheal pathogens. Infants under the age of 6 months who are not breastfed are over 10 times as likely to die from a diarrheal infection as those who are breastfed (Lamberti, et al., 2011).

Low vaccine coverage for rotavirus

An effective vaccine exists for rotavirus, which is the most common cause of moderate-to-severe diarrhea in children under 2, and makes up over 40% of all incidences of moderate-to-severe diarrhea in children under 1, more than double the next highest cause (Kotloff, et al., 2013). However, childhood coverage for this vaccine is still low due to its fairly recent introduction as a global priority and its high cost relative to other vaccines.

Lack of vaccines for Shigella, ST-ETEC, Cryptosporidium and soil-transmitted helminths

With the exception of rotavirus, there is no effective vaccine for any of the other major pathogens that cause diarrheal disease, and there are major scientific challenges to many of these pathogens (Jones, et al., 2003). There are many strains of ST-ETEC, and an effective vaccine would have to produce immunity against an array of antigens. Developing vaccines for parasitic diseases is challenging due to the increased complexity of antigen analysis of higher life forms, as is the case with Cryptosporidium and helminths. The challenge of developing a vaccine against STHs is compounded by the diversity of helminth organisms (Harris, 2011). Many experts believe that the development of additional vaccines is likely a high-cost, time-consuming opportunity relative to existing interventions.
Children do not receive adequate care during a diarrheal episode due to the low coverage of oral rehydration therapy

ORT is a proven intervention and can reduce mortality by 69% but coverage remains low (Bhutta, et al., 2013). Only 39% of children in developing countries with diarrhea receive ORT, and there has been little improvement in this rate since 2000 (WHO-UNICEF, 2009). This is driven by a number of factors including the misconception that diarrhea is ‘part of growing up,’ the fact that often both parents work and have limited time to pay attention to their children, weak healthcare systems, and the lack of awareness that diarrhea can be a major risk to a child’s life.

There are many fundamental scientific questions that remain unanswered

Experts noted many key scientific questions, highlighted below, that require further research to help reduce the burden of diarrheal disease and STHs.
- What is the relative importance of various pathways of transmission?
- What is the relationship between gastrointestinal pathogens and malnutrition?
- What is the burden of disease, other than mortality, that is attributable to gastrointestinal pathogens? (For example, the loss of cognitive development associated with both intestinal parasites as well as growth faltering which may be mediated through environmental enteropathy).
- What is the role of the microbiome in increasing or decreasing the susceptibility of the child to exposure to gastrointestinal pathogens? And, what interventions might contribute to a healthier more protective microbiome?
- How clean does the environment need to be for thriving children and thriving communities?
- What is the underlying cause of environmental enteropathy?
- What are the pathways through which environmental contamination and malnutrition contribute to growth faltering?
- How do we scale up successful pilot projects to better protect large vulnerable populations?
- What are easier, lower cost methods for detecting and measuring the concentration and viability of pathogens in the environment?
- What are better dose-response curves to use for modeling exposure (Quantitative Microbial Risk Assessment) that describe the susceptibility of children to different organisms? Most dose-response data are from studies on healthy adults.

In summary, systemic challenges require systemic solutions. The core challenge, breaking the fecal-oral pathway, is dealt with in developed countries through large government investments in public infrastructure including sewer systems, wastewater treatment plants, water purification facilitates, and ubiquitous piping into households—all of which require constant service and maintenance. This is almost certainly not practical in most of the poorest regions of the world.
SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

There have been several successes in reducing diarrheal disease at a small to mid-level scale, usually in the range of thousands of households. Very few interventions, however, have been proven at a scale comparable to the problem itself—in the range of hundreds of thousands to millions of households. Amidst the successes are an abundance of failed interventions—broken water filters or toilets that were installed but never used or that quickly broke, again highlighting the fact that diarrheal disease is not a challenge that can be solved just by technology, by building infrastructure or by influencing behavior or habits, but rather successful interventions must be holistic and consider the whole system and include business or public financing models to ensure sustainability.

Resource recovery systems for fecal waste

Sanitation systems undergo constant use, requiring ongoing maintenance and cleaning, and often have high upfront costs. This requires either significant public financing or a business model to generate revenue to cover startup and operating costs. One emerging model to support this involves collecting fecal waste for conversion into energy (biogas, biofuel, electricity), or higher value compounds (compost, fertilizer, plastic), or harvesting nutrients which can then be sold to defray costs, or ideally, provide a return on investment.

There are multiple approaches to resource recovery. The most focused on approach thus far has been the production of biofuels (often liquid biofuels), which can be very high value. This, however, has been hindered by the fact that only a fairly small quantity of biofuel can be produced from human fecal sludge and that human waste biofuel is often inconsistent with the embedded fuel infrastructures in developing (and developed) countries. Nitrogen and phosphorus, which are essential for agriculture, can also be harvested from fecal sludge, either through composting or more advanced nutrient harvesting, such as struvite precipitation and ammonia stripping from source-separated urine. Fecal sludge can also be dried, processed (e.g., into fuel pellets), and then sold as a carbon neutral fuel. The ideal recovery solution would be able to extract energy and nutrients while disinfecting and minimizing the volume of any remaining waste.

Technologies that facilitate the conversion of fecal sludge to fertilizer or biofuel exist, but face two major problems. The most immediate is that these technologies generally remain too costly to reach significant market penetration. The broader, and potentially more significant challenge is that it is unclear how much economic value can be actually extracted from fecal waste. The ideal technology would be able to convert fecal waste to a sufficient quantity of energy or another substance to cover the operating costs of the sanitation system, and even generate returns on the investment. However, many experts believe that this level of value extraction is unlikely, and that it is more likely that any technology will only be able to offset costs. If this is the case, it calls into question the viability of resource recovery systems as an at-scale solution to sanitation challenges.

The market readiness of these technologies varies by the type of technology. Technologies that can extract biofuel and nitrogen exist currently, although costs for many technologies remain high. Phosphorus recovery from fecal sludge and nitrogen recovery from urine are likely closer to 4-6 years out, while some of the more novel technologies such as microbial fuel cells are 10-15+ years away from being market ready.

There are many challenges in the distribution of sanitation systems that extract high-value content from fecal waste. In particular, no resource recovery driven sanitation system models have been proven at scale in developing countries yet. Sanitation systems also tend to have fairly high up-front costs,
require skilled labor to install and maintain, and distribution channels are poorly defined. In addition, significant public investment is likely to be still required.

The projected time to market readiness varies by technology ranging from market ready to 15+ years. Given the lack of proven models and the scale of the urban sanitation problem, the level of difficulty for deployment is EXTREMELY CHALLENGING.

Breakthrough 1 – Difficulty of deployment

- Extremely Challenging
  - Policies
  - Infrastructure
  - Human capital
  - Access to user finance
  - Behavior change
  - Existing demand
  - Market fragmentation/Distribution channels
  - Business model innovation

- Challenging
- Complex
- Feasible
- Simple

- Low role of policy / regulation
- Requires some improvements to existing infrastructure
- Moderate need to train a limited number of people
- Significant financing required, limited mechanisms available
- Moderate behavior change required with evidence of behavior change being viable
- Moderate demand
- No identified deployment model, major hurdles identified
- Highly fragmented, challenging to reach customers
Next generation toilets or homes with in-home toilets for the urban poor

Most existing housing for the urban poor does not have an in-home toilet, which is a major barrier towards the use of a proper sanitation system. Development of appropriate toilets for urban houses or inclusion of an in-home toilet as part of the broader opportunity to provide low cost housing to the urban poor could overcome this first barrier of low toilet usage. This will also help address critical problems such as the safety risks women and children face when using shared toilets. An effective model to dispose of fecal waste will still be required to remove waste from houses.

The challenges of an in-home toilet vary depending on whether there is piped water supply and sewerage, which is uncommon in most urban slums. Those living in urban slums also often do not have legal land tenure. When water and sewage infrastructure is expanded into these areas, the cost and value of land increases dramatically, forcing out the most vulnerable populations. Increased land cost indirectly also increases the cost of owning a toilet, which is a low priority for most since it takes up precious space in households that are often extremely small. In considering options to provide sanitation to the very poor, it should be assumed that there will not be adequate piped water or sewerage infrastructure.

Where there is no piped water or sewerage, an in-home toilet must be low-cost, have an effective way to control odor, a system for managing waste, and require minimal space. Ideally, appropriate in-home toilets will be included in the actual construction of each low cost home, leveraging the significant efforts underway to provide better housing for the urban poor. While many organizations are focusing on developing new housing options for the urban poor, most have struggled to develop houses that provide necessary amenities at a reasonable cost to each household. Sanitation facilities, more often than not, end up as a shared resource. Opportunities exist in the development of new, low-cost, robust materials that have the look and feel of current housing materials. Market deployment in urban areas would depend heavily on market models. Ideally new housing models could be pioneered by development companies or governments, which could reach significant scale in urban areas. See the chapter on Healthcare Delivery for a more detailed discussion of opportunities in improved housing. The projected time to market readiness is 6-8 years, and the difficulty of deployment is CHALLENGING.
Additives to facilitate the breakdown and/or disinfection of fecal sludge in pit latrines

One of the major problems with pit latrines is that they often fill up before fecal sludge is fully digested, creating the need to empty pit latrines or build new ones. Pit latrines are often emptied in a way that contaminates nearby land or water sources (from emptying services that don’t remove the sludge appropriately), and the need to build additional pit latrines increases the cost of sanitation for families. Additives can facilitate the breakdown of fecal sludge, reducing the need to empty latrines, which can result in contamination. Several options are currently being developed and tested including addition of higher organisms, microorganisms, and hydrolytic enzymes. In the longer term, opportunities could include use of fermenting organisms, development of new enzymes, or facilitation of the current microorganisms involved in digestion.

Distribution of additives at a meaningful scale is highly challenging, as a high percentage of individuals in a community would need to purchase additives to have a meaningful impact on health. This level of market penetration would require a large and consistent supply chain for biological compounds, which is challenging, particularly in rural areas. Additionally, perceived value to households is often low. There is little existing demand for additives.

The time to market readiness varies by type of additive. Some, such as the addition of higher organisms, are market ready. Others, like new enzymes, are conceptual and 7-10 years away from being market ready. The difficulty of deployment is CHALLENGING.

**Breakthrough 3 – Difficulty of deployment**

- **Extremely Challenging**
  - Policies
  - Infrastructure
  - Human capital
  - Access to user finance
  - Behavior change
  - Existing demand
  - Market fragmentation/Distribution channels
  - Business model innovation

- **Challenging**
  - Low role of policy/regulation
  - Low-moderate need for human capital development
  - Moderate behavior change required with evidence of behavior change being viable
  - Low demand, needs to be built
  - Fragmented market, weak distribution channels
  - Deployment model(s) being tested; major hurdles outstanding

- **Complex**
  - Requires some improvements to existing infrastructure

- **Feasible**
  - Moderate financing needed, viable mechanisms identified

- **Simple**
Water pumps that automatically disinfect with chlorine

Chlorine is considered by many to be an ideal form of water purification as it is simple and provides residual disinfectant properties for treated water (a critical characteristic, given water is often re-contaminated in the household). However, chlorine must be dosed appropriately – if the dose is too low then it will not disinfect the water, and if it is too strong it creates a significant bad taste and can be toxic.

One solution to this has been providing chlorine dispensers at water pumps in communities, which has had some success, but the need for family members to treat the water on an ongoing basis has reduced penetration and adherence. An ideal solution would remove the need for human action or creation of new habits.

A high-impact possibility is to develop water pumps, which automatically dose water as it is pumped, effectively treating water, providing residual protection, and removing the need for behavior change on the part of the user. The key technological challenge is a mechanism that provides appropriate doses of chlorine to water that is flowing dynamically. The mechanism would also need to be robust and low cost.

Challenges to at scale deployment include the lack of effective distribution channels, lack of demand from customers and the lack of clear business or distribution models that can ensure ongoing maintenance. Rather, many pumps are installed by governments or NGOs and rarely receive adequate ongoing attention. Chlorine also presents a specific challenge in having a relatively short half-life, which requires the creation of a reliable chlorine supply chain, although methods to manufacture chlorine at a local level do exist.

No low cost automatic chlorine-dispensing pump has yet been developed, although a handful are under development. The expected time to market readiness is 2-4 years and the difficulty of deployment is COMPLEX.

Breakthrough 4 – Difficulty of deployment

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- Low role of policy / regulation
- Low-moderate need for human capital development
- Minimal behavior change required
- Low demand, needs to be built
- Moderate fragmentation of customers, under-developed channels
- Deployment model(s) being tested
- Moderate financing needed, viable mechanisms identified
- Dependent on existing infrastructure
Extremely simple point-of-use water treatment systems

Multiple studies have shown that household water treatment is effective at reducing microbial contamination of drinking water, as well as reducing diarrheal disease. Both NGOs and major corporations have marketed these products with some success, although adherence and continued usage have been disappointing. Point-of-use water treatment systems tend to be complex and time consuming to use, which has led to low adoption, particularly in sub-Saharan Africa.

Importantly, families that are at the highest risk for diarrheal disease are the least likely to practice adequate household water treatment. In a meta analysis, Rosa and Clasen found that among families in the poorest quintile of surveyed African countries, only 5.5% of households practiced adequate household treatment, in contrast to a regional average of 10.6%, which is already low (Rosa & Clasen, 2010). They also found that rural populations were less likely to practice adequate household water treatment, despite having less access on average to improved water sources (Rosa & Clasen, 2010).

While there are a plethora of household water purification systems, there are none that sufficiently meet the needs of the poor. An adequate household water purification system, in addition to effectively removing all types of pathogens must be extremely simple to use (both in terms of process complexity and time required) as well as inexpensive. An ideal system would eliminate the need for human intervention. Such a system would face some difficulty in wide scale deployment, particularly due to low demand from users who may not see the value in purifying their water, especially if it is time consuming. That said, purification systems have been and continue to be marketed, so distribution channels are somewhat developed, and business models (direct to consumer marketing) are similarly somewhat developed. This provides a starting point for deployment, which could be leveraged by a water purification system that overcomes existing shortcomings for the user. Based on the above analysis, the time to market readiness is 2-4 years, and the difficulty of deployment is COMPLEX.

Breakthrough 5 – Difficulty of deployment

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Dependent on existing infrastructure

Moderate financing needed, viable mechanisms identified

Breakthrough 5
Throughout human history, changing the natural environment in the interest of human welfare and economic output has been an integral part of development efforts. These direct or first-order environmental changes have been hugely beneficial to humans, and were the basis of fundamental human advances—the Agricultural and Industrial Revolutions. However, as the scale of human enterprise increases relative to the scale of natural processes (i.e. those not managed by people), a growing number of indirect or second-order environmental consequences can be seen. Activities that previously were overwhelmingly beneficial now bring both positive and negative effects on human welfare. There are a number of pathways through which environmental changes may significantly impact human development, but direct cause-and-effect has not been clearly articulated, yet. Here we seek to understand the complex chain of events linking environmental change and human welfare.

We identify 7 broad categories that comprehensively describe the first-order environmental changes caused by human actions. Ranging in nature from biotic changes of living organisms to geochemical changes of the physical planet, these direct environmental changes are: altered species...
and population distributions, lower ecosystem complexity, land cover change, carbon cycle alteration, water cycle alteration, nitrogen cycle alteration, and alteration of other geochemical cycles. We further establish the link between these first-order changes and their second-order consequences, including pollution, deforestation, rising sea levels, groundwater depletion, and soil erosion among others. These indirect consequences lead to human development challenges in terms of food security, health, human displacement, and conflict.

Second-order environmental consequences that pose major threats to food security include more frequent and severe droughts and floods, soil loss due to erosion, crop yield reductions due to warmer temperatures, irrigation constraints due to groundwater depletion (especially in South Asia), and long-term constraints on plant nutrient sources. Major threats to human health include water pollution that leads to diarrheal diseases, household air pollution due to indoor burning of solid fuels, altered disease vectors and extreme weather events due to climate change, and outdoor air pollution and environmental toxins. Threats of human displacement are expected for coastal populations affected by rising sea level, desertification leading to abandoned farmland due to untenably low agricultural yields, and agricultural yield limits due to irrigation constraints (especially in South Asia). Threats related to conflict involve questions of control of increasingly limited natural resources, including global markets for fossil fuels and mineral ores, as well as local needs such as water and grazing land.

Identifying solutions to human development challenges arising from environmental change is especially problematic, precisely because the changes have occurred due to human efforts towards development. Many non-technological hurdles exist that may constrain successful mitigation and/or adaptation to environmental change. These include a lack of effective regulatory and enforcement mechanisms, lack of adequate economic means to commit to solutions, and lack of economic incentives among key decision-makers and stakeholders.

Focusing on scientific and technological solutions, many of the breakthroughs identified in other chapters are equally relevant to issues of resilience to environmental change. For example, relevant breakthrough technologies include improved sanitation for human waste, precision irrigation systems, detection and sustainable utilization of groundwater resources, and soil nutrient analysis, as highlighted in our Global Health and Food Security and Agricultural Development sections. Beyond these, we identify 6 technological breakthroughs, 4 of which are relevant for sustainable water use.

- A scalable, low cost method to desalinate water using renewable energy
- Low cost system for precision application of agricultural inputs, ideally combining fertilizers and water
- A scalable method for sustainable integrated aquaculture production
- Low cost, distributed monitoring sensors to identify environmental toxins and their concentrations
By now, there is ample evidence to demonstrate that climate change is already here. As the 2014 Intergovernmental Panel on Climate Change (IPCC) report points out, its effects are being felt; and they will continue to worsen, with vulnerable populations in low income countries bearing the brunt of phenomena like extreme weather events, higher temperatures, rising sea levels, and shifting rainfall patterns. As bad as the impact of climate change on these populations is, it is only a part of the larger problem. In much of the developing world, the combination of broad poverty, rapid economic growth in some populations segments, and the lack of political will and appropriate regulation, has led to significant damage to the environment: outdoor air is polluted because of automobile exhaust; indoor air is polluted due to poor ventilation and cooking methods; water systems are full of fecal pathogens; urban slums accumulate mountains of trash; and whatever factories there are, often feel unencumbered to pollute the air, water and land with toxins.

With the above context in mind, this section analyzes the needs of low income populations globally, through the following analytical lenses:

- We begin by examining which specific human actions lead to which specific direct or first-order environmental changes. We then try to connect these first-order environmental changes to detrimental indirect or second-order environmental consequences. This broad set of issues includes the various phenomena linked to climate change.

- We analyze the aggregate impact of first-order environmental changes and second-order consequences on low income human populations, within the 2050 time horizon. We fully recognize that there are a number of additional major threats that these populations will face beyond 2050, and that environmental change is taking a tremendous toll on other forms of life on the planet, but those aspects go beyond the scope of our study at present.

- Finally, we focus only on those actions that can be taken in developing countries. We recognize that in many cases (such as climate change), it is the actions of industrialized countries that are causing much of the damage. However, we believe that other studies (e.g., the IPCC report) are already addressing actions that must be taken by industrialized countries to mitigate such changes.
CORE FACTS AND ANALYSIS

To satisfy our human needs and desires, we modify our surrounding natural environment in many ways. We cause various direct, or what we term here as first-order, environmental changes—ranging in nature from biotic to geochemical—that enable provision of goods and services in the food, household and industrial sectors. While these first-order environmental changes bring huge benefits to humans, they also have indirect or second-order consequences that pose risks and challenges to human wellbeing in the longer term. Human-caused first-order environmental changes have increased rapidly during the past 100 years, and many second-order consequences are now becoming conspicuous. Some of these second-order effects may cause significant negative human development impacts related to food security, health, conflict, and human displacement.

We propose a new analytical framework to explain the links between environmental change and human development

There are numerous pathways through which environmental changes can seriously impact human development, but direct cause-and-effect has not yet been clearly articulated. We propose a new analytical framework (Exhibit 1), that links human actions to first-order environmental changes, to second-order environmental consequences, and ultimately to human development impacts. These linkages are mapped and further explained later in this section in Exhibit 2, Exhibit 10 and Exhibit 11. Together, they seek to explain the complex chain of events linking environmental change and human welfare.

Linkage between human actions, environmental changes and human development

<table>
<thead>
<tr>
<th>Human Actions</th>
<th>First-order Environmental Changes</th>
<th>Second-order Environmental Consequences</th>
<th>Human Development Impacts</th>
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<tbody>
<tr>
<td>Land conversion</td>
<td>Species distribution</td>
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<td>Food production</td>
<td>Simpler ecosystems</td>
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<td>Land cover change</td>
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<td>Carbon cycle change</td>
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<td></td>
<td>Water cycle change</td>
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<td>Nitrogen cycle change</td>
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<td></td>
<td>Other geochemical cycles</td>
<td>Deforestation</td>
<td></td>
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<td></td>
<td></td>
<td>Resource depletion</td>
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</tbody>
</table>

Exhibit 1: While human-caused environmental changes bring many intended benefits, these changes also lead to indirect consequences that pose long-term challenges. These linkages are mapped and detailed in Exhibits 2, 10 and 11.

As the focus of this report is global human development, this analysis is explicitly conducted from an anthropocentric perspective; we ask how environmental changes will affect human wellbeing. We acknowledge that an assessment of environmental change could be made from other perspectives, e.g. bio-centric or eco-centric, which may yield other conclusions based upon different priorities. Further acknowledging the long-term characteristics of environmental change and sustainability issues, our
main interests here are the implications for global development within the next human generation, i.e. until about 2050.

Seven first-order environmental changes caused by human actions

We humans carry out a range of actions in our quest for a better quality of life, stemming from our needs and choices regarding production and consumption in the food, household, and industrial sectors. To enable production of adequate food for the growing human population, we convert land that is ‘wild’ (i.e. not controlled by human influence), into managed cropland, pastures and orchards. We select certain animals to be domesticated, and care for these species while we actively exclude all other animal species. We favor a relatively small number of plant species such as wheat, rice and maize, and we cultivate these species across huge areas of cropland. All other plant species are considered ‘weeds’ and are eliminated by soil tillage or chemical poisons. We operate irrigation systems to provide water needed for the growth of our favored plants, and we apply chemical fertilizers to the land to provide for their nutrition.

To provide comfortable and healthy household conditions, we convert more wild land to create urban settlements. Within our houses we consume water, food and fuels, and we produce a range of waste products. Households with access to mechanized personal transport, such as automobiles and buses, consume additional fuels to gain mobility.

The food and household sectors are supported by an elaborate industrial system to process and use a wide variety of materials from the environment. This involves conversion of additional wild land for industrial purposes, such as mining and timber production. Raw materials are extracted, refined and processed to become consumer goods. Additional resources, such as water and energy, are also used in manufacturing processes. We generate electricity by various means, and distribute it for many uses. We create vast multi-modal cargo transportation networks, and shift natural resources globally to suit our needs. Our systems for managing wastes, however, are typically less elaborate, and for convenience waste materials are often discarded into our surroundings.

Exhibit 2 lists various examples of these human actions, and describes the first-order environmental changes caused by them. Adapting from Vitousek (1997), we identify 7 broad categories (listed below) that comprehensively describe the first-order environmental changes caused by human actions. There are significant interactions between these 7 categories.

- Humans now largely determine species and population distributions
- Humans are making ecosystems simpler and less diverse
- Humans significantly change the land cover when we use land
- Humans have significantly altered the natural carbon cycle
- Humans have significantly altered the natural water cycle
- Humans have significantly altered the natural nitrogen cycle
- Humans have significantly altered other geochemical cycles
### First-order environmental changes caused by human actions

<table>
<thead>
<tr>
<th>Human actions (examples)</th>
<th>Biotic changes</th>
<th>First-order environmental changes</th>
<th>Geochemical Changes</th>
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<td>Lower ecosystem complexity</td>
<td>Land cover change</td>
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<tr>
<td>Land conversion (Wild land → agricultural land)</td>
<td>Conversion from wild to domesticated species</td>
<td>Relative simplicity of agro-ecosystems</td>
<td>Shift from natural to managed land</td>
</tr>
<tr>
<td>Soil tillage</td>
<td>Tillage to favor crop species</td>
<td>Plant and soil community disturbance</td>
<td>Soil exposed to wind and rain</td>
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<td>Animal Husbandry (intensive/extensive)</td>
<td>Several animal species are favored</td>
<td>Simple system of managed species</td>
<td>Land use for pasture</td>
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<tr>
<td>Irrigation</td>
<td>Crop plant range is expanded</td>
<td>Expands range of agriculture</td>
<td>Watershed management for irrigation</td>
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<tr>
<td>Fertilizer production and use</td>
<td>Target species are eliminated</td>
<td>Loss of target species</td>
<td>Plant cover by target species</td>
</tr>
<tr>
<td>Pesticide/herbicide use</td>
<td>Target species are eliminated</td>
<td>Population reduction from overexploitation</td>
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<td><strong>Household/domestic activities</strong></td>
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<tr>
<td>Land conversion (Wild land → urban land)</td>
<td>Conversion from wild to human habitat</td>
<td>Relative simplicity of urban ecology</td>
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<tr>
<td>Indoor solid fuel burning</td>
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</tr>
<tr>
<td>Mechanized public transport</td>
<td>Carriage of introduced species</td>
<td>Managed river ecosystems</td>
<td>Land cover by road infrastructure</td>
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<td>Household water consumption</td>
<td>Aquatic species affected by dams</td>
<td>Managed river ecosystems</td>
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<tr>
<td>Waste sewage disposal</td>
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<td>Methane from decomposition</td>
<td>Water quality reduction from pollutants</td>
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<td><strong>Industrial activities</strong></td>
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<tr>
<td>Land conversion (Wild land → industrial land)</td>
<td>Conversion from wild to managed forest</td>
<td>Relative simplicity of managed forests</td>
<td>Land cover by managed forests</td>
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<tr>
<td>Extraction and processing of mineral raw materials</td>
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<tr>
<td>Mechanized cargo transport</td>
<td>Carriage of introduce species</td>
<td>Managed river ecosystems</td>
<td>Land cover by road infrastructure</td>
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<td>Material processing and fabrication</td>
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<tr>
<td>Electricity generation and distribution</td>
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<td>Industrial water consumption</td>
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<td>Waste disposal</td>
<td>Aquatic species</td>
<td>Land cover by waste sites</td>
<td>Water quality reduction from pollutants</td>
</tr>
</tbody>
</table>

**Exhibit 2:** Mapping of select human actions (food production, household activities, and industrial activities), to first-order environmental changes.
Humans now largely determine species and population distributions

While humans were once a minor species struggling for existence in a landscape largely full of wild animals and plants, we have now dominated most land ecosystems. By favoring and domesticating certain plant and animal species, humans have developed extensive agricultural ecosystems and caused substantial changes in the number and range of many other organisms. Three types of wild grasses, wheat, rice and maize, have been domesticated and reproduced to such an extent that they now comprise the 3 most abundantly cultivated plants on earth. Domesticated animals are fed and protected by humans, while other animals that threaten them are killed or expelled. Our analysis demonstrates the current dominance of humans and domesticated animals over land by comparing the total mass of different animal species, in terms of carbon content in their collective biomass in living bodies (Exhibit 3). Living humans are estimated to contain about 45 million metric tons (Mt) of carbon; domesticated animals maintained by humans have about 130 Mt of carbon (Smil, 2003) (UN, 2013) (FAOSTAT, 2014) (Dirzo, et al., 2014). These quantities have more than doubled since 1950. In contrast, the biomass of all wild land vertebrates including mammals, birds and reptiles contains less than 5 Mt of carbon, and is steadily decreasing. Humans now largely control which animals live in most land areas of the world. However, human dominance does not extend to the smaller creatures, including the nearly 700 Mt of carbon in invertebrates (e.g. insects), approximately 4000 Mt in fungi, and about 20,000 Mt in soil bacteria (Smil, 2003).

Exhibit 3: Humans and domesticated animals dominate over all other land animals. This figure shows the estimated amount of carbon contained in the living bodies of all humans, domesticated animals, and wild land vertebrates (mammals, birds, reptiles, etc.).
Humans are making ecosystems simpler and less diverse

The population shift from wild to domesticated animals and plants necessarily involves the simplification of the structure and functioning of ecosystems. Humans are causing ecosystems to lose complexity at several levels: species diversity (the number and variety of species), genetic diversity (the genetic possibilities a species contains), and ecosystem diversity (the variation between global ecosystem characteristics) (MEA, 2005). The distribution of species on earth is becoming more homogenous, meaning that the differences are, on average, diminishing between the group of species at one location on the planet and groups at other locations. Different types of species evolved in ecosystems in different regions, through the combination of natural barriers to migration and local adaptations. These regional differences in the biota of the earth are now diminishing. Genetic diversity, which serves as a way for populations to adapt to changing environments, is being lost.

Species tend to come and go, evolutionarily speaking, but human actions are now causing species extinction at a rate 1000 times greater than the natural background rate of extinction (Pimm, et al., 2014). This ongoing simplification is illustrated in Exhibit 4, based on the Living Planet Index that is calculated periodically by WWF International (WWF, 2014). This index estimates changes in the state of the planet’s biodiversity, using trends in population size for vertebrate species from different biomes and regions to estimate average changes in abundance over time (Collen, et al., 2008). Trends in the Living Planet Index suggest that across the globe, wild populations of vertebrate animals were on average 52% smaller in 2010 than they were in 1970. The greatest reductions occurred in tropical regions, in particular the Neotropical biogeographical area that includes South and Central America, and the Indo-Pacific area that includes South Asia and Australasia. Temperate regions show smaller reductions, largely because those lands were cleared for agricultural use long before 1970, and now include abandoned farmlands that are reverting to natural growth. Acknowledging the imprecision of such simple proxy indicators, the global trends toward lower biodiversity and simpler ecosystems are robust.

Change in animal biodiversity since 1970

Exhibit 4: Regional and global biodiversity has generally decreased in recent decades, as estimated by WWF’s Living Planet Index, based on wild populations of vertebrate animals between 1970 and 2010. Error bars represent 95% confidence limits. The 5 regions are biogeographic realms, where terrestrial species have evolved in relative isolation over long periods of time. Afrotropical includes sub-Saharan Africa. Nearctic includes North America. Palearctic includes Europe, North Africa, the Middle East, and most of Asia. Indo-Pacific includes South Asia and Australasia. Neotropical includes South and Central America (WWF, 2014).
Humans significantly change the land cover when we use land

Human use of land typically alters the interface between the atmosphere and the geosphere, affecting interactions between land, plants, air and water. For example, land cover largely determines the partitioning of precipitation into evapotranspiration, runoff, and groundwater flow. Humans have, over a span of centuries, converted land once covered by wild forests and grassland into cropland and pastures. Exhibit 5 shows that about 10 million km$^2$ of forest land has been lost during the last three centuries (Ramankutty & Foley, 1999) (Pongratz, et al., 2008) (FAO, 2010) (World Bank, 2013). Cropland area (the extent of which may vary, depending on the definition used), increased by about 15 million km$^2$ during the same period. The rates of forest land decrease and cropland increase have remained fairly steady over the last 300 years, though have accelerated somewhat since about 1850. The current rate of deforestation is in line with this centuries-old trend, and direct human occupation of land continues to expand.

Exhibit 5: Over the last 3 centuries, humans have converted about 10 million km$^2$ of forest land to other uses, and have turned about 15 million km$^2$ of land into agricultural cropland. During the same period, natural grassland area has decreased, and pasture land area has increased (not shown in figure).

Humans have significantly altered the natural carbon cycle

Carbon is a chemical element, and natural forces cause it to cycle in various forms and rates. Carbon cycles on the earth between the atmosphere as carbon dioxide gas, in the biosphere as organic carbon compounds, in the oceans as dissolved carbon dioxide, and in the lithosphere as carbonate and hydrocarbon minerals. Humans have significantly changed natural carbon cycling by altering living biomass due to land use change, and by shifting carbon from geologic storage in the form of fossil fuels, into the atmosphere in the form of carbon dioxide. Humans have long influenced land cover, even before the introduction of agriculture. For example, fire has long been a relatively easy and effective way for
small-scale societies to reshape the vegetation communities in their regions, to increase the relative abundance of preferred plant and animal food resources (Smith, 2011). During the last century, however, the use of fossil fuels in the form of coal, oil, and gas has become the primary source of human-caused carbon emissions (Exhibit 6) (Le Quéré, et al., 2014) (Houghton, et al. 2012) (Boden, et al., 2013). Humans seek to extract and use the chemical energy stored in fossil hydrocarbon fuels. In doing so, carbon in the fuel changes into a more stable form, carbon dioxide. Currently, about 9 billion metric tons of carbon—over 200 times more than the amount of carbon in all living humans (Exhibit 3)—is emitted each year from fossil fuel use (IPCC, 2013). Another 0.5 billion ton of carbon is emitted each year during cement production, when a raw material (calcium carbonate) is heated in manufacturing kilns, creating carbon dioxide as a waste product. About 1 billion ton of carbon is currently emitted per year, due to land use. There are vast differences in the country-level emissions that comprise these global totals: lower income countries have relatively low emission levels that are dominated by land use, while higher income countries have much higher emission levels that are primarily due to fossil fuel use (IPCC WG3, 2014).

Carbon dioxide emissions caused by humans since 1850

Exhibit 6: Land use change (such as deforestation) had long been the dominant human-caused source of carbon dioxide (CO₂) emissions. During the last 100 years, emissions from the combustion of fossil fuels (coal, oil, natural gas) have increased considerably and are now the largest source of emissions. Process emissions from cement manufacture are shown here as fossil fuel emissions, and comprise about 5% of those emissions.

Between 1750 and 2011, the combustion of fossil fuels and the production of cement have released a cumulative total of about 375 billion metric tons of carbon—over 8,000 times more than the amount of carbon in all living humans. Land use change since 1750, mainly deforestation, has released an additional 180 billion metric tons of carbon. Clearly, humans have a disproportionately large effect on the global carbon cycle. These large and sustained emissions of carbon dioxide have steadily increased the concentration of that gas in the atmosphere. For at least 2 million years prior to the industrial era (i.e. before 1750), the concentration of carbon dioxide in the atmosphere had fluctuated between
Humans have significantly altered the natural water cycle

Water cycles naturally, from when it falls as rain or snow, flows downhill in soils and rivers, may be drawn up into living plants, and eventually returns to the atmosphere as water vapor, from which it falls again. Human actions have changed this cycle in several ways, some intended and others unintended (Meybeck, 2003). Management of the water cycle has improved human wellbeing by controlling floods, generating hydropower, providing transportation, and irrigation. Humans have changed the patterns of surface water flow, e.g. by impounding river water behind dams, and by reducing rainwater infiltration through paved surfaces. Exhibit 7 shows that artificial reservoirs now have the capacity to hold about as much water as contained in Lake Michigan, one of the great lakes of North America (Vörösmarty & Sahagian, 2000) (van der Leeden, et al., 1990). In densely populated areas of the world, actions such as river engineering, water withdrawals, and waste dumping have significantly changed the water and material transfers through river systems, such that these actions now likely exceed the influence of natural drivers (MEA, 2005). Surface runoff and river discharge generally increase when natural vegetation (especially forest) is cleared. Such actions to manage and control water flows have involved environmental trade-offs, including fragmentation and loss of habitat for other organisms, biodiversity loss, and changes in sediment transport.

Global water storage capacity in artificial reservoirs since 1900

Exhibit 7: Human alterations to the water cycle, including intercepting and storing water flows, have increased substantially during the last century. Construction of dams and reservoirs increased significantly after 1950. By 1960 the total water storage capacity within artificial reservoirs globally was equivalent to that of Lake Ontario; by 1980 it was equal to Lake Huron. Currently, human-created reservoirs have the capacity to hold about as much water as there is in Lake Michigan.

In addition to changing the amount and timing of water flows, humans have also changed the quality of water by using water bodies like rivers, lakes and oceans as a dumping ground for biological wastes (e.g. sewage) and inorganic pollutants. Pollution is typically an unintended consequence of other
Humans have significantly altered the natural nitrogen cycle

Nitrogen comprises about 78% of earth’s atmosphere. However, it typically exists in the very stable $N_2$ form, with two nitrogen atoms bound tightly together, unwilling to form partnerships. Nitrogen is essential to life on earth, as it is needed to make amino acids, nucleotides and other basic building blocks of plants, animals and other life forms. A limited amount of nitrogen, known as reactive nitrogen, is ‘fixed’ from the atmosphere and then made available to living organisms in a more reactive form. There are several natural routes of nitrogen fixation, including by particular bacteria living in symbiosis with some types of plants. Humans have long managed croplands to incorporate these types of plants within crops rotation systems, to fix a modest amount of nitrogen within agroecosystems. During the last 50 years, the amount of nitrogen that is fixed through human actions has increased steadily, and now occurs at a scale similar to that of all natural land ecosystems (Robertson & Vitousek, 2009) (Exhibit 8). Most of this increase is due to fertilizer production using the Haber-Bosch process (described in the chapter on fertilizers and soil health, in the section on Food Security and Agricultural Development). The temporary reduction in nitrogen fertilizer production during the early 1990s was due to the collapse of the Soviet Union. Other human actions that fix atmospheric nitrogen include fuel combustion and managed biological fixation. This alteration of the nitrogen cycle has allowed us to grow significantly more food for consumption than otherwise would be possible. However, the increased overall availability of nitrogen fertilizer, coupled with the difficulty of precisely targeting application to ensure maximum absorption by plants, has led to nitrogen runoff well beyond the farmlands the fertilizer is applied to.

Reactive nitrogen fixed by human actions

Exhibit 8: Human production of reactive nitrogen has increased substantially during the last 50 years, and now occurs at the same rate as it does in all natural land ecosystems put together. Most of this increase is due to fertilizer production using the Haber-Bosch process, using natural gas as feedstock (MEA, 2005).
Humans have significantly altered other geochemical cycles

In terms of shaping the surface of the earth, humans now cause about 10 times more erosion and sedimentation than that caused by glaciers, rivers, and other natural processes combined (Wilkinson, 2005). From intentional transport of construction materials and mineral ores, to unintentional facilitation of natural erosion processes through soil tillage, humans have become the dominant geologic force on the planet. In addition to soil erosion and alterations to the carbon, nitrogen and water cycles, humans are affecting changes to other global geochemical cycles at various scales of time and place. An important example is the chemical element phosphorus, which is an essential nutrient for plant growth. Phosphorus fertilizers are important because of the slow natural cycling of phosphorus, the low solubility of natural phosphorus-containing compounds, and the essential nature of phosphorus to living organisms. Traditional sources of agricultural phosphorus are animal manure and guano (bird droppings). Exhibit 9 shows that phosphate rock mining expanded considerably after 1950, and is now the dominant source of phosphorous fertilizer, an essential input to intensive agriculture (Cordell, et al., 2009). The countries currently mining the most phosphate rock include China, US and Morocco (USGS, 2014). Global reserves of phosphate are concentrated in the Western Sahara region of Africa, a disputed region controlled by Morocco. Sustained disruption of supply, whether due to geological or geopolitical forces, would significantly affect food security (Dawson & Hilton, 2011).

Sources of phosphorous fertilizer since 1800

Exhibit 9: Mining of phosphate rock expanded considerably after 1950, and is now the dominant source of phosphorous fertilizer used in agriculture (Cordell, et al., 2009).
First-order environmental changes cause a variety of second-order environmental consequences

The first-order environmental changes described so far have mainly brought positive benefits for human populations, including provision of basic needs like food and shelter. Indeed, these changes were made primarily to improve the quality of our lives. However, as the scale of human enterprise increases relative to the scale of natural (i.e. not managed by people) processes, a number of indirect or second-order consequences can be identified. Activities that were previously overwhelmingly beneficial now bring both positive and negative effects on human welfare.

Exhibit 10 shows how first-order environmental changes lead to second-order environmental consequences for human populations. These are unintended consequences that result from the first-order changes brought about by human activities as described in Exhibit 2. As illustrated in Exhibit 1 earlier, and now in a sectional view reproduced below, second-order environmental consequences have significant human development impacts.

Some of these second-order environmental consequences manifest locally, close to the human actions that provoked them, and others are seen globally. For example, household air pollution occurs immediately within a building where solid fuels are burned for cooking. Climate change, on the other end of the spectrum, is a global phenomenon regardless of where greenhouse gases are emitted.
Second-order environmental consequences of first-order environmental changes

Exhibit 10: Mapping of first-order environmental changes to second-order environmental consequences. (GHGs are greenhouse gases, CO₂ is carbon dioxide, CH₄ is methane, and POPs are persistent organic pollutants)

Second-order environmental consequences lead to significant impacts for low income human populations

Exhibit 11 indicates how second-order environmental consequences lead to challenges for human development, including issues of food security, health, human displacement, and conflict. Major threats to food security include more frequent and severe droughts and floods, soil loss due to erosion, crop yield reductions due to warmer temperatures and/or untimely precipitation, irrigation constraints due to groundwater depletion (especially in South Asia), and long-term limitations on nutrient supplies. Major threats to human health include diarrheal diseases due to water pollution, chronic respiratory and lung diseases caused by household air pollution due to indoor burning of solid fuels, altered disease vectors and extreme weather events due to climate change, and outdoor air pollution and environmental...
Groundwater depletion will constrain irrigated agricultural production, especially in South Asia. As described in detail in the section on Food Security and Agricultural Development, irrigation plays a key role in global food security. While only an estimated 18% of global cropland is irrigated, that land accounts for 40% of global food production (Schultz, 2001). There are two types of groundwater sources used for irrigation. The first are renewable groundwater sources, in which the groundwater is periodically replenished when sufficient precipitation infiltrates the soils or when floodplains become inundated. The second type are non-renewable or fossil groundwater sources, which are typically locked in deep aquifers that have little or no long-term source of replenishment. When this water is extracted, it is effectively

| Threats related to conflict include questions of control of increasingly limited natural resources, including global markets for fossil fuels and metal ores for instance, as well as local needs for water and grazing land. |

### The impact of second-order environment consequences on human development by 2050

<table>
<thead>
<tr>
<th>Second-order environmental consequences (examples)</th>
<th>Impacts on human development by 2050</th>
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<td>Food Security</td>
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<tr>
<td>Groundwater depletion</td>
<td>Limited supply of irrigation water (SA)</td>
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<tr>
<td>Water pollution</td>
<td>Diarrheal diseases and other health issues</td>
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<tr>
<td>Soil erosion</td>
<td>Loss of fertile soil and crop yields</td>
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<tr>
<td>Household air pollution</td>
<td>Burning of solid fuels indoors</td>
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<td>Outdoor air pollution</td>
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<tr>
<td>Environmental toxicity</td>
<td>Contamination of food products</td>
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<tr>
<td>Global avg. temperature rise</td>
<td>Reduced crop yields, expanded pest ranges</td>
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<tr>
<td>Change avg. precipitation</td>
<td>Long-term reduction in water supply (SSA)</td>
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<tr>
<td>Extreme weather events</td>
<td>Food production impacts by droughts and floods</td>
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<td>Sea level rise</td>
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<tr>
<td>Ocean acidification</td>
<td>Change in supply of ocean foods</td>
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<tr>
<td>Deforestation</td>
<td>Displacement of forest populations</td>
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<tr>
<td>Reduced wild food</td>
<td>Reduction in wild fish stock</td>
</tr>
<tr>
<td>Non-renewable resource depletion</td>
<td>Energy for Haber-Bosch process, phosphorous</td>
</tr>
</tbody>
</table>

**Exhibit 11:** Mapping of second-order environmental consequences to likely impacts on human development by 2050 (SA is South Asia and SSA is sub-Saharan Africa).
‘mined’ and the aquifer will eventually be depleted. Globally, about 18% of gross irrigation water demand for the year 2000 was met with non-renewable groundwater extraction (Wada, et al., 2012). Exhibit 12 shows the sources of water used globally for irrigation in 1960 and 2000, during which time the share of non-renewable groundwater increased from 12% to 18%. In absolute terms, the use of non-renewable groundwater more than tripled, from 75 to 230 cubic kilometers per year.

Exhibit 12: Between 1960 and 2000, the share of non-renewable groundwater increased from 12% to 18% of global gross irrigation water. The share of non-local water resources, transported to the regions via canals and pipelines for example, increased from 15% to 19% of global gross irrigation water. Renewable local water comprised a smaller share of global gross irrigation water in 2000 than in 1960. In absolute terms, gross irrigation water use increased two-fold (from 630 to 1340 cubic kilometers per year), and non-renewable groundwater use increased three-fold (from 75 to 230 cubic kilometers per year), between 1960 and 2000. Relatively few countries (described in Exhibit 13) are responsible for most of the non-renewable groundwater use (Wada, et al., 2012).

Relatively few countries, including India, Pakistan and USA, are responsible for most of the non-renewable groundwater use (Gleason, et al., 2012). Exhibit 13 shows that India used more non-renewable groundwater for irrigation than any other country, in year 2000. About 19% of India’s irrigation water came from non-renewable sources. Other countries used smaller amounts of non-renewable water, but it comprised larger proportion of their total irrigation water use. In both Pakistan and USA, the share of non-renewable groundwater was 24%; in Iran it was 40%. In Libya and Saudi Arabia, over 70% of irrigation water was sourced from non-renewable groundwater (Wada, et al., 2012).
Groundwater depletion affects global development primarily due to its impact on food security. It limits the amount of water available for agriculture and other human uses, and makes the available water more difficult to obtain. As groundwater supply becomes more limited, wells may go dry intermittently or constantly. Wells may need to be extended deeper to reach water, and more energy is needed to pump water from greater depths. Water quality of depleting freshwater aquifers may deteriorate due to intrusion of brackish water from surrounding aquifers. Land surfaces may subside, or gradually lower in elevation, as aquifers below become depleted. As a development challenge, South Asia is particularly affected, where strategies for future food security must account for constrained groundwater extraction. Sub-Saharan Africa appears to have relatively abundant renewable groundwater resources (MacDonald, et al., 2012). Unsustainability of groundwater use for irrigation is a concern not only for countries that are using groundwater intensively, but also the world at large since international trade directly links food production in one country to consumption in another.

Exhibit 13: Non-renewable groundwater is a significant part of gross irrigation water use in several major countries. India uses more non-renewable groundwater for irrigation than any other country (68 km³ per year, in year 2000). Iran uses less in absolute terms (20 km³ per year) but more as a percent of total irrigation water: 40% of Iran’s irrigation water is sourced from non-renewable groundwater. ‘Other irrigation water’ includes non-local water and renewable local water (Wada, et al., 2012).

Groundwater depletion affects global development primarily due to its impact on food security. It limits the amount of water available for agriculture and other human uses, and makes the available water more difficult to obtain. As groundwater supply becomes more limited, wells may go dry intermittently or constantly. Wells may need to be extended deeper to reach water, and more energy is needed to pump water from greater depths. Water quality of depleting freshwater aquifers may deteriorate due to intrusion of brackish water from surrounding aquifers. Land surfaces may subside, or gradually lower in elevation, as aquifers below become depleted. As a development challenge, South Asia is particularly affected, where strategies for future food security must account for constrained groundwater extraction. Sub-Saharan Africa appears to have relatively abundant renewable groundwater resources (MacDonald, et al., 2012). Unsustainability of groundwater use for irrigation is a concern not only for countries that are using groundwater intensively, but also the world at large since international trade directly links food production in one country to consumption in another.

Water contamination by organic and inorganic pollutants adversely affects health
Two important types of pollutants that degrade water quality are biological pollutants like human sewage, and inorganic pollutants like fertilizer runoff. Biological water pollution by human sewage is considered in detail in the chapter on diarrheal diseases in the section on Global Health. Another important type of water pollution includes runoff of nitrogen and phosphorus fertilizer from agricultural land. Just as fertilizing agricultural fields can stimulate crop growth, increasing nutrient levels in rivers, lakes and estuaries can cause eutrophication or excessive growth of algae and other aquatic plants. Huge blooms of cyanobacteria (also known as blue-green algae), and other organisms can come to
dominate aquatic ecosystems, seriously degrading water quality (Smith, 2003). Negative effects include hypoxia, or depletion of oxygen in the water, which causes the death of fish and other animals in the water. Over 400 marine ‘dead zones’ resulting from nutrient runoff are reported worldwide, having approximately doubled each decade since the 1960s (Diaz & Rosenberg, 2008). Many cyanobacteria also produce toxic compounds that are hazardous to humans and domesticated animals. Mass blooms of toxic cyanobacteria occur regularly in water subject to nutrient runoff, with the timing and duration of the bloom season varying by location. For example, the water supply for the city of Toledo, Ohio, USA was interrupted for several days in August 2014 due to an algae bloom caused largely by phosphorous fertilizer runoff.

In recent decades, the amount of reactive nitrogen in rivers has increased dramatically (Green, et al., 2004) (MEA, 2005), with river basins in North America, continental Europe, and South and East Asia showing the greatest change (Exhibit 14). Africa suffers little from nutrient pollution, mainly because fertilizer use in Africa is still very low.

**Increase in nitrogen runoff leading to aquatic dead zones**

![Map showing percentage increase in nitrogen transport to river mouth](image)

**Percent increase in nitrogen transport to river mouth**

- **<1**
- **1-50%**
- **50-75%**
- **75-300%**
- **300-500%**
- **>500%**

**Exhibit 14:** Reactive nitrogen flows in many river systems have increased dramatically in recent decades—primarily due to fertilizer runoff from agricultural lands—especially evident in Europe, Asia and North America. This has led to ‘dead zones’ in waterways.

Other sources of inorganic water pollution include silt and sediment from soil erosion, waste discharge from small or large scale industrial activities, heavy metals such as mercury or lead, and synthetic and persistent engineered chemicals like plastics and agricultural pesticides (Meybeck, 2003).
Loss of fertile agricultural soil due to erosion causes significant impacts on farm yields and food security. Soil erosion is the removal of soil from the land surface, typically carried away by rain or wind. Some level of soil erosion is natural, and over geologic time spans it has shaped the river valleys and deltas of our landscape. Soil erosion under native vegetation occurs at roughly the same rate at which new soil is produced through natural geomorphologic processes (Exhibit 15). However, agricultural practices such as tillage and heavy grazing remove vegetative cover and expose the soil surface to rain and wind. Soil erosion from agricultural fields occurs at rates 10 to 100 times greater than erosion from natural land surfaces (Pimentel, 2006) (Montgomery, 2007). Soil erosion is widespread: about 80% of global agricultural land suffers moderate to severe erosion (Pimentel & Burgess, 2013). Erosion is much greater on sloping land, where soil particles are carried away downhill by flowing water. Wind can also carry soil particles for long distances.

Soil erosion affects global development by reducing food security. Loss of fertile, nutrient-rich cropland soil reduces the productive capacity of the land and causes lower harvest yields. This is a major problem for poor rural populations living on marginal land with low soil quality and steep topography. As productivity of agricultural fields is reduced, farmers are compelled to apply fertilizers to maintain yields (Lal, 2009). Eventually, when enough productive soil is lost, the land is not worth using, and is abandoned. It is reported that about 3 million hectares of cropland worldwide are abandoned annually because of productivity declines due to severe land degradation (FAO, 2012).

A related issue is desertification, which is the gradual degradation of drylands to become unfertile. While traditionally ascribed to overgrazing, it is now known that many factors affect desertification, including soil erosion, climate change, soil nutrient management and water cycle changes (D’Odorico, et al., 2013). Underlying driving forces include demographic, economic, technological, institutional, socio-cultural, and meteorological factors. Land degradation and desertification is caused by interactions between natural processes such as weather variability including droughts and floods, and human actions of unsustainable land use practices on fragile resources. External forces are also key drivers, including inadequate governance mechanisms, ineffective land tenure, and global economic forces. Locally, this leads to decreased land productivity, overexploitation, and a worsening spiral of land degradation, poverty, and food insecurity.

Loss of fertile soil due to erosion from cropland

Exhibit 15: On average, about 1 to 3 millimeters of soil are lost each year from typical farmland. Soil erosion rates in mountainous regions can be 10 times greater. Under natural conditions, rates of natural soil formation and of soil erosion from land are at least 10 times lower.
Household air pollution from burning solid fuels is a significant, yet largely preventable, health risk. Household air pollution (HAP) in developing countries is primarily caused by burning solid fuels indoors for domestic purposes like cooking or heating. Around 3 billion people cook and heat their homes using open fires and simple stoves that burn biomass—wood, animal dung, crop residues—and coal. Household air pollution from solid fuel combustion affects global development because of chronic health impacts on affected populations. About 4.3 million people die prematurely every year from illness attributable to household air pollution from cooking with solid fuels (WHO, 2014). This is detailed by location and type of disease in Exhibit 16. In total, about 34% of deaths are from strokes, 26% from ischemic heart disease or heart attacks, 22% from chronic obstructive pulmonary disease (COPD), 12% are due to pneumonia and 6% are from lung cancer. While overall more deaths are caused by household pollution in Asia, more children are affected by it in Africa. Over half of all deaths among children under 5 from acute lower respiratory infections (ALRI) are due to particulate matter inhaled from indoor air pollution from household solid fuels (WHO, 2014). The combustion smoke that causes household air pollution contains particulate matter (PM), carbon monoxide, benzene and other harmful agents. PM consists of a complex mixture of solid and liquid particles of organic and inorganic substances suspended in the air. They contain sulfates, nitrates, ammonia, sodium chloride, black carbon, mineral dust and water. Most health damage is caused by particles with a diameter of 10 microns or less, (≤ PM10), which can enter deep inside the lungs.

Numerous types of improved cookstoves exist that could substantially reduce household air pollution, if they were more widely adopted. The damages from household air pollution have been increasingly recognized, and considerable effort has been applied toward solutions. Strategies to reduce indoor air pollution have focused on enhancing demand for clean cookstoves and fuels, strengthening the supply of such stoves and fuels, and fostering an enabling environment for their widespread use (GACC, 2011). While a number of improved stove technologies exist, widespread diffusion and use remains elusive (Subramanian, 2014). Long-term solutions to satisfying household heating needs must also consider the sustainability and security of primary energy supplies (e.g. biomass for charcoal production, and supply chains of fossil natural gas).
Exhibit 16: 4.3 million people died in 2012 from illness attributable to household air pollution, which is primarily caused by burning solid fuels indoors for cooking or heating. Of these deaths, about 34% were from stroke, 26% from ischemic heart disease, 22% from chronic obstructive pulmonary disease (COPD), 12% were due to pneumonia and 6% were from lung cancer. More total deaths were caused in Asia, though more children were affected in Africa. The regions indicated are standard WHO regions; the Southeast Asia WHO Region includes South Asia (WHO, 2014).

Outdoor air pollution, largely caused by vehicles, is a significant health risk in many urban areas. Outdoor (ambient) air pollution in both cities and rural areas is estimated to have caused 3.7 million premature deaths globally in 2012 (WHO, 2014). About 80% of premature deaths related to outdoor air pollution were due to strokes and ischemic heart disease, while 14% of deaths were due to chronic obstructive pulmonary disease or acute lower respiratory infections, and 6% were due to lung cancer. About 88% of those premature deaths occurred in low and middle income countries, and the greatest number in the WHO Western Pacific and Southeast Asia regions. As shown in Exhibit 17, concentrations of air pollutants are typically higher in the urban areas of low and middle income countries.

These air pollution related deaths are largely because of exposure to small particulate matter (PM) with diameter of 10 micrometers or less (PM10 and PM2.5). Chronic exposure to PM contributes to the risk of developing cardiovascular and respiratory diseases, as well as lung cancer. Other serious risks to health from outdoor air pollution are due to excessive exposure to ozone (O₃), nitrogen dioxide (NO₂) and sulfur dioxide (SO₂). Ozone plays a major role in asthma morbidity and mortality, while nitrogen dioxide and sulfur dioxide contribute to asthma, bronchial symptoms and reduced lung function. Outdoor air pollution primarily comes from fuel combustion, mainly from mobile sources such as vehicles and also from stationary sources such as power plants. Most air pollution in cities in developing countries is attributed to vehicle emissions (UNEP, 2014). In rural areas, outdoor air pollution is typically much less of a problem, and may result from burning of agricultural waste, forest fires and activities like charcoal production.
Exposure to outdoor air pollution in urban areas

Exhibit 17: Health conditions due to outdoor (ambient) air pollution are primarily caused by exposure to particulate matter (PM10). Concentrations of PM10 were measured in 1600 urban areas from 2008 to 2013; mean annual concentrations are shown here. Particulate matter levels are highest in urban areas in Asia. Most cities in North America and Europe have low levels. Few data points are available for African cities (WHO, 2014).

Exposure to a broad range of environmental toxins causes chronic health conditions

People are exposed to environmental toxins—a diverse range of chemicals with potentially serious health effects—through air, water, food, or other means. Important examples of environmental toxins include heavy metals and persistent organic pollutants (POPs). Environmental toxins play a role in global development primarily due to their observed or projected chronic health impacts. Acute health impacts can also occur. Toxic materials from industry, mining and agriculture, including substances such as heavy metals and pesticides, affect populations in many countries throughout the world (GAHP, 2013). Although environmental toxins may be less prevalent overall in developing countries because of lower industrial activity compared to industrialized countries, the less stringent industrial regulations typically found in developing countries is a serious concern. Sources of toxic pollution include small- to large-scale mining and processing (e.g. battery recycling) activities, agricultural run-off containing fertilizer and pesticide residues, and toxic wastes that have been illegally disposed of in developing countries. Locations in developing countries that process e-waste (post-use electronic devices) have become ‘hot-spots’ of toxic exposure. The Agbogbloshie area in Accra, Ghana is a prime example (Blacksmith Institute, 2013). Industrial accidents such as the tragic 1984 gas leak at a pesticide factory in Bhopal, India are another source of exposure and lingering, adverse health effects.

An important type of environmental toxin is persistent organic pollutants (POPs), which are organic compounds that do not degrade readily and persist in the environment. They tend to bioaccumulate in organisms, meaning that it remains and accumulates within bodies. Many POPs are pesticides (such as DDT), either currently in use or formerly used but still present in the environment. This chemical...
Global average temperatures will become warmer in the future, affecting agricultural yields and human health. Climate change is a long-term alteration of global weather patterns, due to increased heat energy accumulated in the earth system, largely as a result of greenhouse gases emitted into the atmosphere. Some level of future climate change is unavoidable due to previous emissions, which remain in the atmosphere for long time spans. The extent of future climate change impacts will depend on levels of current mitigation efforts and future adaptation efforts. Current greenhouse gas emissions trajectories also includes dioxins, furans and polychlorinated biphenyls. Dioxins are formed during incomplete combustion and when materials containing chlorine (e.g. some plastics) are burned. Another important type of environmental toxin are heavy metals, which are basic metal elements such as lead, mercury, cadmium and chromium. As elemental materials, they cannot be degraded or destroyed and also bioaccumulate in the body over time. Exposure to lead affects multiple body systems. Young children are particularly vulnerable to the toxic effects of lead and can suffer profound and permanent brain and nervous system damage. An emerging threat from some environmental toxins is their potential impact to the endocrine system. Some chemicals, including POPs and heavy metals, act as endocrine disruptors, interfering with the body’s natural hormones. This leads to reproductive and other health problems in humans and animals, including infertility and early puberty (Frye, et al., 2011).

There have been few quantitative analyses of human risks due to environmental toxins in developing regions (Prüss-Ustün, et al., 2011). Impact estimates will likely increase as the problems are more clearly understood. WHO (2013) estimates that childhood lead exposure contributes to about 600,000 new cases of children developing intellectual disabilities every year. They estimate that lead exposure accounts for 143,000 deaths per year, with the highest burden in developing regions. About half of the burden of disease from lead occurs in the WHO Southeast Asia Region (which includes India), with about one-fifth each in the WHO Western Pacific Region (including China) and Eastern Mediterranean Region (including Egypt and Pakistan). Studies carried out at 373 toxic waste sites in India, Indonesia, and the Philippines found that 8.6 million people were at risk of exposure, resulting in 0.83 million DALYs (range of 0.81 to 1.56 million) (Chatham-Stephens, et al., 2013). This disease burden is comparable to the estimated disease burdens for outdoor air pollution (1.45 million DALYs) and malaria (0.73 million DALYs) in these countries. Exposure to lead and hexavalent chromium accounted for 99% of the total DALYs from exposure to environmental toxins. A study on human exposure to POPs in India found high levels of the pesticides DDT and HCH, often exceeding limits established by international regulatory agencies (Sharma, et al., 2014). Results from human biomonitoring showed levels of these pesticides in human milk and blood exceeding safety limits. This is due to the elevated use of pesticidal POPs in agriculture until recent years, and the ongoing application of DDT for malaria control.

In addition to direct impacts on human health, environmental toxins may also significantly impact global development through their deleterious effects on other species. For example, honey bees provide an invaluable environmental service by pollinating many human crop plants. For almost a decade, bee populations have suffered from the symptomatic disease of colony collapse disorder (CCD), apparently due to exposure to neonicotinoids (Lu, et al., 2014). Neonicotinoids are a class of neuroactive, nicotine-based systemic insecticide that was brought into commercial use in the mid-1990s. Neonicotinoids have a high persistence in soil and water, resulting in sustained and chronic exposure of non-target organisms, such as honeybees and other invertebrates. Because they are relatively water-soluble, they run off into aquatic habitats easily, and are still toxic even at very low doses. Use of neonicotinoids is expected to result in substantial impacts on biodiversity and ecosystem functioning, including the distribution, abundance, and effectiveness of pollinators (van der Sluijs, et al., 2014). This could significantly impact food security due to reduced crop production.

Global average temperatures will become warmer in the future, affecting agricultural yields and human health. Climate change is a long-term alteration of global weather patterns, due to increased heat energy accumulated in the earth system, largely as a result of greenhouse gases emitted into the atmosphere. Some level of future climate change is unavoidable due to previous emissions, which remain in the atmosphere for long time spans. The extent of future climate change impacts will depend on levels of current mitigation efforts and future adaptation efforts. Current greenhouse gas emissions trajectories...
correspond closely to high emission scenarios (RCP8.5) modeled by climate scientists. Continuation of such trends can be expected to result in a global mean temperature increase of about 4°C by 2100 (IPCC WG2, 2014) (Exhibit 18). Global cooperation towards greatly reduced emissions (RCP2.6 scenario) could result in a smaller temperature rise. Such cooperation has not been forthcoming, to date.

**Historical and projected global average surface temperature, 1900 to 2100**

![Graph showing temperature increase](image)

**Exhibit 18:** Global average surface temperature is projected to increase during this century. The temperature increase will be greater if greenhouse gas emissions continue at high levels, following the RCP8.5 emission scenario. A much smaller temperature increase is projected to occur if emissions are limited to the lower RCP2.6 scenario. Temperature changes are shown relative to average 1986-2005 temperature (IPCC WG2, 2014).

Rising temperatures due to climate change are expected to affect global development due to potentially significant effects on food security, water supply, and health. Over most land areas, the coldest days and nights will be warmer and fewer, and the hottest days and nights will be warmer and more frequent. At lower latitudes, especially in seasonally dry and tropical regions, crop productivity is projected to decrease with even a small rise in average temperature (IPCC WG2, 2014). At mid to high latitudes, crop productivity is projected to increase slightly with a small rise in temperature, and eventually decrease as temperatures rise further due to limited heat tolerance by crop plants. **Exhibit 19** summarizes numerous estimates from the peer-reviewed literature of the impact of climate trends on yield of several major crops. Yields of wheat, rice and maize are projected to decrease by several percent per decade. Soy is more heat tolerant, and should be less affected. Water pollution issues are also expected to increase due to higher water temperature and altered water flow patterns. Incidence of some vector-borne diseases, such as malaria, is expected to increase in highland regions as temperatures rise (Siraj, et al., 2014).
Projected impact of climate change on yields of 4 food crops

Exhibit 19: Yields of wheat, rice and maize are expected to decline due to climate trends including rising temperatures. This exhibit summarizes estimates from peer-reviewed literature of the impact of recent climate trends on yields for four major crops. The boxplots indicate the median (vertical line), 25th - 75th percentiles (box), and 10th - 90th percentiles (whiskers) for estimated impacts, and n indicates the number of estimates. The studies were taken from the peer-reviewed literature and used different methods (i.e., physiological process-based crop models or statistical models), spatial scales (stations, provinces, countries, or global), and time periods (median length of 29 years). Some included positive effects of CO₂ fertilization trends but most did not. Values from all studies were converted to percentage yield change per decade. Each study received equal weighting as insufficient information was available to judge the uncertainties of each estimate (IPCC WG2, 2014).

Average long-term precipitation patterns will shift, and some areas will become dryer
Changes in the global water cycle are projected to occur as the climate warms (IPCC, 2013). Average global precipitation is projected to gradually increase in the 21st century. The global hydrological cycle will intensify generally due to global warming, and mean water vapor, evaporation and precipitation are projected to increase on global average. Changes of average precipitation in a much warmer world will not be uniform, with some regions experiencing increases, and others with decreases or little change. Precipitation is expected to increase in many wet tropical areas and at high latitudes. Many mid latitude and subtropical arid and semi-arid regions will likely experience less precipitation. The Asian monsoon will likely increase in average total precipitation, but with greater variation from year to year. The melting of snowpack and glaciers will affect the amount and timing of water flows in downstream areas.

Despite variability and uncertainty in climate change projections, there is now agreement from a number of different climate models that Africa is at the highest risk from climate change, given the magnitude of existing stresses in the continent (UNDP, 2009). It is highly likely that significant areas of African drylands will see changing rainfall patterns in the coming decades. Exhibit 20 shows model projections of future changes in annual precipitation in Africa, under high and low emission scenarios. Average precipitation is expected to decrease in northern and southern Africa, and increase in central and eastern Africa.
Extreme weather events such as drought, storms and floods will become more frequent and more intense.

Global climate change is expected to result in more frequent and intense extreme weather events. Warm spells and heat waves will very likely occur more frequently (IPCC WG2, 2014). Storms such as tropical cyclones are expected to become more severe, including storm surges in coastal areas. Precipitation is more likely to come as heavy rainfall (even in regions that receive less total precipitation), leading to increased erosion, landslides and flooding. Precipitation extremes are projected to negatively affect water quality, due to increased sediment, nutrient and pollutant loadings caused by heavy rainfall, reduced dilution of pollutants during droughts, and disruption of treatment facilities during floods.

The most significant impact of extreme weather events on human development will likely be due to frequent and prolonged droughts in some regions. Many climate models project an increased likelihood of agricultural droughts in regions that are presently dry, with extended decreases in soil moisture (IPCC WG2, 2014). Farmers and pastoralists in drylands with insufficient access to drinking and irrigation water risk the loss of agricultural productivity. This will affect the livelihoods of rural people, particularly those depending on water-intensive agriculture. There is a corresponding risk of food insecurity and conflict over available water and food resources (UNDP, 2009). Droughts also affect

Exhibit 20: Results from climate models suggest that annual precipitation patterns in Africa will change, by the mid-21st century (left) and late-21st century (right), under high emission scenario (RCP8.5; top) and low emission scenario (RPC2.5; bottom). Average precipitation is expected to decrease in northern and southern Africa, and increase in central and eastern Africa (IPCC WG2, 2014).

Projected future changes in annual precipitation in Africa
Sea level will slowly but inevitably rise in the future, affecting coastal populations. Global mean sea level has risen about 0.2 meters since 1900, at a rate of about 1.7 millimeters per year (IPCC WG2, 2014). Sea level is expected to continue rising at an accelerating pace, depending on future greenhouse gas emission scenarios. Forecasting future sea level rise is challenging, but modeling capabilities have improved in recent years and current projections are fairly robust (Horton, et al., 2014). For the low emission climate scenario (RCP2.6), sea level is expected to rise by another half meter by 2100. For the high emission climate scenario (RCP8.5) it is expected to rise a full meter by 2100 (Exhibit 21). Much of this sea level rise is due to thermal expansion of the slowly warming ocean water. Another, more uncertain, contribution to rising sea levels will be melting glaciers and ice caps. Sea level rise will affect global development due to permanent or episodic displacement of coastal populations, inundated agricultural land, and reduced freshwater supply due to saltwater intrusion into aquifers.

Droughts can also significantly affect energy security, because they reduce the energy supply from hydropower stations and can force water-cooled thermal power stations to shut down. A major drought in 2001 in Brazil, where 80% of electricity is from hydropower, caused a 20% reduction in electricity supplies in the country and led the government to introduce rationing (Lee, at al., 2012). Ethiopia is particularly vulnerable to droughts, because of its high dependence on agriculture as well as hydropower for electricity.

Urban populations with inadequate water services, who risk an insufficient water supply for domestic and industrial use, causing health and economic impacts. Droughts can also significantly affect energy security, because they reduce the energy supply from hydropower stations and can force water-cooled thermal power stations to shut down. A major drought in 2001 in Brazil, where 80% of electricity is from hydropower, caused a 20% reduction in electricity supplies in the country and led the government to introduce rationing (Lee, at al., 2012). Ethiopia is particularly vulnerable to droughts, because of its high dependence on agriculture as well as hydropower for electricity.
Coastal areas are highly vulnerable to extreme events, such as storms and their associated surge, which will be exacerbated with higher average sea levels. River delta regions are highly vulnerable to the impacts of climate change, particularly sea level rise and changes in runoff. Many delta plains, especially those in Asia, are very densely populated. Some studies estimate (Ericson, et al., 2006) that over a million people will be directly affected by 2050 in three megadeltas: the Ganges-Brahmaputra delta in Bangladesh, the Mekong delta in Vietnam, and the Nile delta in Egypt. Their modeling suggests that 75% of the population affected by sea level rise live on deltas in Asia, and many of the remainder live on African deltas. About 8.7 million people could be affected by coastal inundation by 2050. GIS based models (Dasgupta, et al., 2009) estimate that a 1 meter rise in sea level will directly affect over 56 million people in developing countries. Several countries are expected to be particularly impacted, including Vietnam and Egypt; both countries may see 10% of their population being displaced by a 1 meter rise in sea level. Some freshwater aquifers in coastal areas are expected to become brackish, due to the intrusion of rising salt water levels (Werner, et al., 2013).

Coastal adaptation practices can seek to protect, accommodate or retreat in response to rising sea levels. Protection efforts can involve ‘hard’ or ‘soft’ measures, but will face increasing pressure over time and may ultimately be untenable. Efforts at accommodation focus on reducing damage from

**Exhibit 21:** Global mean sea level has risen at a rate of about 1.7 millimeters per year since 1900, rising a total of about 0.2 meters since pre-industrial times. The mean sea level is projected to continue to rise at an accelerating pace through 2100 and beyond. Future sea level rise is projected for the low emission RCP2.6 scenario (blue) and the high emission RCP8.5 scenario (red) (IPCC WG2, 2014).
Ocean water is absorbing atmospheric CO₂ and becoming more acidic, affecting sea plants and animals. As described earlier, the concentration of carbon dioxide (CO₂) gas in the atmosphere has risen from about 280 parts per million (ppm) during pre-industrial times to about 400 ppm now. Some of the CO₂ that is emitted into the atmosphere is absorbed by the oceans, and this has a significant impact on the chemistry of seawater. CO₂ reacts with water to form carbonic acid (H₂CO₃), which increases the acidity of the ocean. Acidity is measured in pH units using a logarithmic scale: a 1 unit decrease in pH corresponds to a 10-fold increase in hydrogen ion concentration, or acidity. Since the beginning of the industrial era, the pH of ocean surface water has changed by about 0.1 unit (from about 8.2 to 8.1, on the full pH scale). This corresponds to a 26% increase in hydrogen ion concentration (IPCC, 2013). While not directly related to the changing climate, ocean acidification is caused by the same global drivers, and is typically considered as an impact of global climate change.

Ocean acidification is expected to increase in the future, as the oceans absorb additional CO₂ from the atmosphere. Climate models project a global increase in ocean acidification for all greenhouse gas emissions scenarios (IPCC, 2013). The high emission scenario (RCP8.5) is projected to lead to a decrease in the pH of surface ocean water by about 0.3 units by the end of 21st century. The low emission scenario (RCP2.6) would decrease the ocean water pH by only about 0.07 units by 2100.

The consequences of changes in ocean acidity for marine organisms and ecosystems are just beginning to be understood, but are expected to affect fundamental biological and chemical processes of the sea. Geological records, as well as results from laboratory, field, and modeling studies, suggest that marine ecosystems are highly sensitive to changes in ocean acidity. For example, the acidity of seawater largely determines the saturation state of calcium carbonate minerals, which affects the formation of shells for marine animals such as corals, plankton, and shellfish. Some marine species like reef fishes and shelled mollusks are expected to be negatively affected by ocean acidification, while other species like crustaceans may fare better (Branch, et al., 2013). Overall effects on primary productivity and food webs will be complex, and hard to predict.

Forest land continues to be converted to agricultural land, especially in Latin America. Deforestation is the removal of trees from a forested area, where the land is then converted to non-forest use. Globally, about 31% of total land area is covered by forests, corresponding to a forest area of just over 4 billion hectares (FAO, 2010). Global forest area has decreased by about 1 billion hectares during the last three centuries, corresponding to an average deforestation rate of 3.2 million hectares per year (see Exhibit 5). More recently, forest area decreased at a rate of about 5.2 million hectares per year during the period 2000 to 2010, down from an estimated 8.3 million hectares per year during the period 1990 to 2000. Net global decrease in forest area is the result of two opposing processes. First, deforestation occurred at a rate of about 13 million hectares per year during the period 2000 to 2010, down from about 16 million hectares per year in the 1990s. Second, afforestation and natural expansion of forests occurred in other areas. Globally, much of the increase in forest area occurs in China, where large-scale afforestation efforts increased the forest area by an average of 3 million hectares per year during the period 2000 to 2010. Most of the loss of forest currently occurs in South America (4 million hectares per year) and Africa (3.4 million hectares per year). Table 1 lists the countries with the largest annual net loss of forest area between 2000 and 2010.
Countries with the highest annual loss of forest area, 2000-2010

<table>
<thead>
<tr>
<th>Country</th>
<th>Annual loss of forest area (2000-2010)</th>
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<th>Percentage change per year</th>
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<td>Australia</td>
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<tr>
<td>Total</td>
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</table>

Table 1: These 10 countries experienced the largest net loss of forest area between 2000 and 2010. The decrease in Australia’s forest area is due to extended drought (FAO, 2010).

Around 80% of deforestation worldwide is driven by agriculture (Kissinger, et al., 2012). In Latin America, where most deforestation occurs, about 95% is caused by agriculture (including livestock), primarily commercial agriculture (Exhibit 22). In Africa and subtropical Asia, about 70-75% of deforestation is due to agriculture, of which about half is commercial and half is subsistence agriculture. In terms of impact on human development, deforestation occurs largely due to conversion of forest area to agricultural land, with corresponding positive implications for food security. However, deforestation has negative short-term to medium-term ramifications like landslides, flooding and loss of access to forest products, as well as potential long-term consequences on biodiversity, habitat for wild species, and global climate. The net effect of deforestation on global development is a balance of these forces.
Exhibit 22: Deforestation is driven largely by agriculture. Most deforestation occurs in Latin America, and is largely due to commercial agriculture. Less deforestation occurs in Africa and Asia, where it is driven by both subsistence and commercial agriculture (Kissinger, et al., 2012).

Supplying food by catching wild fish is becoming increasingly difficult and constrained.
Sources of wild food have become less important for humans since the adoption of agriculture and animal husbandry as food security strategies. Meat from wild land animals, or bushmeat, continues to form only a minor part of the human diet in select countries. Bushmeat was reported in 1997 to contribute about 8% of total protein consumption in several African countries including DR Congo, Liberia, and Ghana (FAO, 1997). More recent figures are unavailable, but overall consumption is expected to have decreased since 1997. Most animal protein for humans now comes from domesticated land animals such as cattle and poultry.

Although the ocean environment is more challenging than land for humans, a similar transition from wild fish catch to cultivated fish production is underway. Protein from wild fish continues to be an important component in some regions; fish constitute at least half of total animal protein intake in Bangladesh, Cambodia, Ghana, The Gambia, Indonesia, Sierra Leone and Sri Lanka (FAO, 2012). In 2009, fish accounted for 16.6% of the global population’s intake of animal protein and 6.5% of all protein consumed. However, global stocks of wild marine fish are increasingly overexploited to provide this supply of food (Exhibit 23). The global catch of wild fish has remained roughly level since the late 1980s, despite a greater capture effort (Watson, et al., 2013). The gap has been made up by aquaculture production, allowing expanded human consumption of fish (Exhibit 24).
Gradual depletion of non-renewable natural resources will increase their real cost

Non-renewable resource depletion results from human use and dissipation of one-time stocks of natural resources that were created over geologic time periods, such as fossil fuels, metal ores and other minerals. Public discourse regarding resource depletion is typically polarized in two camps. Cornucopians maintain that technological innovation and market forces will overcome resource scarcity, by developing substitutes or by improving efficiencies of extracting and using the resources. Doomers believe that our historical success at improving human welfare has resulted precisely from our one-time exploitation of the most concentrated and accessible of these resources, and fundamental limits to human activities will then be seen. A broader analysis suggests that elements of both arguments can be

Exhibit 23: Human exploitation of global marine fish stocks is becoming less sustainable, and catching wild fish today requires more effort than before (FAO, 2012) (Watson, et al., 2013).

Exhibit 24: Global catch of wild fish has remained roughly level since the 1990s, while aquaculture fish production has increased significantly since then (FAO, 2012).
seen currently in effect, and can be expected to continue into the future.

Geologic resources such as mineral ores and fossil fuels, which have played essential roles in human development to date (e.g. the Iron Age), were created in fixed amounts in the earth’s crust over geologic time spans of millions of years. An ore is a rock with a relatively high concentration of some desired element, and results from geological and meteorological forces such as plate tectonics, volcanoes, folding, faulting, weathering, erosion and sediment deposition. For example, the earth’s crust as a whole contains an average of only about 0.004 grams of gold per ton, but at particular locations and depths it contains several grams per ton. These locations are prospected and selected to become gold mines. Sites with the highest ore grade are typically exploited first, because the cost and effort of mining and processing metal increase strongly as the concentration of metal in the ore decreases. In particular, the energy needed to refine the ore increases exponentially as ore grade decreases (Norgate, et al., 2007). Exhibit 25 shows historical trends in gold ore grade from 1840 to 2010 in major gold-producing countries (UNEP, 2011). Although gold is not essentially related to global human development, it is a well documented natural resource for which long-term data are available, and serves as a proxy for more functional metals such as copper. The ore grade fluctuates from year to year as individual deposits of gold are exploited, but the long-term trend is of declining ore grade in all regions. Clearly discerning the effect of this trend on gold prices and production levels is difficult due to concurrent changes in economic and technologic factors, though it has necessarily made the physical exploitation of gold resource more challenging. Similar trends toward lower ore grades are seen for most other industrially-important metals, like copper (Harmsen, et al., 2013).

**Quality of gold ore in major producing countries since 1840**

<table>
<thead>
<tr>
<th>Year</th>
<th>Australia</th>
<th>Brazil</th>
<th>Canada</th>
<th>South Africa</th>
<th>USA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1857</td>
<td>50.05</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1858</td>
<td>41.23</td>
<td></td>
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</tbody>
</table>

**Exhibit 25:** The quality of gold ore has decreased considerably since 1840, and high-grade deposits are no longer encountered (UNEP, 2011).
Another important example is fossil fuel use and sourcing. The three types of fossil fuels—coal, oil and natural gas—supply about 82% of all global primary energy use (IEA, 2014). Globally, we are heavily dependent on fossil fuels for transportation, electricity, heat and other energy services such as nitrogen fertilizer production. Fossil fuels were formed from decayed organic matter that was exposed to heat and pressure in the earth's crust over long periods of time. Most fossil fuels are made from plants and animals that were alive during the Carboniferous Period, about 350 million years ago. As such, fossil fuels are clearly non-renewable over time scales of interest, and long-term human development will require a transition to renewable energy sources. Notwithstanding, the global use of fossil fuels has more than doubled in the last 40 years, and overwhelmingly remains the dominant source of energy for human society (Exhibit 26). Geologic deposits of fossil fuels have shown declines in resource quality over time, similar in nature to that shown for gold in Exhibit 25 (Hall, et al., 2014). However, continued expansion of fossil fuel production has been made possible by a range of advanced technologies such as deepwater drilling, horizontal drilling, hydraulic fracturing and oil sand recovery. These techniques to exploit unconventional fossil fuel resources come at an economic and energetic cost, and have become necessary only because the preferred conventional reserves have become increasingly depleted.

**Global total annual primary energy use since 1971**

![Graph of global total annual primary energy use since 1971](image)

**Exhibit 26**: The total annual primary energy used globally has more than doubled since 1971; fossil fuels remain the dominant source of energy. Global energy use is shown here by the source of the primary energy, in units of million tons of oil equivalent (Mtoe) per year (IEA, 2014).

As available deposits of natural resources become less concentrated and less accessible, increasing effort must be dedicated by society to obtain the still available natural resources. Other things equal, this will result in less surplus resource wealth that can be applied to improving human welfare (Murphy, 2013). As increasingly complex unconventional techniques are needed to access and exploit remaining fossil fuel resources, the real cost, including externalities, is likely to increase. This may affect human
development by constraining potential solutions that are too energy or resource intensive to scale effectively (Lee, et al., 2012). The concern is less about running out of a resource, but of bearing the increasing costs and risks involved with obtaining it. In this light, our increasing use of unconventional fossil fuel extraction techniques (such as hydraulic fracturing and oil sand recovery) is less of an energy revolution and more of an evolution toward the use of lower grade resources.

Prudent planning of human development efforts should not pre-suppose the existence of indefinitely plentiful natural resources, but should anticipate long-term supply shifts. As a vital example, virtually all nitrogen fertilizer, which is necessary to maintain agricultural yields, is made with fossil natural gas. Dynamic resolution will occur at the intersection of increasing human demand, decreasing geologic abundance, and improving efficiency of extraction and utilization technologies. Early transition to renewable energy sources and production systems will offer increasing benefits over time, as the quality of accessible non-renewable resources further declines. Deployment of renewable energy has strong synergies with sustainable development goals (Sathaye, et al., 2010).

The various environmental changes and consequences are driven by global and local actions, but not all of them have significant impact on human development by 2050

The level of impact of the numerous second-order environmental consequences on human development will vary, and only some of these problems can be fully resolved through actions within developing countries. Exhibit 27 shows the estimated severity of impacts on human development goals, and whether the primary drivers of environmental change are global or local actions. Some of the primary drivers like indoor air pollution and soil erosion are clearly local, meaning that these problems could, in principle, be fully solved through local efforts. Other environmental consequences like ambient air pollution and groundwater depletion have regional drivers, and require some level of regional administration to overcome. Some consequences, including climate change and natural resource depletion, have clearly global drivers, and will cause local damages regardless of the location of the drivers. These problems require global cooperation for effective mitigation, while local adaptation measures are needed to accommodate inevitable changes. The drivers of other environmental consequences like deforestation and reduced wild ocean food are more challenging to localize, in part because local actions such as logging and fishing may be stimulated by global market forces.

The four quadrants of Exhibit 27 represent issues with varying severity of impacts and potentials of solution.

- **Quadrant A** contains high impact problems with local focus of mitigation and/or adaptation.
- **Quadrant B** contains medium impact problems with local focus of mitigation and/or adaptation.
- **Quadrant C** contains high impact problems with local adaptation focus. Mitigation, where possible, will require global cooperation.
- **Quadrant D** contains medium impact problems with local adaptation focus. Mitigation will require global cooperation.
Anticipated human development impacts of environmental change consequences

Exhibit 27: Matrix of environmental change consequences, showing anticipated impacts on human development by 2050 on the vertical axis, and source of primary drivers on the horizontal axis (left = local drivers, right = global drivers).
KEY CHALLENGES

Identifying major barriers will help define the constraints and requirements of potential breakthroughs. Beyond scientific and technological challenges, many hurdles exist that may constrain successful resilience to environmental changes.

1. Many environmental processes are interlinked, and problems often have multiple causes that cannot be addressed independently. Advances in one field of human development may cause setbacks in other fields.

2. There is often a time lag between beneficial first-order environmental changes and detrimental second-order consequences. Current political and economic systems, with their focus on short-term rewards, are ill-suited to confront these long-term challenges.

3. Many current environmental problems result from externalities of economic activities, meaning the costs are borne by people not involved in the original activities. Externalities are poorly incorporated into current economic metrics of success.

4. Definitive solutions to environmental change issues may also require breakthroughs in human behavior. Many aspects of the lifestyle in industrialized countries remain as aspirational goals for developing country populations, yet are clearly unsustainable at scale.

5. Depending on context, other important barriers may include the lack of effective regulatory and enforcement mechanisms, lack of adequate economic means to commit to solutions, and lack of economic incentives among key decision-makers and stakeholders.
Prescribing solutions to human development problems arising from environmental changes is especially challenging, because the changes have occurred precisely due to human efforts towards development. The approaches used successfully in the past to enable human development, e.g. the coal-powered Industrial Revolution in Europe and North America in the 18th and 19th centuries, and the resource intensive Green Revolution in Asia and Latin America in the 20th century, have allowed great advances in human development. However, the compromises and consequences of these approaches, and their potential threats to long-term human wellbeing, are growing more evident. Future-oriented human development efforts should learn from both the successes and failures of past approaches.

Numerous high-potential technological breakthroughs are being pursued for use in industrialized countries, and if successful could also apply to developing countries. For example, scalable means of harnessing and storing solar energy could resolve primary energy supply constraints. While beneficial to industrialized countries due to enhanced energy security, such a technology, if successful, could fundamentally benefit human development goals that promote universal energy availability. In this section, however, we focus on potential breakthroughs with primary applications within developing regions.

Please note that a number of the breakthroughs identified in other sections of this study are equally relevant to the issues discussed in this section. For example, breakthrough technologies relevant to resilience against environmental change include:

- Sanitation for human waste
- Precision irrigation systems
- Detection and utilization of groundwater resources
- Soil nutrient analysis

Additional critical breakthroughs are described below.

**A scalable low cost method to desalinate water using renewable energy**

Desalination is the process of making potable water from saline water sources (sea water or brackish water). The mineral/salt content of water is typically measured in milligrams of total dissolved solids (TDS) per liter of water. The salinity of ocean water averages 35,000 mg/L globally, varying from about 32,000 to 38,000 mg/L. Water is considered potable when it contains TDS less than 500 to 1000 mg/L. The vast majority, about 97.5%, of the earth’s water is seawater. Of the remaining 2.5% fresh water, 70% is frozen in polar ice and snow, and the rest is mostly groundwater (MEA, 2005). A breakthrough technology for scalable desalination using renewable energy would allow greater access to the huge resource of ocean water.

Desalination is currently used in select regions of the world. There are more than 7500 desalination facilities worldwide, over half of which are located in the Middle East (Shatat & Riffat, 2012). Virtually all are powered by fossil fuels, and are often integrated with, and use waste heat from, electricity generating stations.

There are currently two main types of desalination processes: thermal and membrane. Thermal desalination involves evaporating and condensing water, as in distillation. Various thermal processes operate at different temperatures and pressures, including the dominant multi-stage flash process, and the multi-effects distillation process (Shatat & Riffat, 2012). In recent decades, membrane technologies
have matured and most new desalination installations use membranes. Of these, the reverse osmosis (RO) process is the most common, and uses a semi-permeable membrane through which pressurized saline water is forced. Other membrane processes include electrodialysis and membrane distillation. A major difference between the various processes is the source of energy that drives desalination; heat, pressure, and electricity are used in different processes. The cost of the energy supply strongly affects the cost of desalination. The cost of the various processes also varies, and is heavily dependent on scale. Larger facilities are far less expensive per cubic meter of fresh water (Exhibit 28).

**Cost of current desalination processes**

<table>
<thead>
<tr>
<th>Capacity (m³ per day)</th>
<th>Desalination cost (US$ per m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverse Osmosis (seawater)</td>
<td></td>
</tr>
<tr>
<td>Multi-effects distillation</td>
<td></td>
</tr>
<tr>
<td>Multi-stage flash</td>
<td></td>
</tr>
</tbody>
</table>

**Exhibit 28:** The cost of current desalination processes ($ per m³ of fresh water) varies depending on the technology used and the scale of the process. The cost of energy inputs is also a significant variable. Conventional desalination technologies are too expensive and energy intensive to scale sufficiently to provide fresh water for significant global human development (Shatat & Riffat 2012).

As an illustration of desalination costs, let’s consider the 68 million km³ of non-renewable groundwater used for irrigation by Indian farmers each year (Exhibit 13; contribution of non-renewable groundwater to irrigation water demand). If this water were produced from sea water using the least expensive process (large-scale reverse osmosis), it would cost $30 billion per year, equivalent to about 1.5% of India’s GDP. Furthermore, based on the energy intensity of current RO processes (about 2 kWh of electricity per cubic meter of fresh water (Fritzmann, et al., 2007)), producing this amount of water
would use 140 terawatt-hours (TWh) of electricity, or about 12% of total annual electricity generation in India (IEA, 2014). Conventional desalination technologies are clearly too expensive and too energy intensive to provide significant amounts of water, in order to contribute to global human development. For desalination to play a lasting role in human welfare, processes will have to be powered by renewable energy sources instead of fossil fuels. A breakthrough technology allowing low cost water desalination using renewable energy could mitigate future problems of groundwater salinization (e.g. due to over-extraction or sea level rise) as well as expand freshwater resources to cater for growing water demands.

Substantial research and development work is required, and we expect that it will take 5-10 years for this breakthrough to be ready. Deployment challenges include access to finance, and policies regarding location and discharge streams. We rate the difficulty of deployment, COMPLEX.
Low cost system for precision application of agricultural inputs, ideally combining fertilizers and water

As described in detail elsewhere in this report, nutrient management is critical for optimal agricultural yields. Some areas, such as much of Africa, would benefit greatly from additional plant nutrients in the form of fertilizer. In areas where fertilizer is available, overuse can be significantly reduced. Crop yields respond very well with initial inputs of fertilizer, but as additional nutrients are supplied the marginal yield increase becomes smaller. Optimal results occur somewhere along that gradient, depending on the cost of fertilizer, land, and harvested crops. Furthermore, it is necessary to apply not just the right quantity of fertilizer, but also at the right time and right place, for optimal nutrient use (Roberts, 2007). The efficiency of using agricultural inputs such as fertilizer is low in conventional farming. It is estimated that overall efficiency of applied fertilizers is about 50% for nitrogen, less than 10% for phosphorous, and about 40% for potassium (Baligar, et al., 2001). The rest of the applied resource is unavailable to the plants and is wasted as runoff. The mismatched timing between availability of nitrogen and crop need for nitrogen is likely the single greatest contributor to excess nitrogen loss in annual cropping systems (Robertson & Vitousek, 2009). Ideally, nutrients should be applied in multiple small doses when plant demand for them is greatest.

A low cost, robust, scalable technology is needed to precisely meter and distribute plant nutrients and/or other inputs. This would allow farmers to apply the right amounts of fertilizer, at the right time, to maximize economic returns and reduce nutrient loss.

Another major type of environmental damage caused by agriculture is overuse of water from non-renewable sources, as seen in South Asia. Different crops need different amounts of water, at different stages in the lifecycle. Application techniques also vary by crop; some crops need longer, infrequent deep watering, while others need more frequent watering with lower volumes per session.

The proposed breakthrough can be strongly leveraged by low cost soil nutrient analysis and low cost and efficient irrigation methods (identified as breakthroughs in other chapters). This would provide farmers with decision support tools that allow them to better predict crop nutrient requirements over time, avoid over-fertilization, and better schedule irrigation. This could be complemented with adjusted crop rotation patterns and additional biotic complexity to improve the plant community’s ability to take up more of the available nutrients. By allowing better management of the timing, placement, and formulation of fertilizer in cropping systems, this would ensure that nutrients are available where and when needed by the plant. Economic outcomes for farmers would improve, because less fertilizer would be needed to achieve optimal yields. This would also protect watersheds and populations downstream from farm fields, by greatly reducing runoff.

If resources are devoted to accomplish this breakthrough, we expect that it will take less than 5 years to be market ready. Once ready, it will face a number of deployment challenges including a fragmented market (of farmers), access to finance for potential users, and training of farmers to install, use and maintain the technology. In addition, a significant amount of behavior change will be required, given the low demand for such inputs (in sub-Saharan Africa), and the limited incentives for sustainable use (in South Asia). Therefore, deployment will likely be CHALLENGING.
A scalable method for sustainable integrated aquaculture

As shown earlier in Exhibits 23 and 24, the global catch of wild fish has remained roughly constant since the late 1980s, and yet the effort necessary to catch the same amount of fish has increased. The gap in fish supply has been made up by aquaculture, which has allowed increasing human consumption of fish. Aquaculture, the farming of aquatic organisms such as fish, crustaceans and aquatic plants, is currently the fastest growing animal food-producing sector. Within 30 years, between 1980 and 2010, global aquaculture production of fish has expanded by almost 12 times, at an average annual rate of 8.8% (FAO, 2012). In 2010, about 60 million metric tons of farmed food fish was produced globally. Asia accounted for almost 90% of world aquaculture production by volume in 2010; this was dominated by China, which produced more than 60% of global aquaculture volume. Other major producers are India, Vietnam, Indonesia and Bangladesh. Freshwater fish account for 56% of global aquaculture production, followed by mollusks (24%), crustaceans (10%), diadromous fish such as salmon (6%), and marine fish (3%).

Despite the increasing importance of aquaculture to human food supply, current models of aquaculture production are largely unsustainable, and their ability to substantially scale up is questionable. Two-thirds of all farmed food fish production currently relies on artificial feeding. This share has increased from less than half in 1980. Artificial feeding requires prepared fish feed, and results in relatively faster growth rates compared to non-fed species. Fishmeal has been the preferred feed for aquaculture production, and is made by cooking, pressing, drying, and grinding fish or fish byproducts. Small pelagic species of fish, such as anchoveta, are typically caught and used for fishmeal production. A substantial portion, roughly one-third, of all wild-caught fish is used for non-food uses including fishmeal production. Fishmeal production peaked in 1994 at about 30 million tons (live weight equivalent) and has fluctuated since then, dropping to 15 million tons in 2010 due to reduced anchoveta catches (FAO, 2012). While fishmeal was once a cheap commodity used widely as animal feed, demand has increased strongly while supply has fluctuated (Olsen & Hasan, 2012). The current
reliance of aquaculture on fishmeal feeding is unscalable and untenable in the long term. Current aquaculture production is also vulnerable to disease and changing environmental conditions. Disease outbreaks in recent years have affected aquaculture in numerous countries around the globe, resulting in significant loss of production (FAO, 2012). In 2010 in China, aquaculture production suffered losses of 1.7 million metric tons caused by natural disasters, diseases, and pollution. Disease outbreaks almost eliminated marine shrimp farming production in Mozambique in 2011.

A breakthrough is needed to develop a scalable method of sustainable integrated aquaculture. About 71% of the earth’s surface is covered by water, and a large share of sunlight received by the planet falls on water. A successful aquacultural technique that directly captures this sunlight through managed photosynthesis processes and converts the accumulated biomass into various food products, could greatly enhance global food security. An ecologically appropriate system would focus on integrating flows of energy, nutrients and biomass through the system. This may include integrating aquatic and terrestrial food production, for example, by using waste material from land as food and nutrients. Important issues with current generation aquaculture systems will need to be overcome. Advances are needed in hatchery systems, feeds and feed-delivery systems, and disease management (Godfray, et al., 2010). Other potential improvements may come from better stock selection, optimizing scale of production technologies, and the culture of a wider and synergistic range of species. Other important issues are disease resistance and tolerance to temperature and salinity variation, to enable a broader range of production options. To avoid unintended consequences, a scalable system would avoid discharge of organic effluents or disease treatment chemicals, and avoid being a source of diseases or genetic contamination among wild species.

Substantial research and development work is required for this breakthrough. We expect that it will take 5-10 years for this to be market ready, given adequate resources. Concurrent with technology development, appropriate business models must be developed to allow wide scale-up in developing regions. Deployment challenges include access to finance, and policies regarding land and water use. The difficulty of deployment is CHALLENGING.
Breakthrough 4

Low cost, distributed monitoring sensors to identify environmental toxins and their concentrations

Human health is threatened by exposure to a diverse range of environmental toxins such as heavy metals and persistent organic pollutants (POPs). Reducing exposure to environmental toxins is complex due to the variety of chemicals, exposure pathways, and time horizon of effects. Progress towards reducing exposure and improving health outcomes is hindered by the sparseness of data on the presence and concentrations of various toxins throughout the environment. A breakthrough is needed to develop a robust and affordable monitoring technology to identify health threats due to local exposure to toxins, and make the data publicly available and comparable. This may lead to increased regulatory accountability, reduced emissions of toxic agents, improved knowledge of critical remediation sites, and decreased long-term health risks.

Current monitoring techniques to identify environmental toxins are inadequate. The analysis is typically done in a laboratory, meaning that samples must be collected and transported to a centralized location. After various pre-treatment steps, the samples are analyzed with techniques such as chromatography to determine their makeup. This process can take several days from sample collection to results, and can cost up to $1000 per sample (Ho, et al., 2005). Separate analyses are typically required for each toxic material under investigation. Conventional electrochemical sensors for detecting heavy metals must be used by skilled operators (Aragay, et al., 2011). These methods are not scalable to allow widespread identification of overall toxic health risks throughout the world, including in developing countries.

A new generation of environmental monitoring technology is needed to accurately and inexpensively identify the presence and concentrations of a range of toxic substances. Rather than bring the samples to the laboratory, this breakthrough would take the laboratory to the field and allow widespread in situ measurement of major environmental toxins in realtime. The technology would be flexible enough to analyze samples of water, soil, food or other media, after simple preparation steps. It would identify levels of inorganic materials (such as mercury, lead and arsenic), synthetic organic chemicals (such as dioxin, PCBs and some pesticides), and volatile organic compounds (such as benzene and formaldehyde). Where feasible, the use of appropriate biomarkers would allow determination of actual human health risk, rather than mere occurrence of a toxin in the environment (Lam, 2009). The initial cost of the hardware would be modest (<$500), perhaps taking the form of a plug-in sensor device that leverages the computing power of an existing mobile device. Cost of consumables would be low (~$1 per test), allowing ubiquitous monitoring even in remote sites in developing regions.

To maximize its effectiveness, this sensor technology would be integrated with a web-based platform to allow collection and comparison of environmental toxicity risks over time and place. The linking of improved toxin sensor technology with mobile communications technology would lead to a system for realtime, spatially-explicit, multi-agent exposure monitoring that would create an unprecedented understanding of global toxic health risks and pathways toward their reduction. Once identified, areas of high risk could be assessed in more detail, and critically contaminated sites in need of remediation can be flagged. On a broader and longer-term level, this monitoring technology may lead to advances in green chemistry and life-cycle product design to permanently eliminate the dangers of toxic exposure.

Progress is being made rapidly in the field of environmental monitoring, though there appears to be no focused effort towards the integrated technology we envision here. If sufficient resources were allocated to allow the necessary research and development efforts, we expect that it will take 5 years for this breakthrough to be ready for use. A significant deployment challenge is the lack of consumer demand for environmental monitoring. Therefore, deployment is likely to be COMPLEX.
Breakthrough 4 – Difficulty of deployment

- **Policies**
  - Simple: Low role of policy/regulation
  - Feasible: Minimal need for infrastructure
  - Complex: Moderate need to train a limited number of people

- **Human capital**
  - Simple: Limited financing required
  - Feasible: Minimal behavior change required
  - Complex: Limited financing required

- **Access to user finance**
  - Simple: Low demand, needs to be built
  - Feasible: Low demand, needs to be built
  - Complex: Low demand, needs to be built

- **Behavior change**
  - Simple: Low demand, needs to be built
  - Feasible: Low demand, needs to be built
  - Complex: Low demand, needs to be built

- **Existing demand**
  - Simple: Deployment model(s) being tested
  - Feasible: Deployment model(s) being tested
  - Complex: Deployment model(s) being tested

- **Market fragmentation/Distribution channels**
  - Simple: Deployment model(s) being tested
  - Feasible: Deployment model(s) being tested
  - Complex: Deployment model(s) being tested

- **Business model innovation**
  - Simple: Minimal need for infrastructure
  - Feasible: Minimal need for infrastructure
  - Complex: Minimal need for infrastructure
Access to electricity is fundamental to every aspect of human development. More than 1 billion people, concentrated mostly in rural Asia and sub-Saharan Africa, lack electricity. The problem is expected to worsen in sub-Saharan Africa as population growth outpaces the increase in electrification. Even as efforts to improve electrification continue, it is important to recognize that it is not electricity itself that changes lives, but rather, what people are able to do with electricity. Recent years have seen an increase in proliferation of ‘pre-electrification’ appliances like solar-powered lights and mobile phone chargers. While this has some benefits, low income households need a number of other appliances such as refrigerators, televisions (or other ICT devices), fans, and tools for improving workplace productivity to improve their overall quality of life. In that context, there are 2 major problems: appliances currently on the market are too expensive for low income populations, and even if they were affordable, the electricity they consume costs much more than the ‘energy budget’ of these users.

While much of South Asia will have electricity through connection to the existing power grids, it is likely that large parts of rural Africa and some parts of rural South Asia will need decentralized mini-grids to have access to electricity. The most cost-effective (and environmentally sustainable) energy sources for rural mini-grids will be renewables like solar, wind and micro-hydro. Of these, solar power
is the most widely available renewable energy resource. Currently, solar photovoltaic (PV) mini-grids are difficult and expensive to install and operate (relative to the resources available in low income rural populations). Combined with weak market economics and misaligned policies, these challenges have made mini-grids commercially unsustainable. While supportive policies and financing mechanisms will need to be a core part of any solution, 5 technological breakthroughs can improve the lives of low income rural people across South Asia and sub-Saharan Africa.

- Suite of solar photovoltaic mini-grid components, to significantly reduce upfront costs
- Appliances for household use (e.g., TV, refrigerator) and income generation (e.g., irrigation pump), which are significantly more affordable and energy efficient than those on the market today
- New bulk storage technologies for decentralized mini-grids, which provide improved performance at a significantly lower cost
- Affordable and easy-to-use grid management solutions for decentralized renewable energy rural mini-grids
- A ‘utility-in-a-box’ for making it simpler, cheaper and faster to set up and operate renewable energy mini-grids
Electricity is the most versatile and efficient way of consuming energy. It can be easily converted to multiple forms of energy for a variety of needs—heat, light, mechanical energy. It is relatively non-polluting and loss free at the point of use, and its use can be calibrated easily, i.e. with the flick of a switch. It can be generated centrally, and distributed conveniently and efficiently across long distances, making it extremely economical (Theraja & Theraja, 2013) (IEC, 2014). This makes it ideal for powering appliances for activities and services that are central to human wellbeing, comfort and productivity.

CORE FACTS AND ANALYSIS

Electricity is vital for human development, but low income countries and populations do not have enough access to it. The lack of access to electricity forms a vicious cycle with development. On one hand, low income countries are not able to invest in the infrastructure to generate and distribute electricity to its citizens (especially in remote areas); on the other, lack of access to electricity is a fundamental barrier to human development. These barriers exist in every fundamental aspect of development.

Health
Without power health facilities cannot operate medical devices, refrigerate temperature-sensitive pharmaceuticals, or even have lighting to provide care at night. An estimated 1 billion people use health facilities which are not electrified (Practical Action, 2014).

Education
Children in low income families cannot get a proper education because their schools cannot operate computers, access the Internet, or operate laboratories for them to learn in (even if they had the computers and other equipment). Worse yet, many students do not have access to appropriate lighting at home to be able to study after sunset.

Food security, agriculture and economic development
Smallholder farmers and agribusinesses cannot operate powered equipment, to grow, preserve and process adequate food for their families, communities and countries. Similarly, businesses in other sectors cannot operate even the equipment needed for offices and factories.

Gender equity
Women are disproportionately affected by the lack of electricity. The lack of appliances leads to significantly more manual work for women. In the absence of electricity for indoor lighting (combined with other forms of clean energy for cooking), women suffer more from indoor air pollution. When outside their homes, they are also exposed to a greater risk of violence due to the absence of outdoor lighting. Similarly, they are at a greater disadvantage compared with men when it comes to operating manual equipment.
Exhibit 1 shows the effect of electrification on development by mapping the UN human development index (HDI) against the rates of electrification (defined by the International Energy Agency as the annual consumption of at least 250 kilowatt-hours (kWh)\(^3\) of electricity in rural areas and 500 kWh in urban areas, for a household of 5), for a representative sample of countries (IEA, 2013) (UNDP, 2014).

The Human Development Index of countries vs. percent of population with electricity

Exhibit 1: The lack of access to electricity forms a vicious cycle with underdevelopment: less developed countries do not have the means to invest in electrification, and the low levels of electrification limits development. This chart shows the electrification rate as the number of connections. The International Energy Agency (IEA) defines electrification as the annual consumption of at least 250 kWh of electricity in rural areas and 500 kWh in urban areas, for a household of 5. Please note that some countries (concentrated in the top right corner of the graph) have negligible populations without access to electricity.

Low income populations pay significantly more for energy than their wealthier counterparts, on a per-output-unit basis

One unfortunate irony is that people who do not have access to electricity actually have to pay a much higher price per unit of energy—compared with wealthier segments of the population—when they use alternatives to electricity such as kerosene. As Exhibit 2 shows, for a given amount of light, the cost of kerosene is 325 times that of an incandescent bulb, and 1,625 times that of a compact fluorescent lamp. Rural households in developing countries spend as much as $10 per month on lighting using candles, kerosene and dry-cell batteries. For households with electricity access in industrialized countries that amount of money can provide 24 bright light sources (Mills, 2002) (UNDP, 2005).

\(^3\) As a frame of reference, 250 kWh can power a floor fan, a mobile telephone and two compact fluorescent light bulbs for about 5 hours per day, over the course of a year (IEA, 2013).
Cost of energy for a given amount of light: kerosene vs. incandescent bulb vs. compact fluorescent light

Exhibit 2: Energy sources available to low income populations often cost much more—on a per-output-unit basis—than those available to higher income populations. For example, to get a given amount of light output, kerosene costs 325 times the cost of lighting an incandescent bulb with electricity, and 1,625 times that for a compact fluorescent light.

More than 1 billion people lack electricity, mostly in rural South Asia and sub-Saharan Africa; the problem will persist in the foreseeable future, and will likely worsen in sub-Saharan Africa

Developing regions suffer from an endemic lack of electricity. Currently, 1.3 billion people, mostly in rural sub-Saharan Africa and South Asia, lack access (based on the IEA definition of electrification). This represents one-fifth of the world’s population (IEA, 2011). As Exhibit 3 shows, Developing Asia has the largest number of people without electrification (675 million out of a regional population of 3.6 billion), while sub-Saharan Africa has the highest percentage of population without electricity (72%). In these regions, more than 80% of the people without electricity live in rural areas. Among the countries in Developing Asia, India has the largest share (42%) of people without electricity.

Despite progress in other aspects of development, the population without access to electricity in sub-Saharan Africa is expected to increase from an estimated 586 million in 2009, to a projected 645 million by 2030. Note that this projection is under the IEA’s ‘optimistic scenario’, in which all countries fulfill their current commitments to policy and investments for expanding electricity infrastructure. In this scenario, the population with electricity in Developing Asia is expected to decrease from 676 million in 2009 to 375 million in 2030. In aggregate, the IEA’s optimistic scenario projects that there will still be 1 billion people without access to electricity in 2030 (Exhibit 4) (IEA, 2014). Most of those without access will still be in rural areas.

Exhibit 2: Energy sources available to low income populations often cost much more—on a per-output-unit basis—than those available to higher income populations. For example, to get a given amount of light output, kerosene costs 325 times the cost of lighting an incandescent bulb with electricity, and 1,625 times that for a compact fluorescent light.

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Please note that some of the source material used for this section combines data for all of Developing Asia (which includes all of South Asia, as well countries from Southeast Asia), while others isolate the data for South Asia. Hence, some exhibits show the data for Developing Asia, while others show it for South Asia.
Exhibit 3: Currently, the largest populations without access to electricity are in Developing Asia and sub-Saharan Africa, and are concentrated in rural areas.
Expected change in the number of people without access under the IEA’s optimistic scenario

(2009-2030; millions)

Exhibit 4: The problem of lack of access to electricity in sub-Saharan Africa is expected to get worse by 2030, even in the IEA’s optimistic scenario in which countries fulfill their current commitments.

Electricity does not, by itself, change lives; it is what people do with it that matters. Hence, beyond access to electricity, low cost, energy efficient appliances are needed

‘Access’ to electricity has been defined differently in different contexts. In some it has meant having an electricity connection, while in others it has meant reliable supply and being able to consume a minimum quantity of electricity. However to be meaningful for human development, access to electricity must be measured by the quality and range of usage of electricity via appliances to improve quality of life and workplace productivity. In other words, merely having an electrical connection is not helpful if the consumer does not have the necessary appliances, and if those appliances cannot be powered by the electricity available. In addition, having access to just enough electricity to power light bulbs, a fan and a mobile phone is unlikely to lead to substantive improvements in quality of life or economic opportunity. As discussed later, an appropriate suite of energy efficient appliances should also include a refrigerator (to preserve high-nutrition perishable food), an ICT device (TV and/or computer), and an appliance to improve economic productivity (e.g., an irrigation pump). There is increasing
Mini-grids offer considerable economic advantages compared with both grid extension and standalone systems, for serving remote rural populations

Electricity is typically delivered using a very large centralized system called the power grid. It is generated in large power plants with hundreds of Megawatts (MW) of capacity by converting energy from coal, natural gas, water in dams and reservoirs, and nuclear fuels, and delivered (almost instantly) to users across large geographical areas. Transmission lines carry electricity over long distances using high-voltage current to reduce transmission losses. When the transmission lines reach clusters of users, the voltage is stepped down and distribution lines carry electricity to end users. Transmission of this nature is expensive due to (among other reasons) the cost of infrastructure, and comprises roughly 40% of the total electricity bill of a power system (IEA, 2010). In many cases (depending on population density and income levels, for instance) it is cost-effective to extend the grid within a range, by extending the transmission or distribution lines. This range, known as the grid perimeter, usually includes urban and peri-urban areas, where even low income populations often have access to grid power. However, the poorer, sparser and smaller a community is, the smaller the grid perimeter. Such a community must then be close to the grid, to make grid extension economically feasible without subsidies. This is usually the dynamic at play with low income rural populations in developing countries. Two-thirds of the world’s poor live in villages which are typically too far from the grid to be feasibly reached via grid extension; this is particularly true in sub-Saharan Africa, where a majority of the population is expected to be in rural areas for the foreseeable future (Exhibit 5). In such cases, decentralized mini-grids—smaller independent grids that are (at least initially) not connected to the main grid—offer more practical alternatives for a variety of technical and financial reasons (Schnitzer, et al., 2014) (Practical Action, 2012). According to recent estimates by the IFC, the average per-connection capital cost for mini-grids starts at $50, whereas extending the grid to a sufficiently adjacent community can start at $500 (IFC, 2012).

Mini-grids are also more advantageous than standalone small (e.g., home-based) systems, due to economies of scale. Standalone small systems are easier to deploy especially where population density is low. They have been promoted by donors and governments, and have scaled up successfully when supported by appropriate financing models (Grameen Shakti, 2014). However standalone systems support limited service levels, and it is hard for them to support multiple appliances simultaneously, especially ones with high power draw such as refrigerators. As such they are more appropriate in the form of limited service, rechargeable, pre-electrification systems supporting individual appliances (IED, 2013). In comparison, mini-grids can support larger loads and higher load variance. They also have lower unit costs compared to home systems, by virtue of economies of scale. They can scale up as local economic activity, and as an outcome local demand, grows. If operated successfully, they can scale up and become attractive for interconnection with the main grid (IFC, 2012). Hence, while continued investment towards improving standalone systems will be valuable in the next few years, mini-grids are ideal for full-fledged electrification and long-term development.

A number of studies underscore the significant development benefits of mini-grids. These studies, including UNDP surveys of a large number of households across many parts of South Asia, demonstrated increases of more than 50% in household income, significant reductions in maternal and childhood mortality rates, as well as improved educational outcomes (Schnitzer, et al., 2014).
Interestingly, however, there is no standard definition of a mini-grid, beyond general characterizations that they are much smaller than main power grids with respect to capacity and size. Based on general usage in available literature, and the capacity needed to sustain household and productive services in small to moderate communities, we assume that a mini-grid has a capacity from 10kW to a few megawatts (IFC, 2012) (IED, 2013). There are no clear threshold criteria for selecting mini-grids over grid extension either. In the past, mini-grids have been installed in places where the population density is greater than 250-300 inhabitants per square km, the distance from the grid has been more than 5 km, and the expected demand was about 150 kWh per person per year (IED, 2013). It should be noted, however, that such considerations are highly contextual (IRENA, 2013) (IED, 2013).

The importance of off-grid solutions in sub-Saharan Africa

Exhibit 5: Only a very small portion of sub-Saharan Africa is currently connected to power grids. With a majority of the population expected to remain rural even as far into the future as 2050, off-grid solutions hold the key to solving the electrification puzzle.

Renewable energy systems are ideal for mini-grids

Currently, only 4% of the world’s electricity is generated using renewable sources like solar and wind (Exhibit 6). Coal and natural gas are the main sources of electricity globally, and more so in South Asia and sub-Saharan Africa. Hydropower—often counted as a renewable source—is the third major source. Renewable sources such as wind, solar, hydropower and biomass are abundant in nature, even
Coal, natural gas and hydropower are the predominant sources of electricity generation across the world. Only 4% of the world’s electricity, and about 1% of all electricity generated in sub-Saharan Africa, comes from renewable resources.

Exhibit 6: Coal, natural gas and hydropower are the predominant sources of electricity generation across the world. Only 4% of the world’s electricity, and about 1% of all electricity generated in sub-Saharan Africa, comes from renewable resources.

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5 Large-scale hydropower dams are very expensive and can have significant environmental impact. On the other hand, smaller-scale micro-hydropower facilities can be economical, with a limited environmental footprint.
IEA estimates of the mechanisms and energy sources required for universal electricity access by 2030

Exhibit 7: To achieve universal electrification by 2030, the IEA estimates that 55% of the power will need to be provided by decentralized systems, with almost all of it from renewable energy sources.

Solar photovoltaics is the most widely suited technology for decentralized renewable energy mini-grids

The various sources of renewable energy—wind, sunlight, biomass, geothermal and hydropower—are present at different intensities in different parts of the world. The optimal renewable energy resource for each location largely depends on the quality and intensity of the available resource at the specific site, the cost of building and operating the system relative to local demand, and the availability of human capital. Of the various renewable energy sources, solar power has the largest scale of application since it is the most widely available resource, and can be produced from many distributed sites (rather than isolated resource-dependent locations). Solar power can be generated in most of Asia and Africa (with a few exceptions due to extreme rains and cloudiness) (IED, 2013). By comparison, hydroelectric power needs to be close to a perennial water current with sufficient strength, and is usually dependent on seasonal factors at smaller scales. Similarly, wind power sources need to be located near shores of water bodies, or at higher altitudes where winds blow more consistently (IED, 2013) (IRENA, 2013). Biomass digesters and gasifiers need to be close to feedstock production to avoid volatility in price and supply and to minimize the cost of transporting the bulky raw material. For instance, sugarcane bagasse—among the most widely produced feedstock in sub-Saharan Africa suitable for gasifiers—cannot be stored for long periods, and is not available for several months a year (DFID & IED, 2013). Biomass power generators are also best suited for locations with ‘anchor clients’ such as small mills and agri-businesses, which have sizable but fixed and predictable power needs (IED, 2013). Since wind and hydro systems are site-specific, their distribution costs are highly variable, depending on population distribution rather than any factor intrinsic to the technology. Solar power, on the other hand, can be located very close to or even in the midst of settlements, significantly reducing...
distribution costs.

Solar photovoltaics (PV) are electronic devices made with semiconducting materials (e.g., silicon, germanium) that generate electricity from sunlight (which provides the electrons with the energy needed to leave their bonds and cross the junction between the two materials). PV cells work with both direct and diffused light, and hence generate electricity even during cloudy days. Electricity production is roughly proportional to the solar irradiance. The modern form of the solar cell was invented in 1954 at Bell Telephone Laboratories in the US, and research has continued since then to improve their efficiency and performance. Since their invention, there have been 3 generations of solar PV technologies. The first generation (wafer-based crystalline silicon) is mature and commercially available. The second generation is made of ‘thin-film’ modules which use a fraction of the material (compared to the first generation) by depositing solar cells on thin substrates like glass, metal and flexible polymers. Thin-film PV tends to have lower efficiency than crystalline silicon, but this is offset by low manufacturing and materials cost. Second generation technologies are still relatively new, and do not yet have significant installed capacity. They do, however, have strong potential for further cost reductions. Due to cost vs. efficiency tradeoffs, first generation PV is better for dedicated home systems while thin-films are suited for mini-grids and utility scale systems.

There are also some emerging third generation PV technologies. Concentrated PV (CPV) uses optical devices to concentrate sunlight on solar cells, and a tracking system. Since the efficiency of silicon solar cells falls with higher temperatures, CPV uses semiconductors with very high conversion efficiencies (e.g., gallium arsenide). Tracking systems and optical components increase cost and complexity, as do cooling systems in some designs and multi-junction solar cells. This nascent technology appears to have significant potential for gains from the learning curve.6 Dye-sensitized solar cells (DSSC), another third generation technology, use photo-electrochemical solar cells which harvest photons from sunlight mimicking photosynthesis. DSSC current has low efficiency, and needs new dyes that can absorb broader spectral ranges. Another issue that needs to be addressed is performance degradation due to UV light. Lastly, Organic PV (OPV) has solar cells composed of organic or polymer materials. OPV uses inexpensive, abundant and non-toxic materials but needs to become much more efficient and stable (IRENA, 2012).

To date, the comparative simplicity of PV technologies have increased the advantage of solar power over other sources of renewable energy

Compared to other sources solar PV systems are relatively easy to set up, operate and maintain. Lead times for construction can be high for micro-hydropower. Transportation can drive up the cost of installing equipment for wind (turbines) and hydroelectric, and of feedstock for biomass. Operations and maintenance (O&M) of wind systems need significant technical expertise. Biomass also demands high O&M due to lack of uniformity of feedstock (particularly for digesters) and complex operation with thousands of mechanical parts requiring significant labor and technical expertise (for gasifiers). Solar PV, on the other hand, is comparatively easier to set up, operate and maintain, with less need for monitoring or technical expertise. This practical consideration is of essence for technology to scale up in underdeveloped rural settings, where the lack of skilled workers and supporting infrastructure can limit adoption of technologies that otherwise work well in other environments (Exhibit 8).

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6 The learning curve or learning rate is defined as the reduction in unit costs, each time the total installed capacity doubles. Hence, a learning rate of 20% for a particular technology means that unit costs have declined by 20% over time, as installed capacity has doubled.
Exhibit 8: The upfront capital expense (CapEx) of solar PV is higher than other renewable energy technologies for mini-grids, but cost and complexity of operations and maintenance (O&M) is low. This is a key consideration for resource-constrained settings. Note that these numbers are mini-grid scale systems in emerging market economies, and costs are much lower for large (utility) scale systems. Costs can also vary highly by location. Distribution costs for wind and micro-hydro are highly variable, since generation facilities are highly site-specific. Finally for renewable energy technologies that are not fully mature i.e., wind and solar PV, costs change quite quickly. For instance, PV module and the balance-of-system (BOS) costs—the key drivers of CapEx—have fallen significantly in recent times. The average price for utility-scale PV project has dropped from $0.21/kWh in 2011 to $0.11/kWh in 2014 (IFC, 2012) (IRENA, 2012) (US Department of Energy, SunShot, 2014).

Solar PV systems are highly modular and configurable
Rural markets are typically small, and vary significantly in size. Because these markets are nascent, demand is hard to estimate at the outset, and systems may need to be scaled up or down with time. This is relatively easy to do with solar PV, without economic losses. Biomass, on the other hand is best for limited and predictable demand. Wind is not very modular, with unit costs of smaller scale applications significantly higher than large scale ones (IRENA, 2013).

Solar PV has significant headroom for cost reductions
Both micro-hydropower and biomass technologies are fairly mature with low potential for further cost reductions. For the latter, opportunities are limited to reducing fuel handling and preparation costs. The learning rate for solar PV is 20%, which is the highest learning among renewable energy technologies. Wind, by comparison, has a learning rate of 7% (IRENA, 2012). This, matched with the global growth of solar PV, resulted in massive cost reductions which are expected to continue, propelled by concerted R&D efforts in industrialized markets, such as the US Department of Energy’s SunShot initiative whose target is to reduce the total installed cost of solar energy systems to $.06 per kWh by 2020.
The relative simplicity of solar PV technology, combined with supportive policy incentives like feed-in tariffs and tax breaks, have made it one of the fastest growing renewable energy technologies. Its global installed capacity, since 2000, has multiplied by a factor of 37, growing at an average of 44% per year, from 1.8 gigawatts in 2000 to 67.4 gigawatts at the end of 2011 (IRENA, 2012). While Solar PV is not the optimal choice in every context, it is generally well suited for many reasons and is applicable extensively across the globe. Table 1 summarizes the pros and cons of various renewable energy technologies, in the context of rural electrification in developing countries (IED, 2013) (IRENA, 2012).

<table>
<thead>
<tr>
<th>Technology</th>
<th>Diffuse (vs. site specific)</th>
<th>Volatility</th>
<th>O&amp;M costs</th>
<th>Modularity</th>
<th>Upfront cost</th>
<th>Levelized cost</th>
<th>Potential for improvement</th>
<th>Remarks</th>
</tr>
</thead>
</table>
| Solar PV   | ![Very favorable](#)         | ![Highly favorable](#) | ![Highly favorable](#) | ![Highly favorable](#) | ![Highly favorable](#) | ![Highly favorable](#) | ![Highly favorable](#) | Widely abundant  
Intermittent but generally predictable  
Low operations & maintenance (O&M) cost and complexity  
Highly modular  
Relatively high upfront and replacement costs  
High learning rate (20%) and deployment growth with room for significant improvements. |
| Wind       | ![Highly unfavorable](#)    | ![Highly unfavorable](#) | ![Highly unfavorable](#) | ![Highly unfavorable](#) | ![Highly unfavorable](#) | ![Highly unfavorable](#) | ![Highly unfavorable](#) | Highly site-specific  
Relatively unpredictable, and requires complex forecasting and demand-side management  
High O&M cost and complexity (for turbines)  
Not modular: high economies of scale with significant losses of economy, as scale reduces  
Relatively high upfront cost  
Moderate learning rate and some room for improvements; turbine O&M costs likely to increase |
| Biomass    | ![Highly unfavorable](#)    | ![Highly unfavorable](#) | ![Highly unfavorable](#) | ![Highly unfavorable](#) | ![Highly unfavorable](#) | ![Highly unfavorable](#) | ![Highly unfavorable](#) | Moderately site-specific, with high transportation costs  
Reliable supply of electricity with simple storage needs, but vulnerable to feedstock supply and price volatility  
High O&M costs: feedstock collection, storage and pre-processing; many moving parts (gasifiers), high need for technical expertise and maintenance  
Environmental concerns: water and byproducts disposal  
Ideal for fixed power generation with predictable demand  
Low upfront costs  
Mature technology with modest cost reduction potential |
Table 1: Pros and cons of different renewable energy technologies in the context of decentralized mini-grids in rural developing regions. Note that one important criterion for comparing the various technologies is levelized cost of electricity (LCOE), which is the ratio of the present value of lifetime system costs (discounted using the rate of cost of capital), to lifetime electricity generation. The drivers of LCOE are capital expenses (cost of infrastructure and installation), cost of capital, operations and maintenance (O&M), the quality and output of the energy resource, the life of the system, and utilization of the system’s capacity.

Storage is a critical component of decentralized renewable energy systems, to ensure a reliable supply of electricity; rechargeable batteries are well suited for this purpose.

A reliable supply of electricity is important to support an adequate range of services for households and income-generating activities. Unlike fuel-based power, non-fuel renewable energy resources are intermittent and unpredictable. Sunlight has varying intensity through the day, and is not available at night, and wind can start and stop anytime. Ensuring uninterrupted electricity—even as demand fluctuates—is a key challenge for power grids. To avoid blackouts conventional power plants are built bigger than they need to be, and operated at peak-load capacity longer just to generate excess electricity in anticipation of peak demand. Storage technologies convert electricity into other forms of energy when surplus electricity is generated, and then convert this back to electricity as needed. Storage is thus used to balance fluctuations in demand, reduce costly peak-load capacity of power plants and help them operate more efficiently.

In conventional power grids water is used for storage; surplus overnight electricity from coal, gas and nuclear plants is used to pump water from a lower to an upper reservoir, and this is used to produce hydropower during high-demand periods as needed. This inexpensive and efficient mechanism accounts for 95% of global storage capacity (IRENA, 2012). Such a mechanism, however, is only practical for large scale systems (100 megawatts or more), because of the volume of water needed to generate enough power.

For renewable energy mini-grids, the power required from storage systems is in the range of 100 kilowatts to a few megawatts, for up to 10 hours at a time. Exhibit 9 shows the power output and discharge times for various storage technologies, highlighting the range that is most applicable for mini-grids. The most commonly used storage system for solar PV mini-grids is deep cycle lead-acid batteries. These are a relatively mature and widely available technology but require some maintenance and can...
add as much as 50% to the cost of a solar PV system (IED, 2013). There are a number of other storage technologies, but most need further development to reach commercial viability for mini-grids. Of these, lithium-ion (Li-ion) batteries are widely used for mobile phones and laptops, but large Li-ion are still too expensive. Sodium sulphur (NaS) and Vanadium Redox flow batteries have been used effectively in small to mid size renewable power systems, but these too are currently much more expensive than deep cycle lead acid. Note that storage is not required for biomass systems, or for hybrid fuel-renewable systems.

**Power output and discharge time of various storage technologies**

![Diagram showing discharge time and power output for different storage technologies.]

**Exhibit 9:** Performance of different storage technologies with regards to power output and discharge time. Technologies in the 100 kW-10 MW power output range and discharge time in the range of hours, are suitable for bulk storage in decentralized renewable energy mini-grids (IRENA, 2012).

**Active grid management is crucial for ensuring effective performance and reducing losses**

Grid management involves monitoring, supervision and (as necessary) repair of the various parts of the grid, from generation, to distribution and consumption. Poor grid management increases operational costs as well as losses from unrealized revenues due to a number of reasons—manual (and hence inaccurate) metering and collection, tampering, payment defaults, under or over utilized capacity.

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7 Of the various storage technologies shown in Exhibit 9, Compressed Air Energy Storage (CAES) stores energy by compressing and storing air in large, low cost natural buffers (e.g., caverns); fly wheels store electricity as mechanical energy, which is then converted back to electricity; and thermal energy storage under demonstration for concentrating solar power (CSP) plants, stores excess solar heat and generates electricity at sunset. Supercapacitors store electricity as electrostatic energy. Superconducting magnetic electrical storage (SMES) uses superconducting technology to store electricity in magnetic fields. Technologies like fly wheels and supercapacitors do not have sufficiently long discharge times. Others like compressed air and pumped hydro can only work with very high capacities (IRENA, 2012).
During generation
Monitoring and troubleshooting operations in realtime, collecting and analyzing system data, optimizing and synchronizing multiple power sources in hybrid systems, managing storage to smooth intermittence of renewable energy supply, and regulating voltage, frequency and load levels (i.e., matching demand with supply).

During distribution
Minimizing technical and non-technical losses from theft and measurement errors, which can exceed 30% in some African countries (IED, 2013).

During consumption
Synchronizing demand and supply (e.g., current limiters, power management administrators, and smart meters), billing and fee collection systems (e.g., prepayment devices, mobile banking systems) and fraud prevention systems (IED, 2013).

Funding for decentralized renewable energy mini-grids is facing significant shortfalls

According to the IEA (and as shown in Exhibit 7), renewable energy mini-grids are expected to be the least-cost path to supply more than half of the additional power generation that is needed for universal access by 2030. It is generally assumed that investment in this infrastructure cannot be fully recovered, because of the weak purchasing power of low income users. Hence, it is expected that significant public or donor funds will be required. According to the IEA, the least-cost path for achieving universal access by 2030 (based on the lowest-cost regional cost per MWh, taking into account relevant regional parameters) will require $44 billion of infrastructure expansion annually—$18 billion for extension to national grids, and $26 billion for decentralized systems (Exhibit 10). Out of this $26 billion, the IEA expects that only $6 billion of funding will materialize, leaving a 77% shortfall, even in the optimistic scenario based on current commitments. Shortfalls related to both grid extension and decentralized systems are expected to be highest in sub-Saharan Africa (Exhibit 11), with decentralized systems facing disproportionately higher share of the funding gap (IEA, 2011). This, combined with Africa’s huge untapped potential for renewable energy resources, presents a compelling case for technological breakthroughs to reduce barriers to expansion of decentralized renewable energy systems (IRENA, 2011).
Investment required to expand electricity infrastructure for universal access by 2030, along with projected funding shortfalls

Exhibit 10: To achieve universal access by 2030, according to the IEA, $44 billion of annual investment is needed for expanding electricity infrastructure. Even in the IEA’s optimistic scenario per current commitments, there are expected to be major shortfalls.

Funding shortfalls in electricity infrastructure expansion to achieve universal access by 2030, by region and type of system

Exhibit 11: According to the IEA, most of the annual shortfall in infrastructure expansion needed for universal access by 2030 is concentrated in sub-Saharan Africa and in decentralized systems.
KEY CHALLENGES

There is considerable interest across the industrialized world in improving renewable energy technologies. However, most of those efforts appear to be geared towards reducing the environmental footprints of wealthier population segments, rather than improving access to electricity for low income populations in developing countries. While there will likely be some spillover benefits, a number of major challenges have to be overcome before anything close to universal access to electricity is possible.

The upfront cost of building renewable energy systems is too high to provide financially self-sustaining services for low income users

The key drivers of CapEx for Solar PV mini-grids are PV modules and the balance-of-system (BOS) which comprises both equipment (e.g., racking structures and inverters) and ‘soft costs’ such as labor, site preparation, licensing fees, etc. (IFC, 2012) (IRENA, 2012). BOS costs vary widely by geography, primarily because of soft costs. Residential PV systems in the US were twice as expensive as those in Germany in 2012 primarily because of soft costs (Seel, et al., 2014).

Efficiency gains can also reduce effective cost of Solar PV. First generation PV is a fairly mature technology but second-generation, i.e., thin-film PV which is ideal for mini-grids, is fairly recent and has the potential for further improvements (Exhibit 12). There are 3 levels of efficiency (of conversion of solar irradiance to electrical energy) demonstrated by any technology (Exhibit 13). Commercial efficiency relates to versions that are manufactured and available at commercial scale. Research efficiency is manifested in research conditions and is higher than commercial efficiency. Lastly, theoretical efficiency as per the laws of science is even higher but likely not feasible in practical conditions. As a technology matures, the learning curve pushes commercial efficiency closer to research efficiency, and further R&D pushes research efficiency closer to theoretical limits.

In the case of large scale on-shore wind systems, up to 85% of CapEx is for production, transportation and installation of wind turbines. Of this, the rotor blades, tower and gearbox comprise 60% of the cost. There is a tradeoff between efficiency and cost—system efficiency increases significantly with the height and span of turbines, but so does cost of production, transport and installation. The cost of operations and maintenance is also significant (20-25% of the LCOE) (IRENA, 2012). Wind is not suitable for small scale applications, because turbines with a smaller diameter are far less efficient than larger ones (IRENA, 2013). This makes wind difficult and costly to deploy in small markets with weak infrastructure. Finally the learning rate for wind is 7%, which means that cost reductions associated with growth in installed capacity are likely to be modest compared to solar PV which is 20-22% (IRENA, 2012).

As mentioned earlier both biomass and micro-hydro technologies are relatively mature, and do not offer much potential for further cost reductions.
Exhibit 12: The cost structure of solar PV installations can vary widely by geography and by scale and configuration of systems. Manufacturing costs for thin-films (which are a relatively new technology), provide opportunities for cost reductions from growth in installed capacity and associated learnings (IRENA, 2012).

Efficiency of various solar PV technologies (%)

Exhibit 13: The commercial, research, and theoretical maximum efficiency of the various second generation solar PV technologies is generally in line with the first generation (single crystalline silicon). Some third generation technologies offer the possibility of higher efficiency (IRENA, 2012).
The high cost of capital, misaligned policies, and weak purchasing power of low income users, collectively make the business case for renewable energy mini-grids even more challenging.

The electricity market for low income rural users in developing countries is still very nascent. Anchor clients—businesses which can guarantee demand—are few and far in between, especially in rural sub-Saharan Africa. Being predominantly agri-based economies, rural markets also have seasonal variation in demand.

Financing for building mini utilities is scarce and have a high cost of capital. As a result, many mini-grids are funded through grants. In-country financing prospects are not encouraging, as governments and utilities in developing countries lack a firm revenue base from taxes and high income consumers, to subsidize projects serving low income users. Utilities in such countries typically run on losses with high rates of non-payment, and appear unlikely to finance new projects. Rural renewable energy mini-grids typically need heavy subsidies to achieve a financial return on investments. For example, projects in Kenya have been observed to need subsidies in the range of 20% to 70% to achieve a 10% internal rate of return (IED, 2013) (IEA, 2011) (IRENA, 2013). Private investors appear to prefer grid extension projects for urban and peri-urban users as they represent more established and profitable business models.

Mini-grids are more complex to deploy than standalone household systems, which despite their limited potential for full-fledged electrification and higher unit cost of electricity, have relatively short payback periods (e.g., 1-5 years for a solar home system). With appropriate financing schemes, such standalone systems are proving to be much easier to deploy in a viable manner. Mini-grids on the other hand, are more complex systems with longer payback periods. They need greater technical and project expertise, have higher up-front costs and need long term loans (>= 10 years) at low to moderate rates (IRENA, 2012). However, they face significant barriers to capital, since local banks often lack access to long term financing, and need guarantees that investors are not able to provide. For instance, average lending rates can be as high as 19% to 29% in Uganda, Mozambique, Malawi, and 67% in DR Congo. In some of these countries, the longest loan terms are 3-5 years. For larger banks, the transaction volume for such investments is too small to be of interest (IED, 2013) (IRENA, 2013).

Finally, domestic energy policies can stack the odds against renewable energy mini-grids, making them less viable than they could otherwise be. Market distortions such as fossil fuel subsidies make alternatives to renewable energy mini-grids such as diesel generator sets artificially less expensive. In 2010, African countries imported $18 billion worth of oil (more than the entire amount they received in foreign aid), with $50 billion of oil subsidies every year (IRENA, 2013).

The cost of powering basic household appliances—even if they were affordable—is currently too high for low income rural users on decentralized solar PV mini-grids.

Access to electricity is more than charging a cell phone or lighting a few bulbs. There are a number of electricity-powered services for basic development needs, to reduce the burden of manual labor and physical discomfort, improve overall health and productivity, and enhance digital inclusion. Unfortunately, poor people have very constrained energy budgets and cannot afford these services without deep subsidies in decentralized renewable energy mini-grids. This presents a bleak prospect for access considering the large gaps in expanding infrastructure.

The ‘effective’ cost of services is a function of two factors—the efficiency of appliances (which determines how much electricity an appliance consumes), and the cost of electricity. In the following analysis, we assume that a portfolio of appliances to meet the basic household needs for a low income rural family includes lighting, a fan, a refrigerator, an ICT device (e.g., a TV), and an appliance to generate income (e.g., an irrigation pump). Assuming the energy efficiency levels of appliances currently on the
market (Craine, et al., 2014) (Greentech Media, 2013), the household will consume roughly 80 kWh each month (Exhibit 14).

Relative power consumption of appliances useful to low income rural households

Exhibit 14: A conservative estimate suggests that a small rural farming household, using an essential set of appliances at current energy efficiency levels, is 80 kWh per month (Craine, et al., 2014) (Greentech Media, 2013).

Currently, the cost of electricity in solar PV mini-grids is estimated at $0.24/kWh.\(^9\) At this level, the effective cost of basic services is $20 per month (assuming no subsidies). The question then becomes: how does this compare to what low income households can afford for monthly electricity bills? While there is variation by country and region, the poorest 4 billion people at the base of the pyramid (BoP) who make less than $5 a day can be grouped into 3 segments based on their relative poverty—‘low income’ (earning $3-$5/day), ‘subsistence’ ($1-$3/day), and ‘extremely poor’ (less than $1/day) (Exhibit 15). These households typically spend 10% of their income on energy, of which roughly half is spent on cooking. This translates to monthly electricity budgets of $7.50, $4.50 and $1.50 respectively, for each of the 3 segments described above. Therefore, it appears that the effective cost of electricity for a basic portfolio of appliances—$20 per month—is almost 3 times what populations living in the $3-$5/day income range can afford, and significantly more than what populations living at ‘subsistence’ and ‘extreme’ levels of poverty can afford (IFC, 2012) (Rangan, et al., 2011).

For electricity to be affordable for the practical needs of human development it needs to become less expensive, and appliances need to become more efficient. In effect, this relationship between the required decrease in the cost of electricity and the increase in appliance efficiency represents an ‘isoquant’, which is shown in Exhibit 16. It is important to note that this is an illustrative analysis using benchmarks, and does not represent actual observed data (which may be influenced by a range of

\(^9\) This estimate assumes solar PV costs as per the 2nd round of bidding for National Solar Mission in India (Abhyankar, et al., 2013). Balance-of-systems costs are based on a standard breakdown of costs in solar PV systems (IRENA, 2012). In addition, we assume storage adds 50% to system costs for solar PV mini-grids (IED, 2013).
factors. For instance, consumption will be influenced by quality of electricity, subsidies and pricing schemes for appliances and electricity. The cost of electricity will vary widely by installation, availability of resources, cost of capital, and subsidies. The purpose of our analysis then is not to pinpoint precise numbers, but rather to illustrate the wide gap between effective cost of electricity for basic needs, and what low income populations can afford.

**Effective cost of electricity for a basic portfolio of appliances, vs. what each BoP population segment can afford**

![Bar chart showing effective cost of electricity for basic appliances compared to affordability of low income populations.](chart)

- **Effective cost of electricity for basic appliances (using solar PV mini-grids):** $20
- **Low income (1.4 billion people):** $7.50 (-60% of $20)
- **Subsistence (1.6 billion people):** $4.50 (-80% of $20)
- **Extreme poverty (1 billion people):** $1.50 (-90% of $20)

**Exhibit 15:** The effective cost of basic services in decentralized solar PV mini-grids with storage needs will have to fall sharply to match the electricity budgets of populations earning less than $5 a day. The effective cost of services is driven by the cost of electricity, and the efficiency of appliances.
‘Isoquant’ curve representing combinations of reductions in cost of electricity vs. electricity consumed by appliances to fit the monthly ‘energy budget’ of populations earning $3-$5 per day

Exhibit 16: The effective cost of electricity can be reduced for low income populations if the cost of electricity reduces and/or if the efficiency of appliances improves. Currently, electricity via solar PV mini-grids costs $0.24 per kWh (including storage), and the illustrative portfolio of basic appliances consumes 80 kWh per month. Based on this, there is a 60% affordability gap (as shown in Exhibit 15).

Hence, either the cost of electricity needs to be reduced by 60%, or the combined energy efficiency of the basic portfolio of appliances needs to improve by 60%. This is an illustrative analysis, not based on actual observation, because low income populations cannot afford the appliances. One assumption is that the cost of the appliances themselves will decrease, at which point their energy efficiency will become a significant barrier to adoption. Note that this analysis applies only to the 1.4 billion people living on $3-$5 per day. The gap for the 2.6 billion people living on less than $3 per day is much higher.

Rechargeable batteries are currently too expensive, and have challenges providing a continuous supply of quality electricity in renewable energy mini-grids

Rechargeable batteries are essential for providing continuous and reliable supply of electricity in solar PV and wind renewable energy mini-grids, in an environmentally sustainable manner. However, neither the cost nor the performance of existing technologies is adequate. Assessing the exact cost for storage is difficult, because of the unpredictability of capacity needed (which can vary significantly from one location to another based on geographic parameters and usage patterns), as well as battery life (which depends on the frequency and depth of discharge, for current technologies like lead-acid batteries). This lack of knowledge is partly due to the limited number of installations, and is particularly true of nascent storage technologies like flow batteries. Even lead-acid batteries, the least expensive commercially available...
option, can add more than 50% to the cost of a PV system, and double the cost of electricity (IED, 2013).

Rechargeable batteries need to perform along a range of parameters to be effective in decentralized systems: high depth of discharge (the ability to come as close to being fully discharged, without adverse effects on battery life); memory effect (reduction in the battery’s maximum capacity, when it is repeatedly recharged without being fully discharged); round trip efficiency (the ratio of energy recovered from a storage device, to the amount of energy put into the device); modularity allows batteries to be scaled down without loss in performance; configurability of power output and capacity; and operating needs such as pumping, cooling, threshold operating temperatures, manual monitoring, and level of technical expertise required for installation and maintenance. Each family of rechargeable batteries has its unique advantages and challenges (Table 2):

► Lead-acid batteries are the least expensive commercially available rechargeable batteries, but have low energy density and a short life for power applications. They also have low depth of discharge, which reduces their life. Advanced deep cycle lead-acid batteries to address these challenges are still emerging. Disposal of lead-acid batteries have environmental and health risks that require careful handling and regulation.

► Li-ion batteries has very high power density, modularity, no memory effect, and high depth of discharge. However, they are expensive, and have limited capacity and safety concerns (about abnormal heating from overcharging and short circuits). Currently, they are best suited for small scale applications, and require significant improvements to achieve reduced cost, higher safety and more capacity.

► NaS batteries are made with low cost, abundantly available materials, and offer significant potential for further cost reduction; hence, they are very well suited for large scale applications in mini-grids. However, they are very bulky (weighing several tons), and have high operating temperatures (300°C). Commercial versions are more expensive than deep cycle lead-acid. They are well suited for storage in megawatt-size, utility-scale mini-grids (village-scale or larger), and are typically available in multiples of 1 megawatt (with installations in the 2-10 megawatt range). As a relatively new technology with low production capacity, there is significant potential for cost reductions. Production of smaller batteries is in its early stages.

► Flow batteries are highly configurable, with very high depth of discharge and long life, but need pumping and cooling. Configuring the battery is extremely simple—both the cell stack size and the electrolyte volume can be changed easily to modify power output. They can be fully discharged without any damage, thereby significantly improving operational range, increasing longevity, and minimizing the need for maintenance. Vanadium Redox Batteries (VRB) flow batteries can last longer than 100 years according to some estimates, although cell stacks need to be replaced every 8-10 years. VRBs are still pre-commercial, and are currently being used in projects ranging from a few kilowatts to a few megawatts (IRENA, 2012) (Sandia, 2013).
Advantages, challenges and future outlook of each type of battery technology

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Advantages</th>
<th>Challenges</th>
<th>Outlook</th>
</tr>
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</table>
| Lead Acid    | - Least-cost commercial storage  
              - Reasonable performance  
              - Advanced deep-cycle versions optimized for solar cycles | - Low energy density  
              - Low depth of discharge  
              - Short life | - Mature technology with limited potential for further improvements  
              - Most attractive in the near term due to acceptable performance at lowest cost |
| Li-ion       | - Better performance than lead-acid  
              - Best performance for power and energy density, cycle efficiency durability, and temperature range  
              - High discharge variability with no memory effect | - Needs significant optimization for cost and capacity  
              - Needs significant optimization for safety and reliability | - High potential for improvements driven by learning rates in other industries (power, electric cars)  
              - Likely best suited for modular, small scale applications |
| NaS          | - Least cost in pre-commercial phase  
              - Operational in wide range of projects  
              - Very cheap, abundant materials  
              - Can sustain MW size applications | - Very high operating temperature (300°C)  
              - Heavy and bulky | - High cost reduction potential  
              - Smaller batteries are emerging  
              - Likely choice for village- or larger-scale mini grids i.e., full fledged rural electrification |
| Flow         | - Easily configurable with dynamic power output and capacity  
              - High discharge variability with no memory effect  
              - Very long life with low maintenance | - Low energy density  
              - Electrolytes need to be pumped to storage tanks  
              - Needs cooling system to absorb heat for charging and discharging | - High cost reduction potential  
              - Likely Choice for village- or larger-scale mini-grinds i.e., full-fledged electrification |

Table 2: Comparative assessment of different rechargeable battery technologies that are suitable for bulk storage services in mini-grids (IED, 2013) (IRENA, 2012).

Appliances for basic household amenities (e.g., fans, refrigerators) are still too expensive and too energy-intensive

In recent years, there has been a proliferation of appliances such as solar lanterns and charging kits for mobile phones (IFC, 2012). It is important to note that these appliances should be considered pre-electrification—valuable tools to improve quality of life, but not a substitute for true access to electricity. The type of appliances required to make fundamental improvements in quality of life—fans, refrigerators, small mechanized tools to improve workplace productivity—are currently unaffordable to the poor. Even if these appliances were somehow procured, their electricity demands would far exceed the ‘energy...
budgets’ of low income populations (Exhibit 14, Exhibit 15 and Exhibit 16). Improving the efficiency of these appliances will not only increase their affordability for the end user, but also directly improve overall grid economics by reducing the burden on the grid and the possibility of power interruptions (Abhyankar & Phadke, 2012).

Some appliances such as light bulbs, fans and TVs have achieved significant gains in efficiency. However, these are still too expensive, sometimes even for middle income consumers. Even if they are not affordable the poor, the energy savings achieved by a number of new, energy efficient appliances can offset their higher cost for consumers who can afford them (Letschert, et al., 2013) (Exhibit 18).

There has been less progress on improving the efficiency of work-related appliances like irrigation pumps. Most of the pumps currently being used are very inefficient, and end up costing farmers a lot of money over time (Phadke, et al., 2005) (Polak, 2013). In countries like India, diesel subsidies intended to ease the financial burden on farmers have led to millions of tons of carbon emissions. Emerging alternatives such as standalone solar pumps are still too expensive (Polak, 2013).

There are few effective solutions or tools for grid management of rural mini-grids

Effective grid management is crucial for operating grids reliably, efficiently and profitably. Weak grid management can lead to a vicious cycle of poor tariff collection and cost recovery, high O&M costs, customer overuse, and degradation in quality of services (Schnitzer, et al., 2014). There is currently very little in the way of a technology solution for effective grid management of rural mini-grids. Low cost and energy efficient smart meters are beginning to be commercialized in low income markets, making it possible to measure consumption and demand for electricity in small, low voltage rural mini-grids. Similarly, inexpensive prepayment meters—which make it significantly easier to manage fraud and fee collection—are being deployed in targeted markets, with the market for them becoming increasingly competitive (e.g., there are more than 20 manufacturers in India). In addition to these technologies, remote payment and monitoring technologies are also beginning to appear on the market, with the expansion of mobile networks and ‘mobile money’ systems. ‘Pay-as-you-go’ systems are also increasingly being used for pre-electrification devices such as solar lanterns, and in demonstration mini-grid projects (IED, 2013).

However several improvements are needed before grid management technologies become affordable and simple enough to be deployed at scale in rural areas. Grid management remains a multifaceted problem requiring several devices to be installed at the point of generation, at the various points of consumption, as well as at points in between. This involves complex integration across the grid’s control system, forecasting tools, sensors, and payment technologies.
Some of the most impactful levers for facilitating universal access to electricity may very well be policy reforms and support for market-based solutions. These solutions include financing mechanisms to improve access to affordable long-term capital, stronger regulations to ensure transparency in tariffs and reduce risk for private sector actors, and leveling the playing field for independent power providers (e.g., through feed-in-tariffs, power purchase agreements, and comparable subsidies for renewable energy systems as are currently provided for fossil fuels). Technological breakthroughs that can reduce the cost and complexity of installation and maintenance of mini-grids, and increase efficiencies for production and consumption, will facilitate the creation of self-sustaining markets that can scale up quickly. We believe 5 breakthroughs can accomplish this.

**Scientific and Technological Breakthroughs**

Solar PV is well suited for rural renewable energy mini-grids in much of sub-Saharan Africa and South Asia, in places where grid extension is unlikely in the foreseeable future. However, the upfront cost of a renewable energy mini-grid system (its CapEx) is a significant driver of cost of electricity for the end user. Reducing the CapEx significantly will have a big impact in improving the economics of renewable energy mini-grids.

The potential for cost reduction in solar PV is promising. First generation PV technologies have a very high learning rate of 20% (i.e., every time the global installed capacity doubles, prices fall by 20%). Second and third generation technologies are relatively new, with scope for cost reductions over time. Specific opportunities include reduction in manufacturing costs (e.g., manufacturing copper indium gallium (di)selenide or CIGS, one of the leading thin film technologies accounts for a substantial proportion of the cost of the PV module), and discovery of new materials (emerging R&D suggests the possibility of using magnesium chloride in the production of cadmium telluride solar cells, which is a lower cost and environmentally safer alternative to cadmium chloride, which is both expensive and toxic) (Semiconductor Today, 2014). There may also be opportunities in improving the efficiency of energy conversion. Although the commercial efficiency of first generation crystalline silicon is close to theoretical efficiency, thin-film solar cells have room for gains (Exhibit 13). The third generation concentrated PV (CPV) technology also offers possibilities, with realized and theoretical efficiencies of 30% and 88%, respectively. Its installed capacity is expected to increase by double-digits annually, growing by 750% between 2013 and 2020. It can also withstand the hot and dry climates typical to sub-Saharan Africa (PV Magazine, 2013). However, CPV components are heavy and fragile, making transportation and installation a challenge.

Even though the economic outlook for PV components is hard to predict (because of the fluctuating cost of materials, and the variability in market and policy environments), solar PV generation is expected to reach parity with conventional grid sources by 2020, in many markets (IEA, 2010) (IRENA, 2012) (Greentech Media, 2013). However, reaching parity will take much longer for decentralized rural mini-grids, because PV system cost reductions are not enough; these mini-grids have to also contend with the (very high) cost of storage, as well as the low purchasing power of low income rural users. Overall, this breakthrough is likely to take over 10 years to materialize.

In terms of deployment, project financing is likely to be a major hurdle. Compared to other renewable energy technologies, PV is relatively simple to set up and operate, however the lack of
technical and business expertise required to run a utility may still be a bottleneck in very resource-constrained settings. The nascent nature of markets comprising low income users with small variable usage patterns will make it harder to serve them profitably, especially in the absence of appropriate and affordable appliances. While these circumstances may change by the time the technology becomes a reality, commercially sustainable deployment will be COMPLEX.

**Breakthrough 1 – Difficulty of deployment**

<table>
<thead>
<tr>
<th>Breakthrough 2</th>
<th>Difficulty of deployment</th>
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<tbody>
<tr>
<td>Simple</td>
<td>Policies</td>
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<td>Infrastructure</td>
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<td>Human capital</td>
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<td>Access to user finance</td>
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<td>Behavior change</td>
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<td>Existing demand</td>
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<td>Market fragmentation/</td>
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<td></td>
<td>Distribution channels</td>
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<td></td>
<td>Business model innovation</td>
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<tr>
<td>Complex</td>
<td>Regulated market with</td>
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<td>supportive policies</td>
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<td></td>
<td>Minimal need for</td>
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<td></td>
<td>infrastructure</td>
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<td></td>
<td>Moderate need to train</td>
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<td>a limited number of</td>
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<td>people</td>
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<tr>
<td>Feasible</td>
<td>Moderate financing</td>
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<td></td>
<td>needed, viable</td>
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<td></td>
<td>mechanisms identified</td>
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<td>Simple</td>
<td>Low demand, needs to</td>
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<td>be built</td>
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<td>Moderate fragmentation</td>
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<td>under-developed</td>
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<td>channels</td>
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<td>Deployment models being</td>
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<td>tested</td>
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**Appliances for household use (e.g., TV, refrigerator) and income generation (e.g., irrigation pump), which are significantly more affordable and energy efficient than those on the market today**

For electricity to have an impact on development and quality of life, users need a range of amenities and services. This requires electrical appliances for reducing manual workloads, physical discomfort and health hazards, increasing the productivity of income generating activities, and enabling digital inclusion. These include lighting, a fan (or other cooling mechanism for the home), a refrigerator (for preserving perishable foods), an ICT device (e.g., a TV or a computer), and in the case of farmers, an irrigation pump. As things stand, ‘pre-electrification’ appliances like solar lights and systems for charging mobile phones are beginning to appear on the market, but are still far from being widely available and adopted. Appliances like TVs and refrigerators are currently not an option for low income rural populations because they are too expensive (by a factor of 3 or more), and require reliable electricity. There is increasing evidence that there will be strong demand for appliances like these. This, in turn, will keep pushing down market prices.

However, even if these appliances became affordable, the amount of electricity currently available appliances consume is more than the ‘energy budget’ of the 4 billion people living on $3-$5 per day or less. While energy efficient versions of some of these appliances are appearing in industrialized markets, they tend to cost more than the energy intensive versions (even though in many cases, the electricity savings eventually compensate for the higher prices). Improving the efficiency of low cost versions of these appliances is critical to ensuring that electrification realizes its potential impact. Improving the overall
affordability of appliances will also lead to an increase in demand for electricity (Batchelor, et al., 1999). Increasing efficiency will reduce the load on mini-grids, in turn reducing the likelihood of power failures and load shedding.

However, businesses have so far been reluctant to invest in development of ultra-low-cost appliances for low income populations because of market uncertainties and high opportunity costs; they have been even more reluctant to invest in energy efficiency improvements for these markets. In emerging markets, urban middle and lower middle income users represent a profitable segment where profits are yet to be fully tapped out, and also have better risk-reward profiles than rural low income markets. To serve the latter with the right kind of energy efficient appliances, businesses need to invest in R&D, build new manufacturing lines (for the new appliances), and create new distribution channels. These are all expensive and risky propositions with long payback periods.

Specific technical challenges and opportunities will vary by type of appliance. For instance, fans with brushless direct current (BLDC) motors can be twice as efficient as ones with conventional induction motors. More efficient blades lead to a two-fold to four-fold increase in efficiency compared to the US EPA’s Energy Star requirements (Sathaye, et al., 2013). Refrigerators can achieve high efficiency gains simply with better insulation, and advances in new refrigerants can improve the efficiency of cooling engines (Shah, et al., 2013). Super efficient TV’s that draw a fraction of the power that currently available ‘efficient’ TV’s consume are also beginning to become commercially available (Cnet.com, 2014). As mentioned earlier, these innovations are currently focused on the environmental concerns of industrialized markets, and are not being designed for the constraints of rural markets. Still, with rapidly growing markets like India, we believe some of these appliances will begin to appear within the next 3 years, while others will take 5 years or more.

The key deployment challenge will be distribution, as is typical for rural markets, especially for products that require post-sales technical support. The upfront cost of appliances will also be a barrier but could potentially be addressed using financing schemes. User support services will be crucial as most target customers will be first time users, and these products will be significant investments for them. Overall, deployment will be COMPLEX.

Breakthrough 2 – Difficulty of deployment

<table>
<thead>
<tr>
<th>Extremely Challenging</th>
<th>Challenging</th>
<th>Complex</th>
<th>Feasible</th>
<th>Simple</th>
</tr>
</thead>
<tbody>
<tr>
<td>Policies</td>
<td>Infrastructure</td>
<td>Human capital</td>
<td>Access to user finance</td>
<td>Behavior change</td>
</tr>
<tr>
<td>Low role of policy / regulation</td>
<td>No need for additional human capital development</td>
<td>Requires some improvements to existing infrastructure</td>
<td>Moderate financing needed, viable mechanisms identified</td>
<td>Minimal behavior change required</td>
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New bulk storage technologies for decentralized mini-grids, which provide improved performance at a significantly lower cost

Consumers will use appliances at different times of the day, based on their specific household and livelihood needs, rather than the availability of power. In the case of distributed solar PV mini-grids, for example, users need lighting precisely when sunlight is not available. Similarly, refrigerators will need to run continuously through night and day. To enable such usage, a continuous and reliable supply of electricity will be required, without which the value for electricity will be limited, as will the willingness of users to pay for it. Some appliances (e.g., refrigerators) will not be very usable without continuous power. This makes bulk electrical energy storage services essential for renewable energy mini-grids, where sources are intermittent, and backup power from main grids is not an option.

Whereas large-scale storage solutions such as pumped water are practical for main grid, there are major gaps in current storage technologies usable for mini-grids. Lead-acid batteries—the only commercially available option—are too expensive, adding over 50% to the system costs for solar PV mini-grids and doubling the cost of electricity to the user. Other rechargeable battery technologies are not yet available at commercial scale, at the right level of cost and performance.

New battery technologies for bulk storage in decentralized renewable energy mini-grids are required to achieve a step change in the economics of rural electrification. Beyond low cost (low enough to support usage by populations living on less than $5 a day), such a technology will also need to be robust, durable, compact, easy to transport, and easy to install. It should also be modular and configurable, with the ability to scale up or down based on usage levels. Operation and maintenance should require minimal technical expertise, and limited additional infrastructure.

Each emerging technology faces its own set of challenges and opportunities. Lithium-ion batteries—currently in broad use for small devices such as mobile phones—will need to address barriers of cost, efficient scaling to mini-grid capacity, and safety hazards from overheating and fires. Flow batteries—relatively easy to configure and scale with limited technical expertise, and with a long life—have low energy densities, and need cooling mechanisms, along with safeguards for potentially toxic chemicals that are needed to make them. Sodium-sulphur batteries appear promising with respect to cost and performance, but are very bulky, operate at very high temperatures, and are corrosive.

The rapid pace of innovation in storage technologies will continue, but mostly for portable batteries. The storage market is expected to increase 20-fold between 2010 and 2020, driven by the Electric Vehicle industry, and more recently by large scale deployment of renewable energy farms in industrialized countries. This will likely benefit lithium-ion technology, which has a very high learning rate of 30% (IRENA, 2012). Optimistic industry projections suggest a reduction of 50-75% in Electric Vehicle battery prices in 5-10 years, and gains in energy density by 30-50% from alternative materials and solutions in both automotive and power applications (Greentech Media, 2010). Since most of the emerging rechargeable battery technologies are still pre-commercial, it will likely take 5-10 years for the first wave of these to materialize.

Batteries are an essential component of decentralized rural mini-grids. Hence, the deployment challenges will be those associated with mini-grids writ large. These include limited demand, the very difficult market economics of a nascent market, and the dearth of technical skills required to install and maintain the systems. In addition, a number of safety issues will need to be addressed for technologies like lithium-ion and sodium-sulphur. While varying a little by the specific battery technology, deployment will be COMPLEX.
Affordable and easy-to-use grid management solutions for decentralized renewable energy rural mini-grids

Grid management involves forecasting, monitoring, regulating and troubleshooting at all stages of the grid: generation, distribution and consumption. It also involves prevention of losses and theft, as well as collection of revenues. Effective grid management can significantly improve quality of service and the overall economics of operating rural mini-grids, which are two of the main challenges currently facing aspiring mini utility providers. While solutions exist for large scale grids, they are not affordable or applicable at mini-grid scale, especially in low income rural settings where skilled workers may not be available.

A number of technical hurdles will need to be overcome: prepayment meters at the point of consumption (along with the hardware and software needed to use them) will need to become significantly less expensive; components for installing and integrating into the grid will need to be simplified and made more robust to deal with environmental factors, low voltage and voltage fluctuations; mobile payment applications will need to be integrated; and geographical-specific forecasting systems for wind and solar will need to be developed. There is currently very limited market-driven pull for such systems. One encouraging trend, however, is the rapid evolution of a range of Internet of Things (IoT) systems (which are discussed in the section on Digital Inclusion) (Schneider Electric, 2014). A market ready solution will take about 10 years.

Grid management will be a key component of decentralized rural mini-grids. As such, the deployment challenges will be those associated with mini-grids writ large; limited current demand, challenging market economics, and a lack of skilled technicians to install and maintain the systems. As such, deployment will be COMPLEX.
A ‘utility-in-a-box’ for making it simpler, cheaper and faster to set up and operate renewable energy mini-grids

Making renewable energy mini-grids inexpensive and easy to install, will significantly help to scale them up. Currently, it is a time consuming, unpredictable and challenging process involving a highly fragmented supply chain. Many components need to be procured, transported and integrated in hard-to-reach places, without supporting infrastructure or adequate skilled labor. A ‘utility-in-a-box’, which is easy for technicians (with some training) to install in a few days, and also easy to maintain on an ongoing basis, will significantly improve the economics of rural mini-grids. Specifically, this will reduce the balance-of-system costs which constitute a major portion of mini-grid installation CapEx. It will also minimize the need for technical expertise for operations by standardizing and simplifying operations and maintenance (which is another major hurdle to the proliferation of mini-grids).

Such a utility-in-a-box should include all the key components of a decentralized renewable energy mini-grid, for generation, storage, and grid management. Standardization and self-help tools for installation, O&M and troubleshooting will be key. Similarly, modularity and configurability—to meet the specific power demands of a particular installation—will be crucial to ensure adequate capacity and maximum capacity utilization. In principle, an early version of such a technology can be developed relatively quickly, since it involves design, integration and standardization of existing tools much more than upstream R&D. An early version of such a system can be market-ready in 2-5 years. Over time, more sophisticated components (e.g., for improved grid management) can be added.

Deployment challenges will be the same as those impacting other breakthroughs related to mini-grids: limited current demand, challenging market economics, and a lack of skilled technicians to install and maintain the systems. As such, deployment will be COMPLEX.
Breakthrough 5 – Difficulty of deployment

- **Extremely Challenging**
  - Policies
  - Access to user finance
  - Behavior change
  - Existing demand
  - Market fragmentation/distribution channels
  - Business model innovation

- **Challenging**
  - Infrastructure
  - Human capital
  - Distribution channels

- **Complex**
  - Minimal need for infrastructure
  - Moderate need to train a limited number of people
  - Moderate behavior change required with evidence of behavior change being viable
  - Low demand, needs to be built
  - Moderate fragmentation of customers, under-developed channels
  - Deployment models being tested

- **Feasible**
  - Regulated market with supportive policies
  - Moderate financing needed, viable mechanisms identified

- **Simple**
  - Simple
It is fair to say that gender equity—defined as a state wherein societies treat women and men alike, by custom, by law, and in practice—does not exist. Not in wealthy countries, and definitely not in low income countries. The root causes are many: deep-seeded religious and cultural beliefs, the persistence of societal stereotypes and ‘boys will be boys’ attitudes, the dearth of female perspective in legislation even in the 21st century, and a host of other male-dominated influences. Even in interventions aimed at poverty alleviation, the solutions—technological or otherwise—are more often than not designed by men, without enough understanding of the real needs of users, the majority of whom end up being women.

This inequity manifests itself in a number of ways. Women do most of the world’s work, but earn only a fraction of the compensation that men do. They frequently face violence and abuse at home, at the workplace, and by men in other positions of power; too often, they have no recourse. They
are vulnerable to a number of health risks that men are not, but do not have access to the necessary healthcare. The majority of women do not have a voice in how they spend the money they earn, and cannot invest in technologies and tools that can alleviate their condition.

Clearly, none of these problems can be addressed without fundamental changes in societal values and attitudes, complemented by strictly enforced legal protections. While technology itself will not be a definitive or permanent solution, we believe that it can play a supplemental yet vital role. We have identified 6 technology breakthroughs that can play a direct part in enhancing gender equity. Some of these have been identified as breakthroughs in other sections of this study as well.

- An easy to operate, affordable, integrated, and solar-powered suite of medical devices specifically for maternal, child and primary care in low resource settings

- Microbicides to provide a method of protection against HIV/AIDS and Human Papillomavirus (HPV), for those who are otherwise vulnerable to infection through sexual contact with their partner

- A new kind of a home—made with strong lightweight material—especially for the urban poor, with a private toilet, solar-powered lighting and ventilation

- A simple point-of-use, low cost DNA-based rape kit capable of delivering rapid results

- Affordable, lightweight, fuel efficient, solar-powered irrigation pumps

- An affordable mechanized tilling and weeding tool
Throughout human history, most societies in the world have been dominated by men. Religious institutions, from every major faith around the world, have been the exclusive preserve of male leadership and perspective. Men have been able to dictate laws and traditions to their own benefit, often ignoring the perspectives of women, and sometimes manifestly suppressing their rights. While recent decades have seen significant improvements in both law and practice, even the most educated and economically advanced societies today are male-centric; lower income countries, more so.

Not surprisingly then, from an early age, girls and women around the world experience inequities in virtually every aspect of life: access to education; conforming to what constitutes acceptable dress and speech; opportunities for employment; appropriate working conditions and fair wages; land and other economic rights; the right to decide when to marry; the right to choose their partner; the right to contraception; the right to choose if, when, and how many children to have; the share of the responsibility for managing their household work and caring for children; protection from health hazards; security from harassment, abuse and violence; and access to adequate healthcare.

CORE FACTS AND ANALYSIS

Women and girls, accounting for 70% of the 1 billion people living on less than $1 per day, bear the brunt of extreme poverty (Women Moving Millions, 2014). The following discussion analyzes specific hurdles they face along the key aspects of development: basic human rights, education, economic, social and political rights, health, and day-to-day life. These challenges exist throughout the world and across economic classes. Our analysis focuses on developing countries and low income populations, when appropriate. Please note that this section draws heavily from one particular source: the World Bank’s 2012 Gender Equity and Development Report.

HUMAN RIGHTS

There are more than 90 million ‘missing women’, primarily in Asia

Sex-selective abortions are common in countries where there is a strong preference among parents for boys, and girls are perceived as an economic burden. In many countries such as India, this is due to social ills like the practice of dowry, as well as a general belief that only boys grow up to support parents in their old age. Other countries have variations of such beliefs. This pressure is further exacerbated by reduced fertility rates, with families now wanting fewer children—and at least one son. China’s ‘one-child
policy’ is an extreme example of external pressure that appears to have compelled parents into sex-selective abortion. Increased access to technologies such as antenatal ultrasound has increased the ability of would-be parents to determine the sex of a fetus, and selectively terminate pregnancies (Kulkarni, 2007) (Hvistendahl, 2011). As a result, the ratio of male-to-female births in a number of Asian countries, particularly China, India, Pakistan, Bangladesh, Afghanistan, Taiwan and South Korea, is well above the expected ratio. The established norm is 105-107 baby boys born for every 100 baby girls. However, in India, the ratio is 113, with some regions going over 155; in China, the number is 119-121, with some regions going as high as 135 (World Economic Forum, 2012) (Hudson & Boer, 2005). This, combined with other health factors, appears to have contributed to a large number of ‘missing women’, estimated at 90.3 million as of 2005 (Hudson & Boer, 2005), with China and India accounting for the majority (Exhibit 1). This phenomenon is discussed in greater detail later in this section.

Actual vs. expected sex ratios, and ‘missing women’

Exhibit 1: Sex-selective abortion, combined with other factors, has led to a higher-than-expected male-female sex ratio in a number of Asian countries. There are as many as 90 million ‘missing women’ in these countries.

Violence against women and girls is common in many parts of the world

Violence and abuse against women and girls is all too common an occurrence, and takes place in many forms—physical, sexual and psychological. While men also face violence, the violence and abuse faced by women is gendered, in that it is usually perpetrated by men and often in the context of a one-sided power dynamic.

Domestic violence

According a UN survey, over 30% of women around the world are subjected to physical violence by their partner at least once in their lifetime, many of them in the last 12 months (Exhibit 2). Women also face
high rates of sexual violence, with more than 20% of women in surveyed countries reporting assault, not including nonviolent incidents of sexual harassment, at least once in their lifetime (Exhibit 3) (UN-ECOSOC, 2010). Equally troubling is that in many countries, violence against women is perceived as acceptable or justifiable, even by the women themselves. Nearly 30% of women in the surveyed countries agreed that wife beating is justified for arguing with the husband, 25% believed it is justified for refusing to have sex, and 21% believe it is justified if the wife accidentally ends up burning the food while cooking. In Guinea, as many as 60% of surveyed women found it permissible to be beaten for refusing sex and in Ethiopia, 81% of women agreed with at least one of these reasons for wife beating (World Bank, 2012).

Proportion of women experiencing physical violence by their partner at least once in their lifetime, and in the last 12 months

Exhibit 2: More than 30% of women in the surveyed countries reported experiencing physical violence by their partner at least once in their lifetime. Nearly 30% of the surveyed women agreed that wife beating is justified for arguing with the husband and 25% believed it is justified for refusing to have sex. Note that statistics for the last 12 months are not available for all the countries (UN-ECOSOC, 2010).
Proportion of women experiencing sexual violence at least once in their lifetime, and in the last 12 months

Exhibit 3: In a majority of surveyed countries, more than 20% women reported facing sexual violence at least once in their lifetime. Note that statistics for the last 12 months are not available for all the countries (UN-ECOSOC, 2010).

Human trafficking
Human trafficking, for sexual exploitation and forced labor, is the fastest growing form of organized crime in the world, and the 3rd largest form of criminal enterprise globally (FBI, 2014). There are more than 20 million trafficking victims, of which more than 12 million are women, trafficked for sexual exploitation (UN-ECOSOC, 2010).

Genital mutilation and other culturally sanctioned violent practices
In a number of countries, girls face specific forms of culturally sanctioned violence. While some practices like breast flattening typically take place to keep young girls from showing any outward signs of puberty and ‘keep them safe from rape’, others like ‘sexual cleansing’ (by paying an older man to have intercourse with girls as young as 9) occur to prepare girls to enter adulthood (The Guardian, 2012) (The Guardian, 2014).

Another major form of violence against girls and young women is female genital mutilation (FGM), which refers to a range of procedures involving removal or partial cutting of external female genitalia for non-medical reasons. A traditional ritual in many cultures, FGM rates are extremely high (over 80%) in
Guinea, Egypt, Eritrea and Mali (UN-ECOSOC, 2010). In the face of advocacy and awareness campaigns, however, the rates have been dropping somewhat in recent years (Exhibit 4).

Percent of women, aged 15-49, subjected to female genital mutilation

Exhibit 4: Female genital mutilation is a major problem in a number of countries, even though recent campaigns have resulted in small improvements (UN-ECOSOC, 2010).

Honor killings

Each year, an estimated 5,000 women and girls are violently killed by members of their own family or community, in so-called honor killings (UNFPA, 2000). Concentrated in South Asia and the Middle East, such violence is perpetrated on women who are considered to have defied traditional norms and embarrassed their family, usually through acts of intimacy before marriage, by marrying someone outside of the community, or for committing adultery.
Rape as a weapon of war
Many conflicts, especially those with an ethnic or religious rift, involve widespread sexual violence against women and girls, perpetrated by combatants or civilians. According to a UN Security Council resolution, “Women and girls are particularly targeted by the use of sexual violence, including as a tactic of war to humiliate, dominate, instill fear in, disperse and/or forcibly relocate civilian members of a community or ethnic group.” (UN Security Council, 2008). Recent examples of large-scale sexual atrocities include the conflicts in the former Yugoslavia, Rwanda, the Democratic Republic of Congo, and Liberia. Seemingly, the motivations range from a desire to humiliate the enemy by impregnating ‘their’ women, to use HIV as a weapon, or to just brutally exercise power over civilians with neither protection nor recourse (Aginam & Rupiya, 2012).

EDUCATION

Despite recent progress in enrollments at the primary school level, gender disparities persist in higher education

A quality education is critical for every girl’s ability to access economic opportunities later in life. Moreover, educated women also take better care of, and invest more in their children, who are then more likely to become well educated themselves. Women are also much more involved in teaching children than men are (World Bank, 2012). In Pakistan, for example, children whose mothers have even a single year of education spend an extra hour studying every day, and do better at school (World Bank, 2012). In addition, children of educated women are more likely to be immunized and have good nutrition, lowering the rate of child mortality.

As shown in the section on Education, recent years have seen considerable increases in enrollment rates in sub-Saharan Africa and South Asia. As Exhibit 5 shows, there have been increases in the relative number of girls and women enrolled across various levels of education. However, gender parity is far from being a reality at the higher levels of education. Only 37% and 43% of tertiary enrollees in sub-Saharan Africa and South Asia, respectively, are women. While the male-female ratio is more on par in primary school, traditional beliefs and opinions about gender roles leads parents to discourage their daughters from pursuing an education as they grow older. As Exhibit 6 and Exhibit 7 show, these disparities are pronounced in lower income regions of the world, especially in poorer population segments. In some parts of the world, discouragement of girls’ education can even turn violent, as recent events in Nigeria and Pakistan have shown (The Guardian, 2014).

While gender disparity, especially in early education today, may seem to be driven more by economic factors than outright gender discrimination (World Bank, 2012), inequality exists and manifests itself in many ways:

- Women today account for two-thirds of the 774 million illiterate adults in the world, a proportion that has remained unchanged since 1990. There are 130 million illiterate women in Africa, and another 341 million in Asia (UN-ECOSOC, 2010).

- In Africa, 41% of women have never attended school, compared with 24% of men. Only 21% of women in Africa have obtained secondary or tertiary education, compared with 30% of men; in Asia, only 25% of women are completing secondary or tertiary school, compared with 41% of men (World Bank, 2012).

- In low and middle income countries, fewer women than men have access to the Internet. The gap is 35% in South Asia, the Middle East and North Africa, and 45% in sub-Saharan Africa (Intel, 2013).
Percent of enrolled students who are female, in South Asia and sub-Saharan Africa

Exhibit 5: Although between 1999 and 2011, female enrollment for all levels of education increased more rapidly than for males, women still comprise a small proportion of total enrollees, especially in sub-Saharan Africa.

Percent of enrolled students who are female, 2011

Exhibit 6: South Asia and sub-Saharan Africa trail the rest of the world when it comes to tertiary education for women.
Gender disparity across income levels

Exhibit 7: In a number of countries in South Asian and sub-Saharan Africa, gender disparities are more conspicuous in lower income population segments (World Bank, 2012). The wealthiest (5th) quintiles have close to equal school enrollment in the 15-19 year age group, while the poorest (1st) quintiles consistently have the highest disparity.
Women are responsible for more work than men, often in the form of unpaid household work or manual labor, especially in the agriculture sector.

Women work two-thirds of the world’s working hours, yet earn only 10% of the world’s income. This is largely because women continue to bear primary responsibility for the home, spending twice as much time as men on unpaid work such as caring for children and dependent family members, preparing meals, and doing housework like cleaning, washing, gathering firewood, and fetching water. More than 50% of rural households and 25% of urban households in sub-Saharan Africa lack easy access to drinking water—and it is women’s work to collect the water, a task that can involve walking many miles and take up the better part of a day. The time women spend on such domestic and otherwise unpaid activities keeps them from schooling and earning (UN-ECOSOC, 2010) (Women Moving Millions, 2014) (World Bank, 2012). Table 1 shows the share of time women and men spend on various categories of activities. As Exhibit 8 shows, agriculture represents the single largest form of economic activity for women in South Asia and sub-Saharan Africa (Food and Agriculture Organization, 2011) (International Labour Organization, 2014). They work as producers, laborers, processors, and traders in domestic markets. Although men do much of the heavy manual labor such as ploughing fields and driving draught animals, women do most of the weeding, fertilizing and harvesting, and contribute to a significant share of the workload in food production (Exhibit 9). In aggregate, women are responsible for 50% of food production worldwide (FAO, 1995) (UN, 2007).

### Table 1: Women spend a disproportionate share of their time taking care of their households (compared with men), rather than on income-generating activities. The countries with the greatest disparities are in Africa and South / Southeast Asia.
Exhibit 8: Women contribute to a substantial portion of agricultural labor in both South Asia and sub-Saharan Africa, far more than the rest of the world.
Women do not enjoy income parity, lack control over income earned, and are deliberately excluded when it comes to owning or inheriting property.

Even when women are paid for their work, a persistent remuneration gap exists. Women’s wages represent only 70-90% of men’s wages in the majority of countries (United Nations, 2010), and in some countries, women earn only 30-50% of what men earn. In Bangladesh, women earn only 12 cents ($0.12) for every dollar earned by men (World Bank, 2012). To make matters worse, women have limited control over how the income they earn is spent. This is particularly true in lower income countries, and even more so in lower income segments of the populations in those countries (Exhibit 10).

Women are also disadvantaged with respect to land and property rights, whether through inheritance or marriage. In many countries in Africa and Asia, only men are allowed to own land, by both law and tradition. Additionally, in many countries, women do not have the legal right to a share in paternal or matrimonial property. The consequence of this systemic bias is obvious: women in Kenya represent only 5% of registered landowners, and in Brazil and Paraguay, they own only 11% and 2% of registered land, respectively. Moreover, women’s land holdings are far smaller than those of their male counterparts: in Ghana, for example, the average land holding for a man is three times the size of that for a woman (World Bank, 2012). Without land or another non-movable asset as collateral, women have very limited access to credit. Without credit, they cannot purchase seeds, fertilizer, irrigation equipment or other mechanisms for increasing farm productivity. Globally, women receive only 10% of small farmer credit, and only 5% of agricultural extension services (World Economic Forum, 2012).

Exhibit 9: Women contribute to a substantial portion of total agricultural labor, ranging from 32% in India, to almost 70% in Cameroon.
Percent of women not involved in decision-making about their own income

Exhibit 10: Women in lower income segments of the population have limited to almost no say in how they spend their own income.
While women have a higher life expectancy, there are 3.9 million ‘excess female deaths’ each year due to factors like selective abortion, maternal mortality, HIV/AIDS, and indoor air pollution.

In every region of the world, and in nearly every country (the only exceptions being Botswana, Mali and Swaziland), women outlive men. As Exhibit 11 shows, average female life expectancy globally is 4.2 years higher—72.5 years for women, compared with 68.3 for men. The difference, however, dwindles in South Asia (57.9 for women vs. 55.4 years men) and sub-Saharan Africa (69.8 years for women vs. 67.0 years for men) (World Bank, 2014). While the specific reasons are not clear, studies point to the higher incidence of heart disease among men, driven by a combination of genetic factors, as well as behaviors like smoking that are more prevalent among men (Waldron & Johnston, 1976) (Waldron, 1983).

**Life expectancy in 2010, males vs. females**

<table>
<thead>
<tr>
<th>Region</th>
<th>Female</th>
<th>Male</th>
</tr>
</thead>
<tbody>
<tr>
<td>European Union</td>
<td>82.6</td>
<td>77.4</td>
</tr>
<tr>
<td>North America</td>
<td>82.1</td>
<td>77.5</td>
</tr>
<tr>
<td>Latin America &amp; the Caribbean</td>
<td>76.7</td>
<td>71.0</td>
</tr>
<tr>
<td>East Asia &amp; the Pacific</td>
<td>76.3</td>
<td>71.5</td>
</tr>
<tr>
<td>East/Central Europe &amp; Central Asia</td>
<td>76.2</td>
<td>68.6</td>
</tr>
<tr>
<td>Middle East &amp; North Africa</td>
<td>75.2</td>
<td>71.5</td>
</tr>
<tr>
<td>Southeast Asia</td>
<td>73.5</td>
<td>68.5</td>
</tr>
<tr>
<td>South Asia</td>
<td>69.8</td>
<td>67.0</td>
</tr>
<tr>
<td>sub-Saharan Africa</td>
<td>57.9</td>
<td>55.4</td>
</tr>
</tbody>
</table>

**Exhibit 11:** Life expectancy of females is higher than that of males, in every region of the world.

These advantages notwithstanding, it is estimated that each year there are 3.9 million cases of ‘excess mortality’ among girls and women (World Bank, 2012). These deaths (Table 2) are concentrated in East Asia (primarily China), sub-Saharan Africa, and South Asia (primarily India). Of these 3.9 million deaths,
1.43 million occur at or before birth due to selective abortion; another 617,000 occur in girls under 5; 158,000 between the ages of 5 and 14 years; 1.35 million in the 15-49 year age range; and 334,000 deaths occur between the ages of 50 and 59 years.

### Excess female deaths in the world, by age and region (thousands)

<table>
<thead>
<tr>
<th>Region</th>
<th>Birth</th>
<th>Under 5</th>
<th>5-14</th>
<th>15-49</th>
<th>50-59</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>sub-Saharan Africa</td>
<td>53</td>
<td>203</td>
<td>77</td>
<td>751</td>
<td>99</td>
<td>1,182</td>
</tr>
<tr>
<td>South Asia</td>
<td>258</td>
<td>323</td>
<td>65</td>
<td>389</td>
<td>126</td>
<td>1,161</td>
</tr>
<tr>
<td>East Asia</td>
<td>1,096</td>
<td>78</td>
<td>14</td>
<td>169</td>
<td>76</td>
<td>1,433</td>
</tr>
<tr>
<td>Middle East &amp; North Africa</td>
<td>6</td>
<td>7</td>
<td>1</td>
<td>24</td>
<td>15</td>
<td>52</td>
</tr>
<tr>
<td>Europe &amp; Central Asia</td>
<td>14</td>
<td>1</td>
<td>0</td>
<td>4</td>
<td>3</td>
<td>23</td>
</tr>
<tr>
<td>Latin America</td>
<td>0</td>
<td>5</td>
<td>1</td>
<td>10</td>
<td>17</td>
<td>33</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1,427</td>
<td>617</td>
<td>158</td>
<td>1,347</td>
<td>334</td>
<td>3,882</td>
</tr>
</tbody>
</table>

Table 2: ‘Excess mortality’ among women and girls is concentrated in South Asia, East Asia and sub-Saharan Africa.

The following discussion highlights the main factors leading to female deaths in post-birth age groups.

**Child mortality**

The reasons for the 617,000 excess deaths of girls under 5 are not clear. While some studies have implicated delays in seeking healthcare for girls (Tarozzi & Mahajan, 2007) (World Bank, 2005), a World Bank study on gender equity (World Bank, 2012) did not find conclusive evidence to show why girls in low income populations are worse affected than boys. Exhibit 12 shows data from the World Bank study (World Bank, 2012) suggesting that there are no meaningful differences between healthcare provided to boys and girls—in countries with higher rates of mortality among girls—when it comes to vaccination, being taken to a health facility for respiratory illness, or stunting.\(^1\) That study concludes that excess female mortality in childhood, “is a result not so much of discrimination as of poor institutions that force households to choose among many bad options, particularly regarding water and sanitation” (World Bank, 2012).

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\(^1\) The immunization rates in this example are for polio and measles, neither of which is one of the major drivers of childhood mortality; however, it is likely that children who are vaccinated for these diseases are also vaccinated for other diseases. Respiratory conditions like pneumonia are among the leading causes of mortality among children under 5. Stunting is one of the leading symptoms of malnutrition among children.
Key health statistics for boys vs. girls, across a large number of low income countries

Exhibit 12: There appears to be little gender disparity among children, with respect to vaccination rates, nutrition outcomes, or use of health services (World Bank, 2012). This makes it difficult to explain the causes behind the 617,000 ‘excess deaths’ of girls under 5.

Maternal mortality
As the chapter on maternal mortality in the Global Health section of our study discusses, about 300,000 women die each year during childbirth (WHO, 2014). It is one of the leading causes of death among women of childbearing age in South Asia and sub-Saharan Africa. Among the main drivers of maternal mortality is the fact that a large number of births take place at home and are administered by untrained traditional birth attendants. There is a systemic absence of maternal healthcare in low income countries—without enough adequately equipped clinics, trained clinicians, or means of escalation in the event of complications. In fact, across the largest countries in South Asia and sub-Saharan Africa, only 37% pregnant women receive the WHO recommended 4+ antenatal care visits, which are crucial for determining the health of both mother and the unborn child. While the majority of maternal deaths are due to weak healthcare systems, 10-15% of maternal deaths are caused by unsafe abortions, in countries where abortion is restricted or is inaccessible.

HIV/AIDS
Women are more susceptible to HIV/AIDS due to both sociological and biological factors. The latter include the surface area of the cervix and vagina (compared to the surface area of parts of the male penis); the
increased likelihood of tears along the surface of the vagina, particularly in younger women who tend to have immature genital tracts (compared with parts of the penis); the higher fluid volume of semen entering the woman’s body (compared with the volume of vaginal secretion entering the man’s body); the higher viral concentration in semen (compared with that in vaginal secretion); and the warm, moist environment inside the vagina, which is ideal for the HIV virus to thrive. Sociological factors include notions about masculinity due to which men tend to have a higher number of—and younger—female sexual partners (than the other way around); the unwillingness of men to use condoms or get circumcised; and the practice of douching (washing the vagina with soap), which destroys natural protective bacteria (UNAIDS, 2011) (World Bank, 2012) (Canada AIDS Society, 2014). As a result, prevalence of HIV among women in sub-Saharan Africa is almost twice that among men (2.5% vs. 1.3%, respectively) (Exhibit 13), women account for 60% of HIV infections, with the gender gap in prevalence largest for younger adults. After age 34, HIV prevalence rates are similar for men and women. Prenatal care, care during childbirth, and children’s vaccination rates have suffered most in regions and areas where HIV rates are the highest.

Prevalence of HIV in 2012, ages 15-24 years

Exhibit 13: In sub-Saharan Africa, the prevalence of HIV among women is almost twice that among men. In other parts of the world, prevalence among men and women is roughly the same.

Cervical cancer
Every year, over 270,000 women die from cervical cancer, which is caused by the Human Papillomavirus (HPV). The infection is acquired through sexual contact, and is the single most common form of viral infection of the reproductive tract. It is most common in the early years of sexual activity, and does not necessarily require penetrative intercourse for transmission. Most cases of HPV infection heal by themselves in a few months and do not lead to life-threatening disease. However, the lesions caused by infection can lead to
cervical cancer in women over the course of 15-20 years, based on a number of risk factors: weak immune system; first intercourse with an infected partner; multiple sexual partners; and tobacco use. HPV vaccines for both men and women—recommended prior to first sexual encounter—are available for the strains most commonly linked to cervical cancer. However, these vaccines are either not broadly available in developing countries, or are unaffordable. Once the cancer sets in, the only methods for treatment are those similar to other forms of cancer—surgery, radiation therapy, and chemotherapy (WHO, 2014).

**Household (indoor) air pollution**

Around the world, women do most of the household cooking. In developing countries, low income women cook using traditional stoves using fuels like wood or biomass, which emit high levels of smoke. This pollution causes respiratory infections, heart disease and lung cancer, leading to 4.3 million deaths each year. Of these, 3.1 million deaths occur in South and Southeast Asia, 600,000 in sub-Saharan Africa, and 200,000 in the Middle East and North Africa. While women face greater exposure to indoor air pollution, men account for a higher share of the mortality from respiratory and lung diseases due to higher underlying disease rates: 46% of the deaths (1.99 million) are those of men, and 41% (1.77 million) are women; 13% (534,000) are children (WHO, 2014). Over the past few years, a number of fuel efficient and clean cookstoves have been developed, but virtually none have achieved sustainable scale. One of the main reasons is that these stoves are competing against an alternative which is free, and the long-standing traditional choice (i.e., the traditional three-stone or mud hearth). In addition, while there is clearly a health imperative in reducing household air pollution through cleaner stoves, it is not clear that there is demand for them. Presumably, this is because those most exposed high indoor air pollution do not see any short-term value in cleaner stoves, especially considering their economic means. In a number of urban markets, liquefied petroleum gas (LPG) stoves appear to be gaining traction (GACC, 2013).

**Sanitation and menstrual hygiene**

There are several other issues which disproportionately affect low income women, but often do not receive adequate recognition in the conversation about global health. Due to the lack of sanitation and safe toilets, millions of women have to urinate and defecate in the open. This is not only a question of basic dignity and hygiene, but also makes women and girls vulnerable to sexual abuse and violence when they use public facilities, or venture out late at night to relieve themselves (BBC, 2014).

Another major issue is the lack of affordable sanitary pads. Without these, women and adolescent girls have to either stay home, or use uncomfortable cloth rags that lead to poor menstrual hygiene, and may cause reproductive tract infections. Lack of access to suitable sanitary care products causes many girls to interrupt their schooling (sometimes even dropout of school), and older women to interrupt their work and livelihood (BBC, 2014). A recent study found that over 70% of menstruating women in India could not afford usable products (Times of India, 2011). Other evidence suggests that the problem is similarly severe in many other low income countries in Africa (One Foundation, 2014).
Women and girls in low income populations have limited voice in critical decisions regarding marriage and family planning

The lack of agency in the context of family life begins at an early age, and is particularly prevalent among lower income families. Many girls from low income families are forced to marry at an early age; and in marriage, many are not able to exercise choice in the use of contraception, or in having children. As Exhibit 14 (World Bank, 2012) shows, women in lower income populations tend to be married at a significantly younger age than their wealthier counterparts. In these populations, one of the main reasons for low contraceptive use is the refusal by men to use male condoms (despite significant improvements in access) and the lack of availability of female condoms. Such factors lead to significantly higher fertility rates among women in lower income groups. As Exhibit 15 shows, women in the poorest quintiles of many countries have twice as many (or more) children as women in the wealthiest quintile. The poorer the country, the greater the gap between the fertility rates of the rich and poor appears to be. Encouragingly, only 18% of women today live in countries where average fertility is above 3 births per woman. This trend is important because lower fertility rates—and the ability of women to have a say in how many children they have, how early they begin having them, how long they wait between pregnancies, and when to stop having children—has proven critical to their own health and wellbeing, as well as that of their children and families (World Bank, 2012). It is also encouraging that long-acting reversible contraceptives (LARCs) like intrauterine devices (IUDs) are becoming increasingly available and affordable in developing countries.
Exhibit 14: Underage marriage is a common phenomenon among low income families in many countries (World Bank, 2012).
Fertility rates across different income quintiles

Exhibit 15: Fertility rates vary dramatically by income quintile; by a factor of two between the wealthiest and poorest income quintiles in many countries (World Bank, 2012).
KEY CHALLENGES

There are many reasons why gender equity does not exist in the world today. Some reasons are obvious, while others are complex and nuanced. Some reasons are seemingly addressable, while others are deep-rooted, and threaten to be an ongoing struggle. Some reasons affect women across income groups, while others are particular to low income populations. The following is a summary—admittedly oversimplified—of the reasons why gender disparities exist among low income populations.

Laws to ensure gender equity and protection of women, already weak or poorly enforced in many countries, are even more badly enforced for low income women

Laws are typically written by male-dominated legislatures and do not reflect the context and challenges faced by women; sometimes, they are outright discriminatory. For example, even in countries like the US, until very recent legislation like the Lilly Ledbetter Fair Pay Act of 2009 (United States Senate, 2009), equal pay for equal work had not been fully guaranteed by law. On the other hand, acts like Kenya’s 2014 polygamy law (The Guardian, 2014), are actively creating barriers against equity. Even when fair laws are on the books, there is strong evidence to suggest that they are not enforced, especially for low income women (World Bank, 2012) (Mehta, 2013). In most regions of the world, fewer than one-fourth of national parliamentarians are women (Exhibit 16).

<table>
<thead>
<tr>
<th>Region</th>
<th>Percent of National Parliamentary Seats Held by Women</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Asia &amp; the Pacific</td>
<td>19%</td>
</tr>
<tr>
<td>Europe &amp; Central Asia</td>
<td>25%</td>
</tr>
<tr>
<td>European Union</td>
<td>27%</td>
</tr>
<tr>
<td>Latin America &amp; the Caribbean</td>
<td>25%</td>
</tr>
<tr>
<td>Middle East &amp; North Africa</td>
<td>16%</td>
</tr>
<tr>
<td>North America</td>
<td>21%</td>
</tr>
<tr>
<td>South Asia</td>
<td>20%</td>
</tr>
<tr>
<td>Sub-Saharan Africa</td>
<td>22%</td>
</tr>
</tbody>
</table>

Exhibit 16: Throughout the world, women comprise a very small portion of national parliaments (World Bank, 2012).
Customary practices, often discriminatory, coexist with formal constitutional laws

A number of countries have plural legal systems, in which traditional laws and practices coexist with more modern constitutions and legal frameworks. To be clear, not all traditional laws are necessarily discriminatory towards women, nor do modern constitutional laws necessarily guarantee more protections. Still, it is reasonable to assume that newer laws, based on international standards and legislative debates, and under higher levels of scrutiny from the media, tend to be more inclusive than traditional practices. As Exhibit 17 shows, almost all countries in sub-Saharan Africa recognize traditional laws, and a substantial number of them are either silent on discriminatory practices or explicitly exempt women from non-discrimination.

Plural legal systems are also an issue in other parts of the world. In Pakistan and other Islamic countries, for example there is heavy pressure from religious leaders to impose Sharia Law (which can impose many restrictions on girls and women, including denial of education). Similarly, the legal systems in countries like India and Israel have also created separate laws for religious groups. Often, such laws based on interpretation of religious scripture—rather than modern constitutional principles—tend to discriminate against women (Amien, 2006) (ACLU, 2014). Across the board, wealthier urban populations and women tend to have access to better legal protections from these traditional laws and practices.

Plural legal systems in sub-Saharan Africa

Exhibit 17: Customary laws are part of the formal legal system in most countries in sub-Saharan Africa. This leads to discriminatory practices and laws in much of the region (World Bank, 2012).
There are a range of barriers preventing women from seeking available services, leading to a lack of transparency into the condition and specific needs of individual women.

Even when women are subjected to physical abuse or other forms of violence, they very often do not seek remedial services available to them. There are a number of reasons: stigma associated with filing claims; a lack of awareness about their rights or the services available; a lack of trust in the system to deliver effective results; the inconvenience of the process involved, given their household and other responsibilities; lack of support from the family or community; and the threat—implicit or explicit—of additional violence.

**Exhibit 18** (World Bank, 2012) shows results from surveys, conducted in a number of countries, which found that only a small portion of the women subjected to domestic violence sought recourse.

**Percent of abused women who seek available remedial services**

<table>
<thead>
<tr>
<th>Urban areas</th>
<th>Ever physically abused</th>
<th>Of which, sought services</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan (Yokohama)</td>
<td>1</td>
<td>13</td>
</tr>
<tr>
<td>Serbia (Belgrade)</td>
<td>3</td>
<td>23</td>
</tr>
<tr>
<td>Thailand (Bangkok)</td>
<td>1</td>
<td>23</td>
</tr>
<tr>
<td>Brazil (Sao Paulo)</td>
<td>4</td>
<td>27</td>
</tr>
<tr>
<td>Namibia (Windhoek)</td>
<td>5</td>
<td>31</td>
</tr>
<tr>
<td>Tanzania (Dar es Salaam)</td>
<td>8</td>
<td>33</td>
</tr>
<tr>
<td>Bangladesh (Dhaka)</td>
<td>1</td>
<td>40</td>
</tr>
<tr>
<td>Peru (Lima)</td>
<td>4</td>
<td>49</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rural areas</th>
<th>Ever physically abused</th>
<th>Of which, sought services</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brazil (Pernambuco)</td>
<td>1</td>
<td>34</td>
</tr>
<tr>
<td>Thailand (Nakhonsawan)</td>
<td>1</td>
<td>34</td>
</tr>
<tr>
<td>Samoa</td>
<td>2</td>
<td>41</td>
</tr>
<tr>
<td>Bangladesh (Matlab)</td>
<td>2</td>
<td>42</td>
</tr>
<tr>
<td>Tanzania (Mbeya)</td>
<td>5</td>
<td>47</td>
</tr>
<tr>
<td>Ethiopia (Butajira)</td>
<td>5</td>
<td>49</td>
</tr>
<tr>
<td>Peru (Cusco)</td>
<td>11</td>
<td>61</td>
</tr>
</tbody>
</table>

**Exhibit 18**: In domestic violence cases, the vast majority of women do not seek available remedial services (World Bank, 2012). This reluctance is driven by cultural practices, social stigma (or, inversely, support), and interpersonal family dynamics.
Technologies aimed at combating poverty are typically not developed with women in mind, even in the face of evidence that women constitute the majority of users. There is a growing body of work that is doing a more accurate accounting of the quantum of work women do, whether or not they are compensated for it, and their contribution to broader economic and social development. Women constitute the majority of farmers, health workers, and educators in many countries, but technologies are often not designed with women users in mind; too often, they are designed by men, with input from men. For example, manual treadle pumps used for irrigation in much of Africa have been reported to be too strenuous and inconvenient for women to use, and women have to employ young men to operate the pumps for them (Kay & Brabben, 2000). Women’s physical strength, size, mobility, traditional clothing constraints, whether or not they carry children with them during their workday, as well as cultural constraints, are all critical factors that are not taken into account often enough in technology and product design. Another important consideration not taken into account is the distance traveled—while carrying various types of loads—by women on a routine basis. By some estimates, over the course of a year, the average rural African woman “transporting water, fuel, or produce will carry more than 80 tons for more than a 1 km distance, while men carry about 10 tons for a 1 km distance.” (Ashby, et al., 2008). Suitable solar-powered solutions that can be adapted to the needs of women in rural or semi-rural areas, like the solar rickshaw in India (India Today, 2012), already exist on the market and are slowly converging toward the right price point. With the right financial and regulatory support, such a product will go a long way in improving the quality of day-to-day life for rural women.

There are significant systemic gaps in basic healthcare, which disproportionately impacts women. While health outcomes have improved dramatically in recent decades, the development of adequate healthcare infrastructure has been left largely unaddressed in many countries. This is especially true for rural or remote areas. There are far too few functional clinics, far too few adequately trained clinicians to operate them, and far too little funding to build and support the infrastructure. Today, significant gaps in basic healthcare exist in much of rural Africa and South Asia. The physical traits unique to women increases their vulnerability to specific health conditions, and the absence of essential health services disproportionately impacts them. Specifically, the lack of adequate maternal care increases the risk of complications and mortality during childbirth; and the nature of women’s reproductive organs increases their vulnerability to sexually transmitted infections like HIV and HPV. As a result, each year, 300,000 women die during childbirth and another 270,000 die from cervical cancer. Also, the prevalence of HIV in sub-Saharan Africa among women is almost twice that among men.

Exposure to a number of health hazards is exacerbated by the poor quality of homes. In particular, inadequate ventilation combined with high levels of indoor air pollution from using traditional cookstoves is a major driver for respiratory diseases. The absence of private toilets exposes women to significantly greater levels of inconvenience and increases the risk of abuse and violence when women are forced relieve themselves in the open or use unsafe public facilities.

The lack of affordable sanitary care products during menstruation increases the risk of reproductive tract infections. While in recent years there has been an increasing effort towards making very low cost sanitary pads available for women, as of 2014, no single product has reached much scale. We believe affordable products will become available within the next 2-3 years but will face the challenge of distribution and adoption, much like other products aimed at the low income retail market.
Technology will not overcome deep-seeded and archaic societal attitudes that predominantly dictate women’s roles and entitlements, and underlie almost every challenge women face. However, when it comes to some disadvantages faced specifically by low income women in developing countries, the following 7 breakthrough technologies can have targeted impact. Note that the issue of gender equity cannot be considered in isolation from other issues discussed in our study. Therefore, the following technological breakthroughs are grouped according the specific aspects of life and development that will be impacted, such as health, agricultural development, digital inclusion and human rights, and have been discussed in other topic-specific sections as well.

**HEALTH**

The main issues impacting the health of low income women are: a systemic lack of basic healthcare for low income communities, a primary driver for maternal mortality; higher physical vulnerability, as well as the practices of male sexual partners that increase the risk of HIV/AIDS or cervical cancer; cultural norms and the limited voice women have in family planning, which leads to higher-than-desired fertility rates among women from poorer populations; and greater exposure to household air pollution and the consequent risk of respiratory diseases, because of poor ventilation and the use of traditional cookstoves and fuels. There are 3 technological breakthroughs than can address some of these health-related problems.

**An easy to operate, affordable, integrated, and solar-powered suite of medical devices specifically for maternal, child and primary care in low resource settings**

Among the many structural challenges in healthcare delivery in developing countries, is the virtual absence of adequately equipped clinics. The majority of clinics, especially in rural areas serving low income populations, lack even the basic amenities, let alone the equipment necessary to provide essential services. To build a clinic with the equipment necessary to provide basic maternal, neonatal and primary healthcare would likely cost in excess of $100,000. This is based on preliminary research on costs of essential medical devices already available on the market including solar panels, lighting, water purifier, ultrasound, IV, suturing, continuous positive air pressure machine, basic infant incubator, sterilizer, medical refrigerator, smart phone, tablet or other computer and imaging device, diagnostics for commonly occurring conditions, and cost of constructing a basic building. In the absence of adequate public funding, this is clearly too expensive for low income populations; by a factor of 10, based on our high-level assessment. In addition, the logistics of procuring the various components and assembling them into a functioning clinic require considerable effort. As such, we believe this type of a suite or a ‘clinic-in-a-box’ can be a significant breakthrough if it:
- Combines the aforementioned devices in an easy-to-install ‘kit’.
- Costs approximately $10,000 - $15,000, based on our high level assessment of financial feasibility, given published data on how much low income rural families in sub-Saharan Africa and South Asia spend on healthcare.
Integrates power management, computation/imaging, data, and communication, so that the various devices are easy to install, use, and replace as necessary.

While some of the listed devices are available at the appropriate price point, many are still priced for industrialized markets. Given the number of groups working towards developing individual devices, we believe enough of them will become available (at the right price point), within the next 3-5 years. Within the same time window, it will be possible to develop a platform to integrate the various devices. However, even once such an integrated suite is developed, it will face a large number of deployment challenges. There is not enough public funding to procure a sufficient number of such clinics, the private market is underdeveloped and fragmented, and the regulatory requirements are unclear. Moreover, significant behavior change, encouraged by some form of insurance or financing to allow affordable access, is required for most low income rural communities to seek regular and formal care. Hence, deployment will be EXTREMELY CHALLENGING.

**Breakthrough 1 – Difficulty of deployment**

Microbicides to provide a method of protection against HIV/AIDS and Human Papillomavirus (HPV), for those who are otherwise vulnerable to infection through sexual contact with their partner

Women, especially those living in societies and situations plagued by gender and income inequality, are often limited in their ability to ensure that their sexual partners use condoms. This risk is exacerbated in places with high rates of sexual violence, and a high prevalence of polygamy. Specific high-risk populations, like sex workers and transgender people, also find themselves restricted in their ability to use protection during sexual contact.
Microbicides are currently under development as vaginal or rectal products designed to protect healthy men and women from HIV/AIDS infection. These products are being tested in multiple forms—vaginal and rectal gels that can be used at the time of sexual contact, and vaginal film, tablets or rings that can slowly release the microbicide drug to provide preventative coverage for up to a month. Unlike vaccines, an effective microbicide must be made into a commodity that individuals will want to and can safely use, on a regular basis. Ideally, microbicides would be discreet (socially acceptable), easy to use, long-lasting, and easy to distribute.

There are several different microbicide candidates currently being studied. In May 2013, 11 phase I trials, 1 phase I/II trial, and 4 phase III trials were underway (AVAC, 2013). Even if a phase III microbicide candidate is found to successfully prevent HIV infection, it will take a few years before it becomes available for use. Any successful product will have to first undergo review and licensing by regulatory agencies. It will also take time to work out the best formulation and dosage, find a suitable delivery method, and identify appropriate distribution channels before the product can be made available to the public. Microbicide gels to prevent HPV, as well as combination microbicides to prevent HIV, HPV and other sexually transmitted infections are also in various stages of development and testing.

Difficulty of deploying microbicides, once available, will depend on human factors, including how easy and convenient they are to use (microbicides require regular reapplication), and whether they are made available to consumers over the counter or by prescription only. To ensure microbicides are widely available to people in low and middle income countries, the price will have to be affordable, and this may mean that profit margins have to be kept low.

Based on the above assessment, the projected time to market readiness is 5-7 years, and the difficulty for deployment is EXTREMELY CHALLENGING.
A new kind of a home—made with strong lightweight material—especially for the urban poor, with a private toilet, solar-powered lighting and ventilation

The majority of the poor live in homes made with found material. In urban shantytowns, these homes are densely packed single-story shacks, which are usually off-grid (or have illegal access to grid power), allow very little light or fresh air, have no running water, and no toilet. This heavily contributes to a range of severe health conditions: illnesses from indoor air pollution, the spreading of infectious diseases like pneumonia and TB, as well as diarrheal diseases because the absence of private toilets or clean and convenient public toilets leads to open defecation. Without addressing the problem of decent living conditions, it is unlikely that remedial medical care will lead to significant gains in health in the long run. Currently, the only option for constructing robust homes is brick and cement, which is far too expensive for the poor. Additionally, the absence of clear land rights—and the threat of eviction—makes such permanent homes a risky investment. A new kind of home, with the characteristics listed below, can contribute to a significant improvement in quality of life:

- Very low cost, so that it is affordable for the poor (recognizing that it will often compete with free, found material).
- Robust, so that it withstands harsh weather, and can potentially support a duplex structure.
- Equipped with basic appliances, e.g., solar-powered LED lighting, and a fan or ventilator.
- Equipped with a private in-home toilet, which can be used even without a connection to running water or drainage systems (in principal the waste can be extracted from outside the home, for disposal).
- Aesthetically pleasing and culturally appropriate.
- Lightweight, so that it can be relocated if necessary.

Such construction material currently does not exist, and it is not clear if there are any efforts underway to develop such material at the right price point. It is also not clear what such material would be made of. As such, we believe such a technology is at least 10 years from becoming a reality. Even when it does become available, there are significant dependencies on behavior change, user finance, and policy changes (e.g., for land tenure). The difficulty of deployment in this case will be EXTREMELY CHALLENGING.
Breakthrough 3 – Difficulty of deployment

<table>
<thead>
<tr>
<th>Difficulty</th>
<th>Policies</th>
<th>Infrastructure</th>
<th>Human capital</th>
<th>Access to user finance</th>
<th>Behavior change</th>
<th>Existing demand</th>
<th>Market fragmentation/Distribution channels</th>
<th>Business model innovation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple</td>
<td></td>
<td></td>
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<tr>
<td>Feasible</td>
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<td></td>
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<tr>
<td>Complex</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Challenging</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extremely Challenging</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

- Highly regulated market with policy changes required
- Requires moderate improvements to infrastructure
- Moderate need to train a limited number of people
- Significant financing required, no identified mechanism
- Significant behavior change needed on daily basis, changes contrary to cultural norms
- Low demand, needs to be built
- No identified deployment model, major hurdles identified
- Highly fragmented, challenging to reach customers

HUMAN RIGHTS

Women often bear the brunt of human rights violations, especially through sexual violence or physical abuse. While this is especially true in the context of conflict, it is far too common in day-to-day life, across geographies and economic classes. In developing countries, particularly, a major challenge in holding perpetrators of sexual violence accountable is the lack of mechanisms to test, preserve and then use biological evidence in the court of law. One breakthrough can make a difference in collecting biological evidence.

**A simple point-of-use, low cost DNA-based rape kit capable of delivering rapid results**

Sexual violence occurs for a whole host of reasons, including gender discrimination, societal and interpersonal power dynamics, and impunity that comes from the lack of accountability. A major challenge is that even if a woman overcomes the stigma associated with being a victim of sexual violence and lodges a formal complaint, there is limited evidence to make a robust legal case. Rape kits—to preserve semen and other degradable biological tissue, and conduct DNA analysis on the samples to match against potential perpetrators—are becoming increasingly common in higher income countries. However, these require skilled technicians and a sophisticated, expensive laboratory to analyze the samples. To be useful in low resource or conflict settings, a rape kit would have to be very low cost (under $10 per test, with the processing equipment not more than a few hundred dollars), usable off-grid, and not require much clinical training to use. In addition, the analysis should be rapid, with the ability to digitize and transmit relevant data for secure (presumably cloud-based) storage. Similar low cost DNA-based technologies being prescribed—and developed—for medical diagnostics, seem to be 3-5 years from becoming available on the market. In principle, a DNA-based rape kit should not take more than 5 years beyond that.
However, once such a technology is developed, it will face significant challenges in deployment, along virtually every dimension. Enough facilities (e.g., health clinics) will need to have the device at hand, those administering the test will need some level of training, and financing will be necessary to cover the costs involved. Without financing it will also be very difficult to ensure a steady supply and maintenance of the kits and the processing equipment. Moreover, policy changes will be necessary to determine how the judicial systems of different countries can best use such evidence in their legal proceedings. But most importantly, the behaviors of victims and the community will still have to evolve considerably. Rape kits can be administered only if a victim seeks help immediately after the incident, while the biological evidence is still intact. In other words, deploying such a technology will be EXTREMELY CHALLENGING.

**Breakthrough 4 - Difficulty of deployment**

<table>
<thead>
<tr>
<th>Difficulty</th>
<th>Policies</th>
<th>Infrastructure</th>
<th>Human capital</th>
<th>Access to user finance</th>
<th>Behavior change</th>
<th>Existing demand</th>
<th>Market fragmentation/Distribution channels</th>
<th>Business model innovation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highly regulated and controversial changes required</td>
<td>Requires national-scale training programs</td>
<td>Requires moderate improvements to infrastructure</td>
<td>Significant behavior change needed on daily basis, changes contrary to cultural norms</td>
<td>Low demand, needs to be built</td>
<td>No identified deployment model, major hurdles identified</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simple</td>
<td>Feasible</td>
<td>Challenging</td>
<td>Complex</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**ECONOMIC OPPORTUNITY**

Women produce 50% of the world’s food. While men may be responsible for the heavy manual labor on farms, women are responsible for the rest of the work, both on and off the farm, like tilling, weeding, and threshing. This work is usually very physically demanding and time consuming. Affordable machines to automate these activities can reduce the workload for women. An important factor to consider is that these machines need not necessarily be affordable to individual farmers, but can potentially be used as a shared commodity, if the community dynamic is supportive. The section on Food Security and Agricultural Development describes, in more detail, the specific issues related to agriculture, but in the context of women, 2 technology breakthroughs are particularly important.
Affordable, lightweight, and fuel efficient solar-powered irrigation pumps

Irrigation is critical for increasing farm yield. The manual (e.g., treadle) pumps currently available are labor intensive and often not suited for the needs of women farmers. Motorized pumps currently on the market require diesel, the cumulative costs of which are high (even though incremental costs might be low). In remote areas, the paucity of distribution mechanisms for diesel is an additional constraint. Affordable solar-powered pumps can be an ideal solution to this problem. A number of organizations are developing solar pumps, and a small number of them are already being used in India. But, the biggest hurdle appears to be throughput—the more the volume of water pumped, the larger and more expensive the solar panel. Considering the effort being dedicated to this problem and the pace with which this market is developing, it is likely that affordable and efficient pumps will become available within the next 2-3 years.

However, even if solar pumps become available, a number of deployment hurdles will need to be tackled; the majority of smallholder farmers in South Asia and sub-Saharan Africa are still extremely poor, live in remote areas, and are used to rain-fed farming. Considerable effort will be necessary for creating demand, providing finance, and training. A critical lesson from the decades of agricultural development in South Asia, is that water can easily be overused, and groundwater easily depleted. It will be important to consider regulating water use in tandem with deploying such pumps, so that irrigation water is used sustainably. Needless to mention, enforcing any such regulations will be very challenging. Hence, we believe that deployment will be COMPLEX.
An affordable mechanized tilling or weeding tool

The Striga family of weeds is the single largest cause of on-farm losses for smallholder farmers. Currently, the only way farmers in Africa deal with the weeds, is to spend countless hours pulling them by hand. Indeed, the quintessential image of the act of weeding, is an African woman hunched over, pulling out weeds. Not only is this physically exhausting, but by the time the weeds are visible on the surface, the damage has already been done to the roots of the crops that the farmers sowed for the coming season. Mechanized tillers used by farmers in industrialized countries are far too expensive for the African context, and typically need diesel. A low cost tiller that is either fully or partially mechanized and not dependent on diesel can help African farmers remove weeds before planting.

The obvious technical challenge is to generate enough force to dig through dry—often hard—soil, with as little fuel input as possible. This problem is the same as those involving mechanization across a range of work genres—creating a higher mechanical advantage using limited input force. Machines supplemented by human energy (e.g., pedal-power machines using a bicycle like movement) have been used to run some devices, but the amount of power generated by such machines (typically 0.5 horsepower or less) tends to be significantly less than what is required for mechanized tilling (the smallest mechanized tillers tend to be 3-5 horsepower). The solution likely lies in some combination of human or animal-supplemented power, solar power, and a highly efficient engine. In principle, such a machine should not be complicated to build, but will require considerable field testing to understand operating parameters in various types of soil. There is reason to believe that such an implement can be on the market within the next 3-5 years.

However, even once such an implement becomes available, many farmers may not see the value in investing in mechanized tilling, since they are accustomed to pulling out the weeds after they become visible. Beyond that, such an implement will face the usual challenges of a highly fragmented market, sparse distribution networks, and limited financing options for smallholder farmers. Therefore, we believe that the difficulty of deployment will be CHALLENGING.

Breakthrough 6 – Difficulty of deployment
Throughout human history, changing the natural environment in the interest of human welfare and economic output has been an integral part of development efforts. These direct or first-order environmental changes have been hugely beneficial to humans, and were the basis of fundamental human advances—the Agricultural and Industrial Revolutions. However, as the scale of human enterprise increases relative to the scale of natural processes (i.e. those not managed by people), a growing number of indirect or second-order environmental consequences can be seen. Activities that previously were overwhelmingly beneficial now bring both positive and negative effects on human welfare. There are a number of pathways through which environmental changes may significantly impact human development, but direct cause-and-effect has not been clearly articulated, yet. Here we seek to understand the complex chain of events linking environmental change and human welfare.

We identify 7 broad categories that comprehensively describe the first-order environmental changes caused by human actions. Ranging in nature from biotic changes of living organisms to geochemical changes of the physical planet, these direct environmental changes are: altered species
and population distributions, lower ecosystem complexity, land cover change, carbon cycle alteration, water cycle alteration, nitrogen cycle alteration, and alteration of other geochemical cycles. We further establish the link between these first-order changes and their second-order consequences, including pollution, deforestation, rising sea levels, groundwater depletion, and soil erosion among others. These indirect consequences lead to human development challenges in terms of food security, health, human displacement, and conflict.

Second-order environmental consequences that pose major threats to food security include more frequent and severe droughts and floods, soil loss due to erosion, crop yield reductions due to warmer temperatures, irrigation constraints due to groundwater depletion (especially in South Asia), and long-term constraints on plant nutrient sources. Major threats to human health include water pollution that leads to diarrheal diseases, household air pollution due to indoor burning of solid fuels, altered disease vectors and extreme weather events due to climate change, and outdoor air pollution and environmental toxins. Threats of human displacement are expected for coastal populations affected by rising sea level, desertification leading to abandoned farmland due to untenably low agricultural yields, and agricultural yield limits due to irrigation constraints (especially in South Asia). Threats related to conflict involve questions of control of increasingly limited natural resources, including global markets for fossil fuels and mineral ores, as well as local needs such as water and grazing land.

Identifying solutions to human development challenges arising from environmental change is especially problematic, precisely because the changes have occurred due to human efforts towards development. Many non-technological hurdles exist that may constrain successful mitigation and/or adaptation to environmental change. These include a lack of effective regulatory and enforcement mechanisms, lack of adequate economic means to commit to solutions, and lack of economic incentives among key decision-makers and stakeholders.

Focusing on scientific and technological solutions, many of the breakthroughs identified in other chapters are equally relevant to issues of resilience to environmental change. For example, relevant breakthrough technologies include improved sanitation for human waste, precision irrigation systems, detection and sustainable utilization of groundwater resources, and soil nutrient analysis, as highlighted in our Global Health and Food Security and Agricultural Development sections. Beyond these, we identify 6 technological breakthroughs that could address some of the challenges of environmental change.

- A scalable, low cost method to desalinate water using renewable energy
- Low cost system for precision application of agricultural inputs, ideally combining fertilizers and water
- A scalable method for sustainable integrated aquaculture production
- Affordable homes that are resilient to extreme weather events, for the poor
- A retrofitted filter to reduce particulate matter exhaust from old heavy-duty vehicles
- Low cost, distributed monitoring sensors to identify environmental toxins and their concentrations
By now, there is ample evidence to demonstrate that climate change is already here. As the 2014 Intergovernmental Panel on Climate Change (IPCC) report points out, its effects are being felt; and they will continue to worsen, with vulnerable populations in low income countries bearing the brunt of phenomena like extreme weather events, higher temperatures, rising sea levels, and shifting rainfall patterns. As bad as the impact of climate change on these populations is, it is only a part of the larger problem. In much of the developing world, the combination of broad poverty, rapid economic growth in some populations segments, and the lack of political will and appropriate regulation, has led to significant damage to the environment: outdoor air is polluted because of automobile exhaust; indoor air is polluted due to poor ventilation and cooking methods; water systems are full of fecal pathogens; urban slums accumulate mountains of trash; and whatever factories there are, often feel unencumbered to pollute the air, water and land with toxins.

With the above context in mind, this section analyzes the needs of low income populations globally, through the following analytical lenses:

- We begin by examining which specific human actions lead to which specific direct or first-order environmental changes. We then try to connect these first-order environmental changes to detrimental indirect or second-order environmental consequences. This broad set of issues includes the various phenomena linked to climate change.

- We analyze the aggregate impact of first-order environmental changes and second-order consequences on low income human populations, within the 2050 time horizon. We fully recognize that there are a number of additional major threats that these populations will face beyond 2050, and that environmental change is taking a tremendous toll on other forms of life on the planet, but those aspects go beyond the scope of our study at present.

- Finally, we focus only on those actions that can be taken in developing countries. We recognize that in many cases (such as climate change), it is the actions of industrialized countries that are causing much of the damage. However, we believe that other studies (e.g., the IPCC report) are already addressing actions that must be taken by industrialized countries to mitigate such changes.
To satisfy our human needs and desires, we modify our surrounding natural environment in many ways. We cause various direct, or what we term here as first-order, environmental changes—ranging in nature from biotic to geochemical—that enable provision of goods and services in the food, household and industrial sectors. While these first-order environmental changes bring huge benefits to humans, they also have indirect or second-order consequences that pose risks and challenges to human wellbeing in the longer term. Human-caused first-order environmental changes have increased rapidly during the past 100 years, and many second-order consequences are now becoming conspicuous. Some of these second-order effects may cause significant negative human development impacts related to food security, health, conflict, and human displacement.

We propose a new analytical framework to explain the links between environmental change and human development

There are numerous pathways through which environmental changes can seriously impact human development, but direct cause-and-effect has not yet been clearly articulated. We propose a new analytical framework (Exhibit 1), that links human actions to first-order environmental changes, to second-order environmental consequences, and ultimately to human development impacts. These linkages are mapped and further explained later in this section in Exhibit 2, Exhibit 10 and Exhibit 11. Together, they seek to explain the complex chain of events linking environmental change and human welfare.

Linkage between human actions, environmental changes and human development

Exhibit 1: While human-caused environmental changes bring many intended benefits, these changes also lead to indirect consequences that pose long-term challenges. These linkages are mapped and detailed in Exhibits 2, 10 and 11.

As the focus of this report is global human development, this analysis is explicitly conducted from an anthropocentric perspective; we ask how environmental changes will affect human wellbeing. We acknowledge that an assessment of environmental change could be made from other perspectives, e.g. bio-centric or eco-centric, which may yield other conclusions based upon different priorities. Further acknowledging the long-term characteristics of environmental change and sustainability issues, our
main interests here are the implications for global development within the next human generation, i.e. until about 2050.

2. Seven first-order environmental changes caused by human actions

We humans carry out a range of actions in our quest for a better quality of life, stemming from our needs and choices regarding production and consumption in the food, household, and industrial sectors. To enable production of adequate food for the growing human population, we convert land that is ‘wild’ (i.e. not controlled by human influence), into managed cropland, pastures and orchards. We select certain animals to be domesticated, and care for these species while we actively exclude all other animal species. We favor a relatively small number of plant species such as wheat, rice and maize, and we cultivate these species across huge areas of cropland. All other plant species are considered ‘weeds’ and are eliminated by soil tillage or chemical poisons. We operate irrigation systems to provide water needed for the growth of our favored plants, and we apply chemical fertilizers to the land to provide for their nutrition.

To provide comfortable and healthy household conditions, we convert more wild land to create urban settlements. Within our houses we consume water, food and fuels, and we produce a range of waste products. Households with access to mechanized personal transport, such as automobiles and buses, consume additional fuels to gain mobility.

The food and household sectors are supported by an elaborate industrial system to process and use a wide variety of materials from the environment. This involves conversion of additional wild land for industrial purposes, such as mining and timber production. Raw materials are extracted, refined and processed to become consumer goods. Additional resources, such as water and energy, are also used in manufacturing processes. We generate electricity by various means, and distribute it for many uses. We create vast multi-modal cargo transportation networks, and shift natural resources globally to suit our needs. Our systems for managing wastes, however, are typically less elaborate, and for convenience waste materials are often discarded into our surroundings.

Exhibit 2 lists various examples of these human actions, and describes the first-order environmental changes caused by them. Adapting from Vitousek (1997), we identify 7 broad categories (listed below) that comprehensively describe the first-order environmental changes caused by human actions. There are significant interactions between these 7 categories.

- Humans now largely determine species and population distributions
- Humans are making ecosystems simpler and less diverse
- Humans significantly change the land cover when we use land
- Humans have significantly altered the natural carbon cycle
- Humans have significantly altered the natural water cycle
- Humans have significantly altered the natural nitrogen cycle
- Humans have significantly altered other geochemical cycles
### Exhibit 2: Mapping of select human actions (food production, household activities, and industrial activities), to first-order environmental changes.

#### Human actions (examples)

<table>
<thead>
<tr>
<th>Human actions (examples)</th>
<th>Biotic changes</th>
<th>First-order environmental changes</th>
<th>Geochemical Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Food production</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land conversion</td>
<td></td>
<td>Conversion from wild to domesticated species</td>
<td>Increased soil erosion</td>
</tr>
<tr>
<td>(Wild land &gt; agricultural land)</td>
<td></td>
<td>Relative simplicity of agro-ecosystems</td>
<td></td>
</tr>
<tr>
<td>Soil tillage</td>
<td></td>
<td>Soil exposed to wind and rain</td>
<td>Altered soil carbon</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Plant and soil community disturbance</td>
<td>Altered water runoff and quality</td>
</tr>
<tr>
<td>Animal Husbandry</td>
<td></td>
<td>Simple system of managed species</td>
<td>Nutrients for animals</td>
</tr>
<tr>
<td>(intensive/extensive)</td>
<td></td>
<td>Land use for pastures</td>
<td>Nutrients for animals</td>
</tr>
<tr>
<td>Irrigation</td>
<td></td>
<td>Crop plant range is expanded</td>
<td>Watered management for irrigation</td>
</tr>
<tr>
<td>Fertilizer production and use</td>
<td></td>
<td>Expands range of agriculture</td>
<td>Salinization of irrigated land</td>
</tr>
<tr>
<td>Pesticide/herbicide use</td>
<td></td>
<td>Loss of target species</td>
<td>Nitrogen leaching via nitrification-process</td>
</tr>
<tr>
<td>Killing/consumption of wildlife</td>
<td></td>
<td>Population reduction from overexploitation</td>
<td>Mining and application of phosphorus</td>
</tr>
</tbody>
</table>

#### Household/domestic activities

<table>
<thead>
<tr>
<th>Human actions (examples)</th>
<th>Biotic changes</th>
<th>First-order environmental changes</th>
<th>Geochemical Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land conversion</td>
<td></td>
<td>Conversion from wild to human habitation</td>
<td>Mining of construction materials</td>
</tr>
<tr>
<td>(Wild land &gt; urban land)</td>
<td></td>
<td>Relative simplicity of urban ecology</td>
<td></td>
</tr>
<tr>
<td>Indoor solid fuel burning</td>
<td></td>
<td>Harvest of wood for charcoal</td>
<td>Contaminants in fuel</td>
</tr>
<tr>
<td>Mechanized public transport</td>
<td></td>
<td>Land cover by road infrastructure</td>
<td>NOx emission from vehicles</td>
</tr>
<tr>
<td>Household water consumption</td>
<td></td>
<td>Carbon in fossil fuels</td>
<td>Lead added to groundwater</td>
</tr>
<tr>
<td>Waste sewage disposal</td>
<td></td>
<td>Water supply infrastructure</td>
<td>Nitrogen content of sewage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Methane from decomposition</td>
<td>Phosphorus content of sewage</td>
</tr>
</tbody>
</table>

#### Industrial activities

<table>
<thead>
<tr>
<th>Human actions (examples)</th>
<th>Biotic changes</th>
<th>First-order environmental changes</th>
<th>Geochemical Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land conversion</td>
<td></td>
<td>Conversion from wild to managed forest</td>
<td>Various elements, e.g., iron, zinc</td>
</tr>
<tr>
<td>(Wild land &gt; industrial land)</td>
<td></td>
<td>Relative simplicity of managed forests</td>
<td></td>
</tr>
<tr>
<td>Extraction and processing of mineral raw materials</td>
<td></td>
<td>Land cover by mines and quarries</td>
<td>Carbon in fossil fuels, cement</td>
</tr>
<tr>
<td>Mechanized cargo transport</td>
<td></td>
<td>Land cover by road infrastructure</td>
<td>NOx emission from vehicles</td>
</tr>
<tr>
<td>Material processing and fabrication</td>
<td></td>
<td>Carbon in fossil fuels</td>
<td>Lead added to groundwater</td>
</tr>
<tr>
<td>Electricity generation and distribution</td>
<td></td>
<td>Carbon in fossil fuels</td>
<td>Industrial material and by-products</td>
</tr>
<tr>
<td>Industrial water consumption</td>
<td></td>
<td>Water supply infrastructure</td>
<td>NOx emission from power plants</td>
</tr>
<tr>
<td>Waste disposal</td>
<td></td>
<td>Land cover by waste sites</td>
<td>Air emission of e.g., chlorine</td>
</tr>
</tbody>
</table>

#### Legend:

- Little effect
- Moderate effect
- Strong effect
- Very strong effect
Humans now largely determine species and population distributions

While humans were once a minor species struggling for existence in a landscape largely full of wild animals and plants, we have now dominated most land ecosystems. By favoring and domesticating certain plant and animal species, humans have developed extensive agricultural ecosystems and caused substantial changes in the number and range of many other organisms. Three types of wild grasses, wheat, rice and maize, have been domesticated and reproduced to such an extent that they now comprise the 3 most abundantly cultivated plants on earth. Domesticated animals are fed and protected by humans, while other animals that threaten them are killed or expelled. Our analysis demonstrates the current dominance of humans and domesticated animals over land by comparing the total mass of different animal species, in terms of carbon content in their collective biomass in living bodies (Exhibit 3). Living humans are estimated to contain about 45 million metric tons (Mt) of carbon; domesticated animals maintained by humans have about 130 Mt of carbon (Smil, 2003) (UN, 2013) (FAOSTAT, 2014) (Dirzo, et al., 2014). These quantities have more than doubled since 1950. In contrast, the biomass of all wild land vertebrates including mammals, birds and reptiles contains less than 5 Mt of carbon, and is steadily decreasing. Humans now largely control which animals live in most land areas of the world. However, human dominance does not extend to the smaller creatures, including the nearly 700 Mt of carbon in invertebrates (e.g. insects), approximately 4000 Mt in fungi, and about 20,000 Mt in soil bacteria (Smil, 2003).

**Biomass of human and animal species since 1950**

- **Wild land vertebrates**
- **Domesticated animals**
- **Humans**

![Exhibit 3: Humans and domesticated animals dominate over all other land animals. This figure shows the estimated amount of carbon contained in the living bodies of all humans, domesticated animals, and wild land vertebrates (mammals, birds, reptiles, etc.).](image-url)
Humans are making ecosystems simpler and less diverse
The population shift from wild to domesticated animals and plants necessarily involves the simplification of the structure and functioning of ecosystems. Humans are causing ecosystems to lose complexity at several levels: species diversity (the number and variety of species), genetic diversity (the genetic possibilities a species contains), and ecosystem diversity (the variation between global ecosystem characteristics) (MEA, 2005). The distribution of species on earth is becoming more homogenous, meaning that the differences are, on average, diminishing between the group of species at one location on the planet and groups at other locations. Different types of species evolved in ecosystems in different regions, through the combination of natural barriers to migration and local adaptations. These regional differences in the biota of the earth are now diminishing. Genetic diversity, which serves as a way for populations to adapt to changing environments, is being lost.

Species tend to come and go, evolutionarily speaking, but human actions are now causing species extinction at a rate 1000 times greater than the natural background rate of extinction (Pimm, et al., 2014). This ongoing simplification is illustrated in Exhibit 4, based on the Living Planet Index that is calculated periodically by WWF International (WWF, 2014). This index estimates changes in the state of the planet’s biodiversity, using trends in population size for vertebrate species from different biomes and regions to estimate average changes in abundance over time (Collen, et al., 2008). Trends in the Living Planet Index suggest that across the globe, wild populations of vertebrate animals were on average 52% smaller in 2010 than they were in 1970. The greatest reductions occurred in tropical regions, in particular the Neotropical biogeographical area that includes South and Central America, and the Indo-Pacific area that includes South Asia and Australasia. Temperate regions show smaller reductions, largely because those lands were cleared for agricultural use long before 1970, and now include abandoned farmlands that are reverting to natural growth. Acknowledging the imprecision of such simple proxy indicators, the global trends toward lower biodiversity and simpler ecosystems are robust.

Change in animal biodiversity since 1970

<table>
<thead>
<tr>
<th>Region</th>
<th>-100%</th>
<th>-75%</th>
<th>-50%</th>
<th>-25%</th>
<th>0%</th>
<th>25%</th>
<th>50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Afrotropical</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Nearctic</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Palearctic</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Indo-Pacific</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neotropical</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Global</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Exhibit 4: Regional and global biodiversity has generally decreased in recent decades, as estimated by WWF’s Living Planet Index, based on wild populations of vertebrate animals between 1970 and 2010. Error bars represent 95% confidence limits. The 5 regions are biogeographic realms, where terrestrial species have evolved in relative isolation over long periods of time. Afrotropical includes sub-Saharan Africa. Nearctic includes North America. Palearctic includes Europe, North Africa, the Middle East, and most of Asia. Indo-Pacific includes South Asia and Australasia. Neotropical includes South and Central America (WWF, 2014).
Humans significantly change the land cover when we use land

Human use of land typically alters the interface between the atmosphere and the geosphere, affecting interactions between land, plants, air and water. For example, land cover largely determines the partitioning of precipitation into evapotranspiration, runoff, and groundwater flow. Humans have, over a span of centuries, converted land once covered by wild forests and grassland into cropland and pastures. Exhibit 5 shows that about 10 million km$^2$ of forest land has been lost during the last three centuries (Ramankutty & Foley, 1999) (Pongratz, et al., 2008) (FAO, 2010) (World Bank, 2013). Cropland area (the extent of which may vary, depending on the definition used), increased by about 15 million km$^2$ during the same period. The rates of forest land decrease and cropland increase have remained fairly steady over the last 300 years, though have accelerated somewhat since about 1850. The current rate of deforestation is in line with this centuries-old trend, and direct human occupation of land continues to expand.

Exhibit 5: Over the last 3 centuries, humans have converted about 10 million km$^2$ of forest land to other uses, and have turned about 15 million km$^2$ of land into agricultural cropland. During the same period, natural grassland area has decreased, and pasture land area has increased (not shown in figure).

Humans have significantly altered the natural carbon cycle

Carbon is a chemical element, and natural forces cause it to cycle in various forms and rates. Carbon cycles on the earth between the atmosphere as carbon dioxide gas, in the biosphere as organic carbon compounds, in the oceans as dissolved carbon dioxide, and in the lithosphere as carbonate and hydrocarbon minerals. Humans have significantly changed natural carbon cycling by altering living biomass due to land use change, and by shifting carbon from geologic storage in the form of fossil fuels, into the atmosphere in the form of carbon dioxide. Humans have long influenced land cover, even before the introduction of agriculture. For example, fire has long been a relatively easy and effective way for
small-scale societies to reshape the vegetation communities in their regions, to increase the relative abundance of preferred plant and animal food resources (Smith, 2011). During the last century, however, the use of fossil fuels in the form of coal, oil, and gas has become the primary source of human-caused carbon emissions (Exhibit 6) (Le Quéré, et al., 2014) (Houghton, et al. 2012) (Boden, et al., 2013). Humans seek to extract and use the chemical energy stored in fossil hydrocarbon fuels. In doing so, carbon in the fuel changes into a more stable form, carbon dioxide. Currently, about 9 billion metric tons of carbon—over 200 times more than the amount of carbon in all living humans (Exhibit 3)—is emitted each year from fossil fuel use (IPCC, 2013). Another 0.5 billion ton of carbon is emitted each year during cement production, when a raw material (calcium carbonate) is heated in manufacturing kilns, creating carbon dioxide as a waste product. About 1 billion ton of carbon is currently emitted per year, due to land use. There are vast differences in the country-level emissions that comprise these global totals: lower income countries have relatively low emission levels that are dominated by land use, while higher income countries have much higher emission levels that are primarily due to fossil fuel use (IPCC WG3, 2014).

**Exhibit 6: Land use change (such as deforestation) had long been the dominant human-caused source of carbon dioxide (CO₂) emissions. During the last 100 years, emissions from the combustion of fossil fuels (coal, oil, natural gas) have increased considerably and are now the largest source of emissions. Process emissions from cement manufacture are shown here as fossil fuel emissions, and comprise about 5% of those emissions.**

Between 1750 and 2011, the combustion of fossil fuels and the production of cement have released a cumulative total of about 375 billion metric tons of carbon—over 8,000 times more than the amount of carbon in all living humans. Land use change since 1750, mainly deforestation, has released an additional 180 billion metric tons of carbon. Clearly, humans have a disproportionately large effect on the global carbon cycle. These large and sustained emissions of carbon dioxide have steadily increased the concentration of that gas in the atmosphere. For at least 2 million years prior to the industrial era (i.e. before 1750), the concentration of carbon dioxide in the atmosphere had fluctuated between
Humans have significantly altered the natural water cycle

Water cycles naturally, from when it falls as rain or snow, flows downhill in soils and rivers, may be drawn up into living plants, and eventually returns to the atmosphere as water vapor, from which it falls again. Human actions have changed this cycle in several ways, some intended and others unintended (Meybeck, 2003). Management of the water cycle has improved human wellbeing by controlling floods, generating hydroelectricity, providing transportation, and irrigation. Humans have changed the patterns of surface water flow, e.g. by impounding river water behind dams, and by reducing rainwater infiltration through paved surfaces. Exhibit 7 shows that artificial reservoirs now have the capacity to hold about as much water as contained in Lake Michigan, one of the great lakes of North America (Vörösmarty & Sahagian, 2000) (van der Leeden, et al., 1990). In densely populated areas of the world, actions such as river engineering, water withdrawals, and waste dumping have significantly changed the water and material transfers through river systems, such that these actions now likely exceed the influence of natural drivers (MEA, 2005). Surface runoff and river discharge generally increase when natural vegetation (especially forest) is cleared. Such actions to manage and control water flows have involved environmental trade-offs, including fragmentation and loss of habitat for other organisms, biodiversity loss, and changes in sediment transport.

**Global water storage capacity in artificial reservoirs since 1900**

Exhibit 7: Human alterations to the water cycle, including intercepting and storing water flows, have increased substantially during the last century. Construction of dams and reservoirs increased significantly after 1950. By 1960 the total water storage capacity within artificial reservoirs globally was equivalent to that of Lake Ontario; by 1980 it was equal to Lake Huron. Currently, human-created reservoirs have the capacity to hold about as much water as there is in Lake Michigan.

In addition to changing the amount and timing of water flows, humans have also changed the quality of water by using water bodies like rivers, lakes and oceans as a dumping ground for biological wastes (e.g. sewage) and inorganic pollutants. Pollution is typically an unintended consequence of other
Humans have significantly altered the natural nitrogen cycle

Nitrogen comprises about 78% of earth’s atmosphere. However, it typically exists in the very stable N\textsubscript{2} form, with two nitrogen atoms bound tightly together, unwilling to form partnerships. Nitrogen is essential to life on earth, as it is needed to make amino acids, nucleotides and other basic building blocks of plants, animals and other life forms. A limited amount of nitrogen, known as reactive nitrogen, is ‘fixed’ from the atmosphere and then made available to living organisms in a more reactive form. There are several natural routes of nitrogen fixation, including by particular bacteria living in symbiosis with some types of plants. Humans have long managed croplands to incorporate these types of plants within crops rotation systems, to fix a modest amount of nitrogen within agroecosystems. During the last 50 years, the amount of nitrogen that is fixed through human actions has increased steadily, and now occurs at a scale similar to that of all natural land ecosystems (Robertson & Vitousek, 2009) (Exhibit 8). Most of this increase is due to fertilizer production using the Haber-Bosch process (described in the chapter on fertilizers and soil health, in the section on Food Security and Agricultural Development). The temporary reduction in nitrogen fertilizer production during the early 1990s was due to the collapse of the Soviet Union. Other human actions that fix atmospheric nitrogen include fuel combustion and managed biological fixation. This alteration of the nitrogen cycle has allowed us to grow significantly more food for consumption than otherwise would be possible. However, the increased overall availability of nitrogen fertilizer, coupled with the difficulty of precisely targeting application to ensure maximum absorption by plants, has led to nitrogen runoff well beyond the farmlands the fertilizer is applied to.

Reactive nitrogen fixed by human actions

Exhibit 8: Human production of reactive nitrogen has increased substantially during the last 50 years, and now occurs at the same rate as it does in all natural land ecosystems put together. Most of this increase is due to fertilizer production using the Haber-Bosch process, using natural gas as feedstock (MEA, 2005).
Humans have significantly altered other geochemical cycles

In terms of shaping the surface of the earth, humans now cause about 10 times more erosion and sedimentation than that caused by glaciers, rivers, and other natural processes combined (Wilkinson, 2005). From intentional transport of construction materials and mineral ores, to unintentional facilitation of natural erosion processes through soil tillage, humans have become the dominant geologic force on the planet. In addition to soil erosion and alterations to the carbon, nitrogen and water cycles, humans are affecting changes to other global geochemical cycles at various scales of time and place. An important example is the chemical element phosphorus, which is an essential nutrient for plant growth. Phosphorus fertilizers are important because of the slow natural cycling of phosphorus, the low solubility of natural phosphorus-containing compounds, and the essential nature of phosphorus to living organisms. Traditional sources of agricultural phosphorous are animal manure and guano (bird droppings). Exhibit 9 shows that phosphate rock mining expanded considerably after 1950, and is now the dominant source of phosphorous fertilizer, an essential input to intensive agriculture (Cordell, et al., 2009). The countries currently mining the most phosphate rock include China, US and Morocco (USGS, 2014). Global reserves of phosphate are concentrated in the Western Sahara region of Africa, a disputed region controlled by Morocco. Sustained disruption of supply, whether due to geological or geopolitical forces, would significantly affect food security (Dawson & Hilton, 2011).

Sources of phosphorous fertilizer since 1800

Exhibit 9: Mining of phosphate rock expanded considerably after 1950, and is now the dominant source of phosphorous fertilizer used in agriculture (Cordell, et al., 2009).
First-order environmental changes cause a variety of second-order environmental consequences

The first-order environmental changes described so far have mainly brought positive benefits for human populations, including provision of basic needs like food and shelter. Indeed, these changes were made primarily to improve the quality of our lives. However, as the scale of human enterprise increases relative to the scale of natural (i.e. not managed by people) processes, a number of indirect or second-order consequences can be identified. Activities that were previously overwhelmingly beneficial now bring both positive and negative effects on human welfare.

Exhibit 10 shows how first-order environmental changes lead to second-order environmental consequences for human populations. These are unintended consequences that result from the first-order changes brought about by human activities as described in Exhibit 2. As illustrated in Exhibit 1 earlier, and now in a sectional view reproduced below, second-order environmental consequences have significant human development impacts.

- Groundwater depletion
- Water pollution
- Soil erosion
- Household air pollution
- Outdoor air pollution
- Environment toxicity
- Global average temperature rise
- Change in average precipitation
- Extreme weather events
- Sea level rise
- Ocean acidification
- Deforestation
- Reduced wild food
- Non-renewable resource depletion

- Food security
- Health
- Human Displacement
- Conflict

Some of these second-order environmental consequences manifest locally, close to the human actions that provoked them, and others are seen globally. For example, household air pollution occurs immediately within a building where solid fuels are burned for cooking. Climate change, on the other end of the spectrum, is a global phenomenon regardless of where greenhouse gases are emitted.
## Second-order environmental consequences of first-order environmental changes

<table>
<thead>
<tr>
<th>First-order environmental changes</th>
<th>Second-order environmental consequences (examples)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biotic changes</td>
<td>Second-order environmental changes</td>
</tr>
<tr>
<td>Species distribution</td>
<td>Groundwater depletion</td>
</tr>
<tr>
<td>Lower ecosystem complexity</td>
<td></td>
</tr>
<tr>
<td>Land cover change</td>
<td>Water pollution</td>
</tr>
<tr>
<td>Carbon cycle alteration</td>
<td>Soil erosion</td>
</tr>
<tr>
<td>Water cycle alteration</td>
<td>Household air pollution</td>
</tr>
<tr>
<td>Nitrogen cycle alteration</td>
<td>Contaminants in fuels</td>
</tr>
<tr>
<td>Other geochemical cycles</td>
<td>Outdoor air pollution</td>
</tr>
<tr>
<td>Reduced infiltration of precipitation</td>
<td></td>
</tr>
<tr>
<td>Sediment flow due to soil erosion</td>
<td>Combustion of solid fuels</td>
</tr>
<tr>
<td>Organic matter in sewage</td>
<td>Combustion of fossil fuels</td>
</tr>
<tr>
<td>Waste dumping into water bodies</td>
<td>N2x from vehicles and industry</td>
</tr>
<tr>
<td>Sewage and fertilizer runoff</td>
<td>Contaminants in fuels</td>
</tr>
<tr>
<td>Other pollutants</td>
<td>Industrial use of heavy metals, POPs, etc.</td>
</tr>
<tr>
<td>Soil erosion</td>
<td>Environmental toxicity</td>
</tr>
<tr>
<td>Loss of soil cover plants</td>
<td>Emission of CH4 from livestock</td>
</tr>
<tr>
<td>Simpler plant communities</td>
<td>Net emission of CO2</td>
</tr>
<tr>
<td>Soil exposed to wind and rain</td>
<td>Emission of CH4 and CO2</td>
</tr>
<tr>
<td>Altered water flows and landform</td>
<td>Emission of N2O</td>
</tr>
<tr>
<td>Soil erosion</td>
<td>Emission of other GHGs</td>
</tr>
<tr>
<td>Burning of land cover</td>
<td>Global avg. temperature rise</td>
</tr>
<tr>
<td>Combustion of fossil fuels</td>
<td>Change avg. precipitation</td>
</tr>
<tr>
<td>N2x from vehicles and industry</td>
<td>Extreme weather events</td>
</tr>
<tr>
<td>Contaminants in fuels</td>
<td>Sea level rise</td>
</tr>
<tr>
<td>Industrial use of heavy metals, POPs, etc.</td>
<td></td>
</tr>
<tr>
<td>Creation of synthetic organic chemicals</td>
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</tbody>
</table>

### Exhibit 10: Mapping of first-order environmental changes to second-order environmental consequences.

(GHGs are greenhouse gases, CO2 is carbon dioxide, CH4 is methane, and POPs are persistent organic pollutants)

Second-order environmental consequences lead to significant impacts for low income human populations

### Exhibit 11 indicates how second-order environmental consequences lead to challenges for human development, including issues of food security, health, human displacement, and conflict. Major threats to food security include more frequent and severe droughts and floods, soil loss due to erosion, crop yield reductions due to warmer temperatures and/or untimely precipitation, irrigation constraints due to groundwater depletion (especially in South Asia), and long-term limitations on nutrient supplies. Major threats to human health include diarrheal diseases due to water pollution, chronic respiratory and lung diseases caused by household air pollution due to indoor burning of solid fuels, altered disease vectors and extreme weather events due to climate change, and outdoor air pollution and environmental...
Groundwater depletion will constrain irrigated agricultural production, especially in South Asia. As described in detail in the section on Food Security and Agricultural Development, irrigation plays a key role in global food security. While only an estimated 18% of global cropland is irrigated, that land accounts for 40% of global food production (Schultz, 2001). There are two types of groundwater sources used for irrigation. The first are renewable groundwater sources, in which the groundwater is periodically replenished when sufficient precipitation infiltrates the soils or when floodplains become inundated. The second type are non-renewable or fossil groundwater sources, which are typically locked in deep aquifers that have little or no long-term source of replenishment. When this water is extracted, it is effectively

The impact of second-order environment consequences on human development by 2050

<table>
<thead>
<tr>
<th>Second-order environmental consequences (examples)</th>
<th>Impacts on human development by 2050</th>
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<tbody>
<tr>
<td>Groundwater depletion</td>
<td>Food Security</td>
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<td></td>
<td>Limited supply of irrigation water (SA)</td>
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<td>Water pollution</td>
<td>Diarrheal diseases and other health issues</td>
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<tr>
<td>Soil erosion</td>
<td>Loss of fertile soil and crop yields</td>
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<td>Household air pollution</td>
<td>Burning of solid fuels indoors</td>
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<td>Outdoor air pollution</td>
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<td>Environmental toxicity</td>
<td>Contamination of food products</td>
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<tr>
<td>Global avg. temperature rise</td>
<td>Reduced crop yields, expanded pest vectors</td>
</tr>
<tr>
<td>Change avg. precipitation</td>
<td>Long-term reduction in water supply (SSA)</td>
</tr>
<tr>
<td>Extreme weather events</td>
<td>Food production impacts by droughts and floods</td>
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<tr>
<td>Sea level rise</td>
<td>Land inundation and groundwater salinization</td>
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<td>Ocean acidification</td>
<td>Change in supply of ocean foods</td>
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<td>Deforestation</td>
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<td>Reduced wild food</td>
<td>Reduction in wild fish stock</td>
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<tr>
<td>Non-renewable resource depletion</td>
<td>Energy for Haber-Bosch process, phosphorous</td>
</tr>
</tbody>
</table>

Exhibit 11: Mapping of second-order environmental consequences to likely impacts on human development by 2050 (SA is South Asia and SSA is sub-Saharan Africa).
‘mined’ and the aquifer will eventually be depleted. Globally, about 18% of gross irrigation water demand for the year 2000 was met with non-renewable groundwater extraction (Wada, et al., 2012). Exhibit 12 shows the sources of water used globally for irrigation in 1960 and 2000, during which time the share of non-renewable groundwater increased from 12% to 18%. In absolute terms, the use of non-renewable groundwater more than tripled, from 75 to 230 cubic kilometers per year.

Exhibit 12: Between 1960 and 2000, the share of non-renewable groundwater increased from 12% to 18% of global gross irrigation water. The share of non-local water resources, transported to the regions via canals and pipelines for example, increased from 15% to 19% of global gross irrigation water. Renewable local water comprised a smaller share of global gross irrigation water in 2000 than in 1960. In absolute terms, gross irrigation water use increased two-fold (from 630 to 1340 cubic kilometers per year), and non-renewable groundwater use increased three-fold (from 75 to 230 cubic kilometers per year), between 1960 and 2000. Relatively few countries (described in Exhibit 13) are responsible for most of the non-renewable groundwater use (Wada, et al., 2012).

Relatively few countries, including India, Pakistan and USA, are responsible for most of the non-renewable groundwater use (Gleason, et al., 2012). Exhibit 13 shows that India used more non-renewable groundwater for irrigation than any other country, in year 2000. About 19% of India’s irrigation water came from non-renewable sources. Other countries used smaller amounts of non-renewable water, but it comprised larger proportion of their total irrigation water use. In both Pakistan and USA, the share of non-renewable groundwater was 24%; in Iran it was 40%. In Libya and Saudi Arabia, over 70% of irrigation water was sourced from non-renewable groundwater (Wada, et al., 2012).
Groundwater depletion affects global development primarily due to its impact on food security. It limits the amount of water available for agriculture and other human uses, and makes the available water more difficult to obtain. As groundwater supply becomes more limited, wells may go dry intermittently or constantly. Wells may need to be extended deeper to reach water, and more energy is needed to pump water from greater depths. Water quality of depleting freshwater aquifers may deteriorate due to intrusion of brackish water from surrounding aquifers. Land surfaces may subside, or gradually lower in elevation, as aquifers below become depleted. As a development challenge, South Asia is particularly affected, where strategies for future food security must account for constrained groundwater extraction. Sub-Saharan Africa appears to have relatively abundant renewable groundwater resources (MacDonald, et al., 2012). Unsustainability of groundwater use for irrigation is a concern not only for countries that are using groundwater intensively, but also the world at large since international trade directly links food production in one country to consumption in another.

Exhibit 13: Non-renewable groundwater is a significant part of gross irrigation water use in several major countries. India uses more non-renewable groundwater for irrigation than any other country (68 km$^3$ per year, in year 2000). Iran uses less in absolute terms (20 km$^3$ per year) but more as a percent of total irrigation water: 40% of Iran’s irrigation water is sourced from non-renewable groundwater. ‘Other irrigation water’ includes non-local water and renewable local water (Wada, et al., 2012).

Groundwater depletion affects global development primarily due to its impact on food security. It limits the amount of water available for agriculture and other human uses, and makes the available water more difficult to obtain. As groundwater supply becomes more limited, wells may go dry intermittently or constantly. Wells may need to be extended deeper to reach water, and more energy is needed to pump water from greater depths. Water quality of depleting freshwater aquifers may deteriorate due to intrusion of brackish water from surrounding aquifers. Land surfaces may subside, or gradually lower in elevation, as aquifers below become depleted. As a development challenge, South Asia is particularly affected, where strategies for future food security must account for constrained groundwater extraction. Sub-Saharan Africa appears to have relatively abundant renewable groundwater resources (MacDonald, et al., 2012). Unsustainability of groundwater use for irrigation is a concern not only for countries that are using groundwater intensively, but also the world at large since international trade directly links food production in one country to consumption in another.

Water contamination by organic and inorganic pollutants adversely affects health
Two important types of pollutants that degrade water quality are biological pollutants like human sewage, and inorganic pollutants like fertilizer runoff. Biological water pollution by human sewage is considered in detail in the chapter on diarrheal diseases in the section on Global Health. Another important type of water pollution includes runoff of nitrogen and phosphorus fertilizer from agricultural land. Just as fertilizing agricultural fields can stimulate crop growth, increasing nutrient levels in rivers, lakes and estuaries can cause eutrophication or excessive growth of algae and other aquatic plants. Huge blooms of cyanobacteria (also known as blue-green algae), and other organisms can come to
dominate aquatic ecosystems, seriously degrading water quality (Smith, 2003). Negative effects include hypoxia, or depletion of oxygen in the water, which causes the death of fish and other animals in the water. Over 400 marine ‘dead zones’ resulting from nutrient runoff are reported worldwide, having approximately doubled each decade since the 1960s (Diaz & Rosenberg, 2008). Many cyanobacteria also produce toxic compounds that are hazardous to humans and domesticated animals. Mass blooms of toxic cyanobacteria occur regularly in water subject to nutrient runoff, with the timing and duration of the bloom season varying by location. For example, the water supply for the city of Toledo, Ohio, USA was interrupted for several days in August 2014 due to an algae bloom caused largely by phosphorous fertilizer runoff.

In recent decades, the amount of reactive nitrogen in rivers has increased dramatically (Green, et al., 2004) (MEA, 2005), with river basins in North America, continental Europe, and South and East Asia showing the greatest change (Exhibit 14). Africa suffers little from nutrient pollution, mainly because fertilizer use in Africa is still very low.

**Increase in nitrogen runoff leading to aquatic dead zones**

![Map of nitrogen runoff](image)

**Percent increase in nitrogen transport to river mouth**

- **<1%**
- **1-50%**
- **50-75%**
- **75-300%**
- **300-500%**
- **>500%**

**Exhibit 14:** Reactive nitrogen flows in many river systems have increased dramatically in recent decades—primarily due to fertilizer runoff from agricultural lands—especially evident in Europe, Asia and North America. This has led to ‘dead zones’ in waterways.

Other sources of inorganic water pollution include silt and sediment from soil erosion, waste discharge from small or large scale industrial activities, heavy metals such as mercury or lead, and synthetic and persistent engineered chemicals like plastics and agricultural pesticides (Meybeck, 2003).
Loss of fertile agricultural soil due to erosion causes significant impacts on farm yields and food security. Soil erosion is the removal of soil from the land surface, typically carried away by rain or wind. Some level of soil erosion is natural, and over geologic time spans it has shaped the river valleys and deltas of our landscape. Soil erosion under native vegetation occurs at roughly the same rate at which new soil is produced through natural geomorphologic processes (Exhibit 15). However, agricultural practices such as tillage and heavy grazing remove vegetative cover and expose the soil surface to rain and wind. Soil erosion from agricultural fields occurs at rates 10 to 100 times greater than erosion from natural land surfaces (Pimentel, 2006) (Montgomery, 2007). Soil erosion is widespread: about 80% of global agricultural land suffers moderate to severe erosion (Pimentel & Burgess, 2013). Erosion is much greater on sloping land, where soil particles are carried away downhill by flowing water. Wind can also carry soil particles for long distances.

Soil erosion affects global development by reducing food security. Loss of fertile, nutrient-rich cropland soil reduces the productive capacity of the land and causes lower harvest yields. This is a major problem for poor rural populations living on marginal land with low soil quality and steep topography. As productivity of agricultural fields is reduced, farmers are compelled to apply fertilizers to maintain yields (Lal, 2009). Eventually, when enough productive soil is lost, the land is not worth using, and is abandoned. It is reported that about 3 million hectares of cropland worldwide are abandoned annually because of productivity declines due to severe land degradation (FAO, 2012).

A related issue is desertification, which is the gradual degradation of drylands to become unfertile. While traditionally ascribed to overgrazing, it is now known that many factors affect desertification, including soil erosion, climate change, soil nutrient management and water cycle changes (D’Odorico, et al., 2013). Underlying driving forces include demographic, economic, technological, institutional, socio-cultural, and meteorological factors. Land degradation and desertification is caused by interactions between natural processes such as weather variability including droughts and floods, and human actions of unsustainable land use practices on fragile resources. External forces are also key drivers, including inadequate governance mechanisms, ineffective land tenure, and global economic forces. Locally, this leads to decreased land productivity, overexploitation, and a worsening spiral of land degradation, poverty, and food insecurity.

Loss of fertile soil due to erosion from cropland

Exhibit 15: On average, about 1 to 3 millimeters of soil are lost each year from typical farmland. Soil erosion rates in mountainous regions can be 10 times greater. Under natural conditions, rates of natural soil formation and of soil erosion from land are at least 10 times lower.
Household air pollution from burning solid fuels is a significant, yet largely preventable, health risk. Household air pollution (HAP) in developing countries is primarily caused by burning solid fuels indoors for domestic purposes like cooking or heating. Around 3 billion people cook and heat their homes using open fires and simple stoves that burn biomass—wood, animal dung, crop residues—and coal. Household air pollution from solid fuel combustion affects global development because of chronic health impacts on affected populations. About 4.3 million people die prematurely every year from illness attributable to household air pollution from cooking with solid fuels (WHO, 2014). This is detailed by location and type of disease in Exhibit 16. In total, about 34% of deaths are from strokes, 26% from ischemic heart disease or heart attacks, 22% from chronic obstructive pulmonary disease (COPD), 12% are due to pneumonia and 6% are from lung cancer. While overall more deaths are caused by household pollution in Asia, more children are affected by it in Africa. Over half of all deaths among children under 5 from acute lower respiratory infections (ALRI) are due to particulate matter inhaled from indoor air pollution from household solid fuels (WHO, 2014). The combustion smoke that causes household air pollution contains particulate matter (PM), carbon monoxide, benzene and other harmful agents. PM consists of a complex mixture of solid and liquid particles of organic and inorganic substances suspended in the air. They contain sulfates, nitrates, ammonia, sodium chloride, black carbon, mineral dust and water. Most health damage is caused by particles with a diameter of 10 microns or less, (≤ PM10), which can enter deep inside the lungs.

Numerous types of improved cookstoves exist that could substantially reduce household air pollution, if they were more widely adopted. The damages from household air pollution have been increasingly recognized, and considerable effort has been applied toward solutions. Strategies to reduce indoor air pollution have focused on enhancing demand for clean cookstoves and fuels, strengthening the supply of such stoves and fuels, and fostering an enabling environment for their widespread use (GACC, 2011). While a number of improved stove technologies exist, widespread diffusion and use remains elusive (Subramanian, 2014). Long-term solutions to satisfying household heating needs must also consider the sustainability and security of primary energy supplies (e.g. biomass for charcoal production, and supply chains of fossil natural gas).
Exhibit 16: 4.3 million people died in 2012 from illness attributable to household air pollution, which is primarily caused by burning solid fuels indoors for cooking or heating. Of these deaths, about 34% were from stroke, 26% from ischemic heart disease, 22% from chronic obstructive pulmonary disease (COPD), 12% were due to pneumonia and 6% were from lung cancer. More total deaths were caused in Asia, though more children were affected in Africa. The regions indicated are standard WHO regions; the Southeast Asia WHO Region includes South Asia (WHO, 2014).

Outdoor air pollution, largely caused by vehicles, is a significant health risk in many urban areas. Outdoor (ambient) air pollution in both cities and rural areas is estimated to have caused 3.7 million premature deaths globally in 2012 (WHO, 2014). About 80% of premature deaths related to outdoor air pollution were due to strokes and ischemic heart disease, while 14% of deaths were due to chronic obstructive pulmonary disease or acute lower respiratory infections, and 6% were due to lung cancer. About 88% of those premature deaths occurred in low and middle income countries, and the greatest number in the WHO Western Pacific and Southeast Asia regions. As shown in Exhibit 17, concentrations of air pollutants are typically higher in the urban areas of low and middle income countries.

These air pollution related deaths are largely because of exposure to small particulate matter (PM) with diameter of 10 micrometers or less (PM10 and PM2.5). Chronic exposure to PM contributes to the risk of developing cardiovascular and respiratory diseases, as well as lung cancer. Other serious risks to health from outdoor air pollution are due to excessive exposure to ozone (O₃), nitrogen dioxide (NO₂) and sulfur dioxide (SO₂). Ozone plays a major role in asthma morbidity and mortality, while nitrogen dioxide and sulfur dioxide contribute to asthma, bronchial symptoms and reduced lung function. Outdoor air pollution primarily comes from fuel combustion, mainly from mobile sources such as vehicles and also from stationary sources such as power plants. Most air pollution in cities in developing countries is attributed to vehicle emissions (UNEP, 2014). In rural areas, outdoor air pollution is typically much less of a problem, and may result from burning of agricultural waste, forest fires and activities like charcoal production.
Exposure to outdoor air pollution in urban areas

**Exhibit 17:** Health conditions due to outdoor (ambient) air pollution are primarily caused by exposure to particulate matter (PM10). Concentrations of PM10 were measured in 1600 urban areas from 2008 to 2013; mean annual concentrations are shown here. Particulate matter levels are highest in urban areas in Asia. Most cities in North America and Europe have low levels. Few data points are available for African cities (WHO, 2014).

**Exposure to a broad range of environmental toxins causes chronic health conditions**

People are exposed to environmental toxins—a diverse range of chemicals with potentially serious health effects—through air, water, food, or other means. Important examples of environmental toxins include heavy metals and persistent organic pollutants (POPs). Environmental toxins play a role in global development primarily due to their observed or projected chronic health impacts. Acute health impacts can also occur. Toxic materials from industry, mining and agriculture, including substances such as heavy metals and pesticides, affect populations in many countries throughout the world (GAHP, 2013). Although environmental toxins may be less prevalent overall in developing countries because of lower industrial activity compared to industrialized countries, the less stringent industrial regulations typically found in developing countries is a serious concern. Sources of toxic pollution include small- to large-scale mining and processing (e.g. battery recycling) activities, agricultural run-off containing fertilizer and pesticide residues, and toxic wastes that have been illegally disposed of in developing countries. Locations in developing countries that process e-waste (post-use electronic devices) have become ‘hot-spots’ of toxic exposure. The Agbogbloshie area in Accra, Ghana is a prime example (Blacksmith Institute, 2013). Industrial accidents such as the tragic 1984 gas leak at a pesticide factory in Bhopal, India are another source of exposure and lingering, adverse health effects.

An important type of environmental toxin is persistent organic pollutants (POPs), which are organic compounds that do not degrade readily and persist in the environment. They tend to bioaccumulate in organisms, meaning that it remains and accumulates within bodies. Many POPs are pesticides (such as DDT), either currently in use or formerly used but still present in the environment. This chemical
Global average temperatures will become warmer in the future, affecting agricultural yields and human health. Climate change is a long-term alteration of global weather patterns, due to increased heat energy accumulated in the earth system, largely as a result of greenhouse gases emitted into the atmosphere. Some level of future climate change is unavoidable due to previous emissions, which remain in the atmosphere for long time spans. The extent of future climate change impacts will depend on levels of current mitigation efforts and future adaptation efforts. Current greenhouse gas emissions trajectories...
correspond closely to high emission scenarios (RCP8.5) modeled by climate scientists. Continuation of such trends can be expected to result in a global mean temperature increase of about 4°C by 2100 (IPCC WG2, 2014) (Exhibit 18). Global cooperation towards greatly reduced emissions (RCP2.6 scenario) could result in a smaller temperature rise. Such cooperation has not been forthcoming, to date.

**Historical and projected global average surface temperature, 1900 to 2100**

Exhibit 18: Global average surface temperature is projected to increase during this century. The temperature increase will be greater if greenhouse gas emissions continue at high levels, following the RCP8.5 emission scenario. A much smaller temperature increase is projected to occur if emissions are limited to the lower RCP2.6 scenario. Temperature changes are shown relative to average 1986-2005 temperature (IPCC WG2, 2014).

Rising temperatures due to climate change are expected to affect global development due to potentially significant effects on food security, water supply, and health. Over most land areas, the coldest days and nights will be warmer and fewer, and the hottest days and nights will be warmer and more frequent. At lower latitudes, especially in seasonally dry and tropical regions, crop productivity is projected to decrease with even a small rise in average temperature (IPCC WG2, 2014). At mid to high latitudes, crop productivity is projected to increase slightly with a small rise in temperature, and eventually decrease as temperatures rise further due to limited heat tolerance by crop plants. Exhibit 19 summarizes numerous estimates from the peer-reviewed literature of the impact of climate trends on yield of several major crops. Yields of wheat, rice and maize are projected to decrease by several percent per decade. Soy is more heat tolerant, and should be less affected. Water pollution issues are also expected to increase due to higher water temperature and altered water flow patterns. Incidence of some vector-borne diseases, such as malaria, is expected to increase in highland regions as temperatures rise (Siraj, et al., 2014).
Projected impact of climate change on yields of 4 food crops

Exhibit 19: Yields of wheat, rice and maize are expected to decline due to climate trends including rising temperatures. This exhibit summarizes estimates from peer-reviewed literature of the impact of recent climate trends on yields for four major crops. The boxplots indicate the median (vertical line), 25th - 75th percentiles (box), and 10th - 90th percentiles (whiskers) for estimated impacts, and n indicates the number of estimates. The studies were taken from the peer-reviewed literature and used different methods (i.e., physiological process-based crop models or statistical models), spatial scales (stations, provinces, countries, or global), and time periods (median length of 29 years). Some included positive effects of CO₂ fertilization trends but most did not. Values from all studies were converted to percentage yield change per decade. Each study received equal weighting as insufficient information was available to judge the uncertainties of each estimate (IPCC WG2, 2014).

Average long-term precipitation patterns will shift, and some areas will become dryer

Changes in the global water cycle are projected to occur as the climate warms (IPCC, 2013). Average global precipitation is projected to gradually increase in the 21st century. The global hydrological cycle will intensify generally due to global warming, and mean water vapor, evaporation and precipitation are projected to increase on global average. Changes of average precipitation in a much warmer world will not be uniform, with some regions experiencing increases, and others with decreases or little change. Precipitation is expected to increase in many wet tropical areas and at high latitudes. Many mid latitude and subtropical arid and semi-arid regions will likely experience less precipitation. The Asian monsoon will likely increase in average total precipitation, but with greater variation from year to year. The melting of snowpack and glaciers will affect the amount and timing of water flows in downstream areas.

Despite variability and uncertainty in climate change projections, there is now agreement from a number of different climate models that Africa is at the highest risk from climate change, given the magnitude of existing stresses in the continent (UNDP, 2009). It is highly likely that significant areas of African drylands will see changing rainfall patterns in the coming decades. Exhibit 20 shows model projections of future changes in annual precipitation in Africa, under high and low emission scenarios. Average precipitation is expected to decrease in northern and southern Africa, and increase in central and eastern Africa.
Projected future changes in annual precipitation in Africa

Exhibit 20: Results from climate models suggest that annual precipitation patterns in Africa will change, by the mid-21st century (left) and late-21st century (right), under high emission scenario (RCP8.5; top) and low emission scenario (RCP2.6; bottom). Average precipitation is expected to decrease in northern and southern Africa, and increase in central and eastern Africa (IPCC WG2, 2014).

Extreme weather events such as drought, storms and floods will become more frequent and more intense.

Global climate change is expected to result in more frequent and intense extreme weather events. Warm spells and heat waves will very likely occur more frequently (IPCC WG2, 2014). Storms such as tropical cyclones are expected to become more severe, including storm surges in coastal areas. Precipitation is more likely to come as heavy rainfall (even in regions that receive less total precipitation), leading to increased erosion, landslides and flooding. Precipitation extremes are projected to negatively affect water quality, due to increased sediment, nutrient and pollutant loadings caused by heavy rainfall, reduced dilution of pollutants during droughts, and disruption of treatment facilities during floods.

The most significant impact of extreme weather events on human development will likely be due to frequent and prolonged droughts in some regions. Many climate models project an increased likelihood of agricultural droughts in regions that are presently dry, with extended decreases in soil moisture (IPCC WG2, 2014). Farmers and pastoralists in drylands with insufficient access to drinking and irrigation water risk the loss of agricultural productivity. This will affect the livelihoods of rural people, particularly those depending on water-intensive agriculture. There is a corresponding risk of food insecurity and conflict over available water and food resources (UNDP, 2009). Droughts also affect...
Sea level will slowly but inevitably rise in the future, affecting coastal populations

Global mean sea level has risen about 0.2 meters since 1900, at a rate of about 1.7 millimeters per year (IPCC WG2, 2014). Sea level is expected to continue rising at an accelerating pace, depending on future greenhouse gas emission scenarios. Forecasting future sea level rise is challenging, but modeling capabilities have improved in recent years and current projections are fairly robust (Horton, et al., 2014). For the low emission climate scenario (RCP2.6), sea level is expected to rise by another half meter by 2100. For the high emission climate scenario (RCP8.5) it is expected to rise a full meter by 2100 (Exhibit 21). Much of this sea level rise is due to thermal expansion of the slowly warming ocean water. Another, more uncertain, contribution to rising sea levels will be melting glaciers and ice caps. Sea level rise will affect global development due to permanent or episodic displacement of coastal populations, inundated agricultural land, and reduced freshwater supply due to saltwater intrusion into aquifers.

Urban populations with inadequate water services, who risk an insufficient water supply for domestic and industrial use, causing health and economic impacts. Droughts can also significantly affect energy security, because they reduce the energy supply from hydropower stations and can force water-cooled thermal power stations to shut down. A major drought in 2001 in Brazil, where 80% of electricity is from hydropower, caused a 20% reduction in electricity supplies in the country and led the government to introduce rationing (Lee, at al., 2012). Ethiopia is particularly vulnerable to droughts, because of its high dependence on agriculture as well as hydropower for electricity.

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Coastal areas are highly vulnerable to extreme events, such as storms and their associated surge, which will be exacerbated with higher average sea levels. River delta regions are highly vulnerable to the impacts of climate change, particularly sea level rise and changes in runoff. Many delta plains, especially those in Asia, are very densely populated. Some studies estimate (Ericson, et al., 2006) that over a million people will be directly affected by 2050 in three megadeltas: the Ganges-Brahmaputra delta in Bangladesh, the Mekong delta in Vietnam, and the Nile delta in Egypt. Their modeling suggests that 75% of the population affected by sea level rise live on deltas in Asia, and many of the remainder live on African deltas. About 8.7 million people could be affected by coastal inundation by 2050. GIS based models (Dasgupta, et al., 2009) estimate that a 1 meter rise in sea level will directly affect over 56 million people in developing countries. Several countries are expected to be particularly impacted, including Vietnam and Egypt; both countries may see 10% of their population being displaced by a 1 meter rise in sea level. Some freshwater aquifers in coastal areas are expected to become brackish, due to the intrusion of rising salt water levels (Werner, et al., 2013).

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Coastal adaptation practices can seek to protect, accommodate or retreat in response to rising sea levels. Protection efforts can involve ‘hard’ or ‘soft’ measures, but will face increasing pressure over time and may ultimately be untenable. Efforts at accommodation focus on reducing damage from

Exhibit 21: Global mean sea level has risen at a rate of about 1.7 millimeters per year since 1900, rising a total of about 0.2 meters since pre-industrial times. The mean sea level is projected to continue to rise at an accelerating pace through 2100 and beyond. Future sea level rise is projected for the low emission RCP2.6 scenario (blue) and the high emission RCP8.5 scenario (red) (IPCC WG2, 2014).
high waters through flood-resilient infrastructure or floating agricultural systems, for instance. Retreat options may ultimately be inevitable, but if opted for in populated areas will result in large numbers of ‘climate refugees’ who will need permanent resettlement elsewhere.

Ocean water is absorbing atmospheric CO$_2$ and becoming more acidic, affecting sea plants and animals

As described earlier, the concentration of carbon dioxide (CO$_2$) gas in the atmosphere has risen from about 280 parts per million (ppm) during pre-industrial times to about 400 ppm now. Some of the CO$_2$ that is emitted into the atmosphere is absorbed by the oceans, and this has a significant impact on the chemistry of seawater. CO$_2$ reacts with water to form carbonic acid (H$_2$CO$_3$), which increases the acidity of the ocean. Acidity is measured in pH units using a logarithmic scale: a 1 unit decrease in pH corresponds to a 10-fold increase in hydrogen ion concentration, or acidity. Since the beginning of the industrial era, the pH of ocean surface water has changed by about 0.1 unit (from about 8.2 to 8.1, on the full pH scale). This corresponds to a 26% increase in hydrogen ion concentration (IPCC, 2013). While not directly related to the changing climate, ocean acidification is caused by the same global drivers, and is typically considered as an impact of global climate change.

Ocean acidification is expected to increase in the future, as the oceans absorb additional CO$_2$ from the atmosphere. Climate models project a global increase in ocean acidification for all greenhouse gas emissions scenarios (IPCC, 2013). The high emission scenario (RCP8.5) is projected to lead to a decrease in the pH of surface ocean water by about 0.3 units by the end of 21st century. The low emission scenario (RCP2.6) would decrease the ocean water pH by only about 0.07 units by 2100.

The consequences of changes in ocean acidity for marine organisms and ecosystems are just beginning to be understood, but are expected to affect fundamental biological and chemical processes of the sea. Geological records, as well as results from laboratory, field, and modeling studies, suggest that marine ecosystems are highly sensitive to changes in ocean acidity. For example, the acidity of seawater largely determines the saturation state of calcium carbonate minerals, which affects the formation of shells for marine animals such as corals, plankton, and shellfish. Some marine species like reef fishes and shelled mollusks are expected to be negatively affected by ocean acidification, while other species like crustaceans may fare better (Branch, et al., 2013). Overall effects on primary productivity and food webs will be complex, and hard to predict.

Forest land continues to be converted to agricultural land, especially in Latin America

Deforestation is the removal of trees from a forested area, where the land is then converted to non-forest use. Globally, about 31% of total land area is covered by forests, corresponding to a forest area of just over 4 billion hectares (FAO, 2010). Global forest area has decreased by about 1 billion hectares during the last three centuries, corresponding to an average deforestation rate of 3.2 million hectares per year (see Exhibit 5). More recently, forest area decreased at a rate of about 5.2 million hectares per year during the period 2000 to 2010, down from an estimated 8.3 million hectares per year during the period 1990 to 2000. Net global decrease in forest area is the result of two opposing processes. First, deforestation occurred at a rate of about 13 million hectares per year during the period 2000 to 2010, down from about 16 million hectares per year in the 1990s. Second, afforestation and natural expansion of forests occurred in other areas. Globally, much of the increase in forest area occurs in China, where large-scale afforestation efforts increased the forest area by an average of 3 million hectares per year during the period 2000 to 2010. Most of the loss of forest currently occurs in South America (4 million hectares per year) and Africa (3.4 million hectares per year). Table 1 lists the countries with the largest annual net loss of forest area between 2000 and 2010.
Around 80% of deforestation worldwide is driven by agriculture (Kissinger, et al., 2012). In Latin America, where most deforestation occurs, about 95% is caused by agriculture (including livestock), primarily commercial agriculture (*Exhibit 22*). In Africa and subtropical Asia, about 70-75% of deforestation is due to agriculture, of which about half is commercial and half is subsistence agriculture. In terms of impact on human development, deforestation occurs largely due to conversion of forest area to agricultural land, with corresponding positive implications for food security. However, deforestation has negative short-term to medium-term ramifications like landslides, flooding and loss of access to forest products, as well as potential long-term consequences on biodiversity, habitat for wild species, and global climate. The net effect of deforestation on global development is a balance of these forces.

<table>
<thead>
<tr>
<th>Country</th>
<th>Annual loss of forest area (2000-2010)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1000 hectares per year</td>
</tr>
<tr>
<td>Brazil</td>
<td>-2640</td>
</tr>
<tr>
<td>Australia</td>
<td>-560</td>
</tr>
<tr>
<td>Indonesia</td>
<td>-500</td>
</tr>
<tr>
<td>Nigeria</td>
<td>-410</td>
</tr>
<tr>
<td>Tanzania</td>
<td>-400</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>-330</td>
</tr>
<tr>
<td>DR Congo</td>
<td>-310</td>
</tr>
<tr>
<td>Myanmar</td>
<td>-310</td>
</tr>
<tr>
<td>Bolivia</td>
<td>-290</td>
</tr>
<tr>
<td>Venezuela</td>
<td>-290</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>-6040</strong></td>
</tr>
</tbody>
</table>

*Table 1:* These 10 countries experienced the largest net loss of forest area between 2000 and 2010. The decrease in Australia’s forest area is due to extended drought (FAO, 2010).
Exhibit 22: Deforestation is driven largely by agriculture. Most deforestation occurs in Latin America, and is largely due to commercial agriculture. Less deforestation occurs in Africa and Asia, where it is driven by both subsistence and commercial agriculture (Kissinger, et al., 2012).

Supplying food by catching wild fish is becoming increasingly difficult and constrained
Sources of wild food have become less important for humans since the adoption of agriculture and animal husbandry as food security strategies. Meat from wild land animals, or bushmeat, continues to form only a minor part of the human diet in select countries. Bushmeat was reported in 1997 to contribute about 8% of total protein consumption in several African countries including DR Congo, Liberia, and Ghana (FAO, 1997). More recent figures are unavailable, but overall consumption is expected to have decreased since 1997. Most animal protein for humans now comes from domesticated land animals such as cattle and poultry.

Although the ocean environment is more challenging than land for humans, a similar transition from wild fish catch to cultivated fish production is underway. Protein from wild fish continues to be an important component in some regions; fish constitute at least half of total animal protein intake in Bangladesh, Cambodia, Ghana, The Gambia, Indonesia, Sierra Leone and Sri Lanka (FAO, 2012). In 2009, fish accounted for 16.6% of the global population’s intake of animal protein and 6.5% of all protein consumed. However, global stocks of wild marine fish are increasingly overexploited to provide this supply of food (Exhibit 23). The global catch of wild fish has remained roughly level since the late 1980s, despite a greater capture effort (Watson, et al., 2013). The gap has been made up by aquaculture production, allowing expanded human consumption of fish (Exhibit 24).
Gradual depletion of non-renewable natural resources will increase their real cost

Non-renewable resource depletion results from human use and dissipation of one-time stocks of natural resources that were created over geologic time periods, such as fossil fuels, metal ores and other minerals. Public discourse regarding resource depletion is typically polarized in two camps. Cornucopians maintain that technological innovation and market forces will overcome resource scarcity, by developing substitutes or by improving efficiencies of extracting and using the resources. Doomers believe that our historical success at improving human welfare has resulted precisely from our one-time exploitation of the most concentrated and accessible of these resources, and fundamental limits to human activities will then be seen. A broader analysis suggests that elements of both arguments can be

Exhibit 23: Human exploitation of global marine fish stocks is becoming less sustainable, and catching wild fish today requires more effort than before (FAO, 2012) (Watson, et al., 2013).

Exhibit 24: Global catch of wild fish has remained roughly level since the 1990s, while aquaculture fish production has increased significantly since then (FAO, 2012).
seen currently in effect, and can be expected to continue into the future.

Geologic resources such as mineral ores and fossil fuels, which have played essential roles in human development to date (e.g. the Iron Age), were created in fixed amounts in the earth’s crust over geologic time spans of millions of years. An ore is a rock with a relatively high concentration of some desired element, and results from geological and meteorological forces such as plate tectonics, volcanoes, folding, faulting, weathering, erosion and sediment deposition. For example, the earth’s crust as a whole contains an average of only about 0.004 grams of gold per ton, but at particular locations and depths it contains several grams per ton. These locations are prospected and selected to become gold mines. Sites with the highest ore grade are typically exploited first, because the cost and effort of mining and processing metal increase strongly as the concentration of metal in the ore decreases. In particular, the energy needed to refine the ore increases exponentially as ore grade decreases (Norgate, et al., 2007). Exhibit 25 shows historical trends in gold ore grade from 1840 to 2010 in major gold-producing countries (UNEP, 2011). Although gold is not essentially related to global human development, it is a well documented natural resource for which long-term data are available, and serves as a proxy for more functional metals such as copper. The ore grade fluctuates from year to year as individual deposits of gold are exploited, but the long-term trend is of declining ore grade in all regions. Clearly discerning the effect of this trend on gold prices and production levels is difficult due to concurrent changes in economic and technologic factors, though it has necessarily made the physical exploitation of gold resource more challenging. Similar trends toward lower ore grades are seen for most other industrially-important metals, like copper (Harmsen, et al., 2013).

Quality of gold ore in major producing countries since 1840

Exhibit 25: The quality of gold ore has decreased considerably since 1840, and high-grade deposits are no longer encountered (UNEP, 2011).
Another important example is fossil fuel use and sourcing. The three types of fossil fuels—coal, oil and natural gas—supply about 82% of all global primary energy use (IEA, 2014). Globally, we are heavily dependent on fossil fuels for transportation, electricity, heat and other energy services such as nitrogen fertilizer production. Fossil fuels were formed from decayed organic matter that was exposed to heat and pressure in the earth's crust over long periods of time. Most fossil fuels are made from plants and animals that were alive during the Carboniferous Period, about 350 million years ago. As such, fossil fuels are clearly non-renewable over time scales of interest, and long-term human development will require a transition to renewable energy sources. Notwithstanding, the global use of fossil fuels has more than doubled in the last 40 years, and overwhelmingly remains the dominant source of energy for human society (Exhibit 26). Geologic deposits of fossil fuels have shown declines in resource quality over time, similar in nature to that shown for gold in Exhibit 25 (Hall, et al., 2014). However, continued expansion of fossil fuel production has been made possible by a range of advanced technologies such as deepwater drilling, horizontal drilling, hydraulic fracturing and oil sand recovery. These techniques to exploit unconventional fossil fuel resources come at an economic and energetic cost, and have become necessary only because the preferred conventional reserves have become increasingly depleted.

Exhibit 26: The total annual primary energy used globally has more than doubled since 1971; fossil fuels remain the dominant source of energy. Global energy use is shown here by the source of the primary energy, in units of million tons of oil equivalent (Mtoe) per year (IEA, 2014).

As available deposits of natural resources become less concentrated and less accessible, increasing effort must be dedicated by society to obtain the still available natural resources. Other things equal, this will result in less surplus resource wealth that can be applied to improving human welfare (Murphy, 2013). As increasingly complex unconventional techniques are needed to access and exploit remaining fossil fuel resources, the real cost, including externalities, is likely to increase. This may affect human
development by constraining potential solutions that are too energy or resource intensive to scale effectively (Lee, et al., 2012). The concern is less about running out of a resource, but of bearing the increasing costs and risks involved with obtaining it. In this light, our increasing use of unconventional fossil fuel extraction techniques (such as hydraulic fracturing and oil sand recovery) is less of an energy revolution and more of an evolution toward the use of lower grade resources.

Prudent planning of human development efforts should not pre-suppose the existence of indefinitely plentiful natural resources, but should anticipate long-term supply shifts. As a vital example, virtually all nitrogen fertilizer, which is necessary to maintain agricultural yields, is made with fossil natural gas. Dynamic resolution will occur at the intersection of increasing human demand, decreasing geologic abundance, and improving efficiency of extraction and utilization technologies. Early transition to renewable energy sources and production systems will offer increasing benefits over time, as the quality of accessible non-renewable resources further declines. Deployment of renewable energy has strong synergies with sustainable development goals (Sathaye, et al., 2010).

The various environmental changes and consequences are driven by global and local actions, but not all of them have significant impact on human development by 2050

The level of impact of the numerous second-order environmental consequences on human development will vary, and only some of these problems can be fully resolved through actions within developing countries. Exhibit 27 shows the estimated severity of impacts on human development goals, and whether the primary drivers of environmental change are global or local actions. Some of the primary drivers like indoor air pollution and soil erosion are clearly local, meaning that these problems could, in principle, be fully solved through local efforts. Other environmental consequences like ambient air pollution and groundwater depletion have regional drivers, and require some level of regional administration to overcome. Some consequences, including climate change and natural resource depletion, have clearly global drivers, and will cause local damages regardless of the location of the drivers. These problems require global cooperation for effective mitigation, while local adaptation measures are needed to accommodate inevitable changes. The drivers of other environmental consequences like deforestation and reduced wild ocean food are more challenging to localize, in part because local actions such as logging and fishing may be stimulated by global market forces. The four quadrants of Exhibit 27 represent issues with varying severity of impacts and potentials of solution.

- Quadrant A contains high impact problems with local focus of mitigation and/or adaptation.
- Quadrant B contains medium impact problems with local focus of mitigation and/or adaptation.
- Quadrant C contains high impact problems with local adaptation focus. Mitigation, where possible, will require global cooperation.
- Quadrant D contains medium impact problems with local adaptation focus. Mitigation will require global cooperation.
Anticipated human development impacts of environmental change consequences

Exhibit 27: Matrix of environmental change consequences, showing anticipated impacts on human development by 2050 on the vertical axis, and source of primary drivers on the horizontal axis (left = local drivers, right = global drivers).
Identifying major barriers will help define the constraints and requirements of potential breakthroughs. Beyond scientific and technological challenges, many hurdles exist that may constrain successful resilience to environmental changes.

Many environmental processes are interlinked, and problems often have multiple causes that cannot be addressed independently. Advances in one field of human development may cause setbacks in other fields.

There is often a time lag between beneficial first-order environmental changes and detrimental second-order consequences. Current political and economic systems, with their focus on short-term rewards, are ill-suited to confront these long-term challenges.

Many current environmental problems result from externalities of economic activities, meaning the costs are borne by people not involved in the original activities. Externalities are poorly incorporated into current economic metrics of success.

Definitive solutions to environmental change issues may also require breakthroughs in human behavior. Many aspects of the lifestyle in industrialized countries remain as aspirational goals for developing country populations, yet are clearly unsustainable at scale.

Depending on context, other important barriers may include the lack of effective regulatory and enforcement mechanisms, lack of adequate economic means to commit to solutions, and lack of economic incentives among key decision-makers and stakeholders.
Prescribing solutions to human development problems arising from environmental changes is especially challenging, because the changes have occurred precisely due to human efforts towards development. The approaches used successfully in the past to enable human development, e.g. the coal-powered Industrial Revolution in Europe and North America in the 18th and 19th centuries, and the resource intensive Green Revolution in Asia and Latin America in the 20th century, have allowed great advances in human development. However, the compromises and consequences of these approaches, and their potential threats to long-term human wellbeing, are growing more evident. Future-oriented human development efforts should learn from both the successes and failures of past approaches.

Numerous high-potential technological breakthroughs are being pursued for use in industrialized countries, and if successful could also apply to developing countries. For example, scalable means of harnessing and storing solar energy could resolve primary energy supply constraints. While beneficial to industrialized countries due to enhanced energy security, such a technology, if successful, could fundamentally benefit human development goals that promote universal energy availability. In this section, however, we focus on potential breakthroughs with primary applications within developing regions.

Please note that a number of the breakthroughs identified in other sections of this study are equally relevant to the issues discussed in this section. For example, breakthrough technologies relevant to resilience against environmental change include:

- Sanitation for human waste
- Precision irrigation systems
- Detection and utilization of groundwater resources
- Soil nutrient analysis

Additional critical breakthroughs are described below.

**A scalable low cost method to desalinate water using renewable energy**

Desalination is the process of making potable water from saline water sources (sea water or brackish water). The mineral/salt content of water is typically measured in milligrams of total dissolved solids (TDS) per liter of water. The salinity of ocean water averages 35,000 mg/L globally, varying from about 32,000 to 38,000 mg/L. Water is considered potable when it contains TDS less than 500 to 1000 mg/L. The vast majority, about 97.5%, of the earth’s water is seawater. Of the remaining 2.5% fresh water, 70% is frozen in polar ice and snow, and the rest is mostly groundwater (MEA, 2005). A breakthrough technology for scalable desalination using renewable energy would allow greater access to the huge resource of ocean water.

Desalination is currently used in select regions of the world. There are more than 7500 desalination facilities worldwide, over half of which are located in the Middle East (Shatat & Riffat, 2012). Virtually all are powered by fossil fuels, and are often integrated with, and use waste heat from, electricity generating stations.

There are currently two main types of desalination processes: thermal and membrane. Thermal desalination involves evaporating and condensing water, as in distillation. Various thermal processes operate at different temperatures and pressures, including the dominant multi-stage flash process, and the multi-effects distillation process (Shatat & Riffat, 2012). In recent decades, membrane technologies
have matured and most new desalination installations use membranes. Of these, the reverse osmosis (RO) process is the most common, and uses a semi-permeable membrane through which pressurized saline water is forced. Other membrane processes include electrodialysis and membrane distillation. A major difference between the various processes is the source of energy that drives desalination; heat, pressure, and electricity are used in different processes. The cost of the energy supply strongly affects the cost of desalination. The cost of the various processes also varies, and is heavily dependent on scale. Larger facilities are far less expensive per cubic meter of fresh water (Exhibit 28).

**Cost of current desalination processes**

<table>
<thead>
<tr>
<th>Capacity (m³ per day)</th>
<th>Desalination cost (US$ per m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverse Osmosis (brackish water)</td>
<td>40K-46K</td>
</tr>
<tr>
<td></td>
<td>20-1200</td>
</tr>
<tr>
<td></td>
<td>&lt;20</td>
</tr>
<tr>
<td>Reverse Osmosis (seawater)</td>
<td>100K-320K</td>
</tr>
<tr>
<td></td>
<td>15k-60K</td>
</tr>
<tr>
<td></td>
<td>250K-1K</td>
</tr>
<tr>
<td></td>
<td>&lt;100</td>
</tr>
<tr>
<td>Multi-effects distillation</td>
<td>&gt;91K</td>
</tr>
<tr>
<td></td>
<td>12k-55K</td>
</tr>
<tr>
<td></td>
<td>&lt;100</td>
</tr>
<tr>
<td>Multi-stage flash</td>
<td>23K-528K</td>
</tr>
</tbody>
</table>

Exhibit 28: The cost of current desalination processes ($ per m³ of fresh water) varies depending on the technology used and the scale of the process. The cost of energy inputs is also a significant variable. Conventional desalination technologies are too expensive and energy intensive to scale sufficiently to provide fresh water for significant global human development (Shatat & Riffat 2012).

As an illustration of desalination costs, let’s consider the 68 million km³ of non-renewable groundwater used for irrigation by Indian farmers each year (Exhibit 13; contribution of non-renewable groundwater to irrigation water demand). If this water were produced from sea water using the least expensive process (large-scale reverse osmosis), it would cost $30 billion per year, equivalent to about 1.5% of India’s GDP. Furthermore, based on the energy intensity of current RO processes (about 2 kWh of electricity per cubic meter of fresh water (Fritzmann, et al., 2007)), producing this amount of water...
would use 140 terawatt-hours (TWh) of electricity, or about 12% of total annual electricity generation in India (IEA, 2014). Conventional desalination technologies are clearly too expensive and too energy intensive to provide significant amounts of water, in order to contribute to global human development. For desalination to play a lasting role in human welfare, processes will have to be powered by renewable energy sources instead of fossil fuels. A breakthrough technology allowing low cost water desalination using renewable energy could mitigate future problems of groundwater salinization (e.g. due to over-extraction or sea level rise) as well as expand freshwater resources to cater for growing water demands.

Substantial research and development work is required, and we expect that it will take 5-10 years for this breakthrough to be ready. Deployment challenges include access to finance, and policies regarding location and discharge streams. We rate the difficulty of deployment, COMPLEX.

**Breakthrough 1 – Difficulty of deployment**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Difficulty Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Policies</td>
<td>Simple</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>Simple</td>
</tr>
<tr>
<td>Human capital</td>
<td>Challenging</td>
</tr>
<tr>
<td>Access to user finance</td>
<td>Complex</td>
</tr>
<tr>
<td>Behavior change</td>
<td>Challenging</td>
</tr>
<tr>
<td>Existing demand</td>
<td>Feasible</td>
</tr>
<tr>
<td>Market fragmentation/distribution channels</td>
<td>Simple</td>
</tr>
<tr>
<td>Business model innovation</td>
<td>Challenging</td>
</tr>
</tbody>
</table>

- Regulated market with supportive policies
- Moderate need to train a limited number of people
- Minimal behavior change required
- Significant financing required, limited mechanisms available
- Fairly concentrated market and/or well defined channels
- Deployment model(s) being tested
- Requires some improvements to existing infrastructure
- Strong existing demand
- Minimal behavior change required
- Strong existing demand
As described in detail elsewhere in this report, nutrient management is critical for optimal agricultural yields. Some areas, such as much of Africa, would benefit greatly from additional plant nutrients in the form of fertilizer. In areas where fertilizer is available, overuse can be significantly reduced. Crop yields respond very well with initial inputs of fertilizer, but as additional nutrients are supplied the marginal yield increase becomes smaller. Optimal results occur somewhere along that gradient, depending on the cost of fertilizer, land, and harvested crops. Furthermore, it is necessary to apply not just the right quantity of fertilizer, but also at the right time and right place, for optimal nutrient use (Roberts, 2007). The efficiency of using agricultural inputs such as fertilizer is low in conventional farming. It is estimated that overall efficiency of applied fertilizers is about 50% for nitrogen, less than 10% for phosphorous, and about 40% for potassium (Baligar, et al., 2001). The rest of the applied resource is unavailable to the plants and is wasted as runoff. The mismatched timing between availability of nitrogen and crop need for nitrogen is likely the single greatest contributor to excess nitrogen loss in annual cropping systems (Robertson & Vitousek, 2009). Ideally, nutrients should be applied in multiple small doses when plant demand for them is greatest.

A low cost, robust, scalable technology is needed to precisely meter and distribute plant nutrients and/or other inputs. This would allow farmers to apply the right amounts of fertilizer, at the right time, to maximize economic returns and reduce nutrient loss. Another major type of environmental damage caused by agriculture is overuse of water from non-renewable sources, as seen in South Asia. Different crops need different amounts of water, at different stages in the lifecycle. Application techniques also vary by crop; some crops need longer, infrequent deep watering, while others need more frequent watering with lower volumes per session).

The proposed breakthrough can be strongly leveraged by low cost soil nutrient analysis and low cost and efficient irrigation methods (identified as breakthroughs in other chapters). This would provide farmers with decision support tools that allow them to better predict crop nutrient requirements over time, avoid over-fertilization, and better schedule irrigation. This could be complemented with adjusted crop rotation patterns and additional biotic complexity to improve the plant community’s ability to take up more of the available nutrients. By allowing better management of the timing, placement, and formulation of fertilizer in cropping systems, this would ensure that nutrients are available where and when needed by the plant. Economic outcomes for farmers would improve, because less fertilizer would be needed to achieve optimal yields. This would also protect watersheds and populations downstream from farm fields, by greatly reducing runoff.

If resources are devoted to accomplish this breakthrough, we expect that it will take less than 5 years to be market ready. Once ready, it will face a number of deployment challenges including a fragmented market (of farmers), access to finance for potential users, and training of farmers to install, use and maintain the technology. In addition, a significant amount of behavior change will be required, given the low demand for such inputs (in sub-Saharan Africa), and the limited incentives for sustainable use (in South Asia). Therefore, deployment will likely be CHALLENGING.
As shown earlier in Exhibits 23 and 24, the global catch of wild fish has remained roughly constant since the late 1980s, and yet the effort necessary to catch the same amount of fish has increased. The gap in fish supply has been made up by aquaculture, which has allowed increasing human consumption of fish. Aquaculture, the farming of aquatic organisms such as fish, crustaceans and aquatic plants, is currently the fastest growing animal food-producing sector. Within 30 years, between 1980 and 2010, global aquaculture production of fish has expanded by almost 12 times, at an average annual rate of 8.8% (FAO, 2012). In 2010, about 60 million metric tons of farmed food fish was produced globally. Asia accounted for almost 90% of world aquaculture production by volume in 2010; this was dominated by China, which produced more than 60% of global aquaculture volume. Other major producers are India, Vietnam, Indonesia and Bangladesh. Freshwater fish account for 56% of global aquaculture production, followed by mollusks (24%), crustaceans (10%), diadromous fish such as salmon (6%), and marine fish (3%).

Despite the increasing importance of aquaculture to human food supply, current models of aquaculture production are largely unsustainable, and their ability to substantially scale up is questionable. Two-thirds of all farmed food fish production currently relies on artificial feeding. This share has increased from less than half in 1980. Artificial feeding requires prepared fish feed, and results in relatively faster growth rates compared to non-fed species. Fishmeal has been the preferred feed for aquaculture production, and is made by cooking, pressing, drying, and grinding fish or fish byproducts. Small pelagic species of fish, such as anchoveta, are typically caught and used for fishmeal production. A substantial portion, roughly one-third, of all wild-caught fish is used for non-food uses including fishmeal production. Fishmeal production peaked in 1994 at about 30 million tons (live weight equivalent) and has fluctuated since then, dropping to 15 million tons in 2010 due to reduced anchoveta catches (FAO, 2012). While fishmeal was once a cheap commodity used widely as animal feed, demand has increased strongly while supply has fluctuated (Olsen & Hasan, 2012).
reliance of aquaculture on fishmeal feeding is unscalable and untenable in the long term. Current aquaculture production is also vulnerable to disease and changing environmental conditions. Disease outbreaks in recent years have affected aquaculture in numerous countries around the globe, resulting in significant loss of production (FAO, 2012). In 2010 in China, aquaculture production suffered losses of 1.7 million metric tons caused by natural disasters, diseases, and pollution. Disease outbreaks almost eliminated marine shrimp farming production in Mozambique in 2011.

A breakthrough is needed to develop a scalable method of sustainable integrated aquaculture. About 71% of the earth’s surface is covered by water, and a large share of sunlight received by the planet falls on water. A successful aquacultural technique that directly captures this sunlight through managed photosynthesis processes and converts the accumulated biomass into various food products, could greatly enhance global food security. An ecologically appropriate system would focus on integrating flows of energy, nutrients and biomass through the system. This may include integrating aquatic and terrestrial food production, for example, by using waste material from land as food and nutrients. Important issues with current generation aquaculture systems will need to be overcome. Advances are needed in hatchery systems, feeds and feed-delivery systems, and disease management (Godfray, et al., 2010). Other potential improvements may come from better stock selection, optimizing scale of production technologies, and the culture of a wider and synergistic range of species. Other important issues are disease resistance and tolerance to temperature and salinity variation, to enable a broader range of production options. To avoid unintended consequences, a scalable system would avoid discharge of organic effluents or disease treatment chemicals, and avoid being a source of diseases or genetic contamination among wild species.

Substantial research and development work is required for this breakthrough. We expect that it will take 5-10 years for this to be market ready, given adequate resources. Concurrent with technology development, appropriate business models must be developed to allow wide scale-up in developing regions. Deployment challenges include access to finance, and policies regarding land and water use. The difficulty of deployment is CHALLENGING.

**Breakthrough 3 – Difficulty of deployment**

- **Simple**: Requires some improvement to existing infrastructure.
- **Feasible**: Highly regulated market with policy changes required.
- **Complex**: Requires significant financing, limited mechanisms available.
- **Challenging**: Dependent on deploying model(s) being tested; major hurdles outstanding.
- **Extremely Challenging**: Minimal behavior change required; existing demand.

**Policies**
- Highly regulated market with policy changes required.

**Infrastructure**
- Requires some improvement to existing infrastructure.

**Human capital**
- Moderate need to train a limited number of people.

**Access to user finance**
- Significant financing required, limited mechanisms available.

**Behavior change**
- Minimal behavior change required.

**Existing demand**
- Existing demand.

**Market fragmentation/Distribution channels**
- Moderate fragmentation of customers, under-developed channels.

**Business model innovation**
- Deployment model(s) being tested; major hurdles outstanding.
Affordable homes that are resilient to extreme weather events

Shelter is a fundamental human need, but a large segment of the world’s population is either homeless or lives in very poor housing. More than 43 million people are refugees or displaced persons who have been forced to flee their homes and find shelter elsewhere (UNHCR, 2013). Over 800 million people reside in urban slums, often living in improvised dwellings with insecure land tenure (UN HABITAT, 2011). Long-term trends towards urbanization suggest that the urban population in less developed regions, currently less than 3 billion, will exceed 5 billion people by 2050 (UN, 2012). Creating adequate housing for these people will be challenging. Constructing housing with traditional building materials used in rural areas, such as grass and earth, cannot scale up sufficiently in urban areas with much higher population densities. The only option for poorer segments of the population is to create provisional shelter from found materials such as cardboard and plastic sheets. Life is precarious for these people due to their exposure to physical insecurity and unsanitary living conditions. A further challenge is changing temperature and precipitation patterns, which are expected to alter the habitability and safety of homes. The increased frequency and intensity of extreme weather events is expected to place homes and communities at greater risk (World Bank, 2012). A comprehensive and lasting solution to the problem of inadequate shelter requires concerted action in the political, economic, and technological spheres. In particular, technology-related advances are needed to develop robust, affordable, environmentally compatible housing materials and designs that can scale-up to meet global demand.

A breakthrough is needed to develop a functional, resilient, and very low cost housing system accessible to the global poor. Applied research is needed to identify appropriate types of building materials, and the scale and location of manufacturing facilities, in different social, geographical and cultural contexts. Trade-offs may exist between large-scale centralized production versus smaller-scale decentralized production closer to end users. Trade-offs may also exist between production automation and local employment opportunities. The potential use of locally-available raw materials suggests that various geographically specific solutions may exist. Beyond material properties, sensitive design work is required to produce robust, efficient, comfortable, and culturally-appropriate housing solutions that can scale to the extent needed. Potential integration of renewable energy technologies, e.g., photovoltaic or solar-thermal collectors, could allow synergies between human development goals.

While broad in scope, if resources were allocated to allow adequate research and development efforts, we expect that it will take 5 years for this breakthrough to be deployment ready. Significant deployment challenges include a fragmented building industry with multiple actors and components, access to finance for both producers and end users, and municipal and national policies supporting urban poor. The difficulty of deployment would be COMPLEX.
A retrofitted filter to reduce particulate matter exhaust from old heavy-duty vehicles

Outdoor air pollution primarily comes from fuel combustion, mainly from mobile sources such as vehicles, and to a lesser extent from stationary sources such as power plants. Most air pollution in cities in developing countries is attributed to vehicle emissions (UNEP, 2014). This is due to the large number of older vehicles coupled with poor vehicle maintenance, inadequate infrastructure, and low fuel quality. Vehicles in developing countries are typically older than those in industrialized countries. The average age of the vehicle fleet in Tanzania is about 15 years, and in Kenya and Uganda it is about 13 years (UNEP, 2009). Some vehicles, especially heavy-duty diesel-powered trucks and buses, sometimes operate for over 40 years. These older vehicles are responsible for a high percentage of air pollution, despite their low fleet numbers. These vehicles continue to operate because of the high cost of new vehicles and the existence of maintenance and supply lines for older technology. Due to the inherently slow turnover of a vehicle fleet, and the limited economic means of many truck and bus owners to obtain cleaner replacements, existing heavy-duty fleets are likely to remain in operation for many years.

In the longer term, many improved technologies may enable cleaner urban transport systems. These include electric battery and fuel-cell vehicles, and prioritized rapid urban transit with light rail or other modes. These require an appropriate regulatory framework, and involve economic and behavioral trade-offs. Most sources of outdoor air pollution are beyond the control of individuals, and require action by cities, and perhaps national and international policymakers. Policies and investments are needed to support cleaner transport systems as a means to reduce urban outdoor air pollution. In the shorter term, cleaner fuels (with reduced sulfur and lead content) should be used, and official incentives toward renewal of the heavy-duty vehicle fleet could be imposed, such as inspection and maintenance regimes. However, many authorities are reluctant to force older heavy-duty vehicles off the road, because of the economic importance of the services they provide.

Urban air pollution could be significantly improved if these older vehicles could be easily and
inexpensively retrofitted with a technology to reduce particulate matter emission. A number of retrofit emission technologies currently exist for heavy-duty diesel vehicles, such as catalyzed diesel particulate filters, which remove 95% of particulate matter from exhaust but cost up to $10,000 per vehicle (UNEP, 2009). Current particle emission controls are too expensive for widespread adoption.

The answer lies in a robust, low cost technology that can be retrofitted onto old heavy-duty vehicles to reduce particulate matter exhaust. This engineered solution must be inexpensively produced—less than $1000—with simple retrofitting onto existing fleets of trucks and buses. Operation of the device must not impose significant load on the vehicle, in terms of exhaust back pressure or electricity demand. A successful breakthrough technology would use inexpensive and abundant materials (i.e. no expensive catalysts), would require only simple installation and maintenance, and would produce no harmful byproducts (such as NOx).

Assuming adequate level of support to achieve this breakthrough, we expect that it would take less than 5 years to be market ready. A major deployment challenge is the lack of demand within the current market structure. Some level of policy incentive must be created to encourage vehicle owners to install such a device. The difficulty of deployment in this case would be CHALLENGING.

**Breakthrough 5 – Difficulty of deployment**

**Breakthrough 6 – Low cost, distributed monitoring sensors to identify environmental toxins and their concentrations**

Human health is threatened by exposure to a diverse range of environmental toxins such as heavy metals and persistent organic pollutants (POPs). Reducing exposure to environmental toxins is complex due to the variety of chemicals, exposure pathways, and time horizon of effects. Progress towards reducing exposure and improving health outcomes is hindered by the sparseness of data on the presence and concentrations of various toxins throughout the environment. A breakthrough is needed to develop a robust and affordable monitoring technology to identify health threats due to local exposure to
toxins, and make the data publicly available and comparable. This may lead to increased regulatory accountability, reduced emissions of toxic agents, improved knowledge of critical remediation sites, and decreased long-term health risks.

Current monitoring techniques to identify environmental toxins are inadequate. The analysis is typically done in a laboratory, meaning that samples must be collected and transported to a centralized location. After various pre-treatment steps, the samples are analyzed with techniques such as chromatography to determine their makeup. This process can take several days from sample collection to results, and can cost up to $1000 per sample (Ho, et al., 2005). Separate analyses are typically required for each toxic material under investigation. Conventional electrochemical sensors for detecting heavy metals must be used by skilled operators (Aragay, et al., 2011). These methods are not scalable to allow widespread identification of overall toxic health risks throughout the world, including in developing countries.

A new generation of environmental monitoring technology is needed to accurately and inexpensively identify the presence and concentrations of a range of toxic substances. Rather than bring the samples to the laboratory, this breakthrough would take the laboratory to the field and allow widespread in situ measurement of major environmental toxins in realtime. The technology would be flexible enough to analyze samples of water, soil, food or other media, after simple preparation steps. It would identify levels of inorganic materials (such as mercury, lead and arsenic), synthetic organic chemicals (such as dioxin, PCBs and some pesticides), and volatile organic compounds (such as benzene and formaldehyde). Where feasible, the use of appropriate biomarkers would allow determination of actual human health risk, rather than mere occurrence of a toxin in the environment (Lam, 2009). The initial cost of the hardware would be modest (<$500), perhaps taking the form of a plug-in sensor device that leverages the computing power of an existing mobile device. Cost of consumables would be low (~$1 per test), allowing ubiquitous monitoring even in remote sites in developing regions.

To maximize its effectiveness, this sensor technology would be integrated with a web-based platform to allow collection and comparison of environmental toxicity risks over time and place. The linking of improved toxin sensor technology with mobile communications technology would lead to a system for realtime, spatially-explicit, multi-agent exposure monitoring that would create an unprecedented understanding of global toxic health risks and pathways toward their reduction. Once identified, areas of high risk could be assessed in more detail, and critically contaminated sites in need of remediation can be flagged. On a broader and longer-term level, this monitoring technology may lead to advances in green chemistry and life-cycle product design to permanently eliminate the dangers of toxic exposure.

Progress is being made rapidly in the field of environmental monitoring, though there appears to be no focused effort towards the integrated technology we envision here. If sufficient resources were allocated to allow the necessary research and development efforts, we expect that it will take 5 years for this breakthrough to be ready for use. A significant deployment challenge is the lack of consumer demand for environmental monitoring. Therefore, deployment is likely to be COMPLEX.
Breakthrough 6 – Difficulty of deployment

<table>
<thead>
<tr>
<th>Complexity</th>
<th>Policies</th>
<th>Infrastructure</th>
<th>Human capital</th>
<th>Access to user finance</th>
<th>Behavior change</th>
<th>Existing demand</th>
<th>Market fragmentation/Distribution channels</th>
<th>Business model innovation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple</td>
<td>Moderate</td>
<td>Low role of policy/regulation</td>
<td>Moderate need to train a limited number of people</td>
<td>Limited financing required</td>
<td>Minimal behavior change required</td>
<td>Low demand, needs to be built</td>
<td>Moderate fragmentation of customers, under developed channels</td>
<td>Deployment model(s) being tested</td>
</tr>
<tr>
<td>Feasible</td>
<td>Minimal</td>
<td>Low role of policy/regulation</td>
<td>Moderate need to train a limited number of people</td>
<td>Limited financing required</td>
<td>Minimal behavior change required</td>
<td>Low demand, needs to be built</td>
<td>Moderate fragmentation of customers, under developed channels</td>
<td>Deployment model(s) being tested</td>
</tr>
<tr>
<td>Challenging</td>
<td>Simple</td>
<td>Low role of policy/regulation</td>
<td>Moderate need to train a limited number of people</td>
<td>Limited financing required</td>
<td>Minimal behavior change required</td>
<td>Low demand, needs to be built</td>
<td>Moderate fragmentation of customers, under developed channels</td>
<td>Deployment model(s) being tested</td>
</tr>
<tr>
<td>Complex</td>
<td>Simple</td>
<td>Low role of policy/regulation</td>
<td>Moderate need to train a limited number of people</td>
<td>Limited financing required</td>
<td>Minimal behavior change required</td>
<td>Low demand, needs to be built</td>
<td>Moderate fragmentation of customers, under developed channels</td>
<td>Deployment model(s) being tested</td>
</tr>
</tbody>
</table>
**CONCLUSION**

**What it will take to realize the breakthroughs**

Making these breakthroughs come to life will require fundamentally new approaches and business models for funding, technology development, and deployment. The technology-for-development space is currently dominated by NGOs, academic institutions and small-scale social entrepreneurs, predominantly operating on philanthropic grants, with a small but growing amount of ‘impact investments’. Most of these recipients are based in—or originate from—the US or Europe. For technology to truly contribute to sustainable global development, we believe this model needs to change in three closely related ways.

**Different funding modalities: Funding that creates financial viability rather than simply subsidizing unsustainable products and business models**

The breakthroughs identified in this study will require considerable funding—likely hundreds of millions of dollars, if not well over $1 billion. However, more than merely increasing the amount of funding, we believe it is important to change how the funds are deployed.

Currently, most of the funding in the technology-for-development space comes from philanthropic grants. We believe this model does not lead to products which entirely meet the demands of the intended beneficiaries, but rather only to financially unsustainable, small-scale efforts with limited or no accountability beyond the duration of the grant.

In its simplest interpretation, financial sustainability means that products eventually pay for themselves without the need for ongoing subsidies. Presumably, this is because the intended users find them valuable enough to pay for them. However, some population segments will be able to pay enough for some products to make them profitable, while other segments will be too poor to do so. A nuanced analysis is required to segment the market and understand the price elasticity of each income segment. Products that meet the economic constraints of the users require considerable technical and operational prowess. We strongly believe that it is critical to make products inexpensive enough to be affordable to some—even if not all—of the relevant market segments, rather than make them too expensive, and as a result dependent on subsidies for market uptake.

This implies that the traditional model of grant funding needs to evolve much more than it has in recent years, with a much greater emphasis on investments. As illustrated in the matrix below, some technologies will have attractive commercial prospects in both industrialized and developing markets, and hence should be thought of as purely commercial investments, while some will have an attractive market in developing countries only, and hence will require investments at rates-of-return that may be less than those in industrialized markets. Some technologies can be financially sustainable in the long run, but need grants for R&D and initial product development, and a few technologies are not appropriate for generating profits or even revenues. Per our analysis, only 3 of the breakthroughs identified in this study are appropriate for purely philanthropic funding, 23 will likely require grants for R&D and initial product development, and the rest are appropriate for some type of investment.

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1 This matrix has been reproduced here from the List of the 50 Breakthroughs that appears earlier in the report.
## Funding mechanisms for the breakthroughs

<table>
<thead>
<tr>
<th>Non-commercial</th>
<th>Commercial potential</th>
<th>Attractive for emerging markets</th>
<th>Attractive for industrialized markets</th>
</tr>
</thead>
<tbody>
<tr>
<td>6. Biometric ID systems</td>
<td>46. Distributed sensors for environmental toxins</td>
<td>40. DNA-based rape kit</td>
<td>3-4. Vaccines for HIV, TB, Malaria</td>
</tr>
<tr>
<td>28. Precision agriculture systems for irrigation and fertilizer</td>
<td>23. Off-grid vaccine refrigerator</td>
<td>42. IoT for low income populations</td>
<td>8. New generation of homes for the poor</td>
</tr>
<tr>
<td>7. Affordable smartphones</td>
<td>27. Long cost refrigerated vehicle</td>
<td>44. Affordable homes resilient to extreme climate events</td>
<td></td>
</tr>
<tr>
<td>32. Low cost tilling machine</td>
<td>35. Wireless broadband technologies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>41. Wireless broadband technologies</td>
<td>30. Solar powered irrigation pumps</td>
<td></td>
<td></td>
</tr>
<tr>
<td>51. Low cost family transport</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Smart electronic textbooks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>38. Wearable cameras</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>39. Low cost aerial vehicles for imagery</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>13. Long-lasting antiretroviral for HIV</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>36. Spatial on-farm pest repellent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>49. New bulk storage technologies</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24. Thermo-stabilizing mechanism for vaccines</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Likely time to market (years), as proxy for funding required: 0-3, 3-6, 6-8, 8-10, >10
Innovative approaches to R&D, in the absence of enough institutions dedicated to scientific research for advancing global development

Bringing these breakthroughs to life will require a considerable amount of advanced R&D, in several fields including pharmaceuticals, biomedical sciences, crop and soil sciences, food sciences, electrical engineering, mechanical engineering and software development.

Within the technology-for-development space today, dedicated R&D capabilities exist only for crop, soil and food sciences through the Consortium of International Agricultural Research Centers (CGIAR). Beyond this, the little R&D that is conducted, is undertaken by institutions that are not necessarily aligned with the objectives of global poverty alleviation. For example, most of the research for vaccines and other drugs is conducted by pharmaceutical companies in industrialized countries. These organizations are required by their corporate mandate to focus on profit-maximization rather than creating solutions for low income populations. The other source of R&D is universities (also mostly in industrialized countries), where the direct incentives of faculty and students are aligned with academic objectives like professorial tenure and grades. We believe this problem is exacerbated by excessive reliance on grants that do not incorporate mechanisms for accountability beyond the duration of the funding.

The long-term solution is concerted investment in regional and local R&D capabilities in developing countries, through government-run labs, appropriately structured academic research centers, and industrial partnerships. In the meantime, a number of creative structures and funding mechanisms will be required to extract more value from the institutions currently capable of conducting the necessary R&D, including:

- Greater utilization of private sector research in industrialized countries, potentially even subsidizing their R&D through philanthropic or public funds, or by contracting out the research. This is particularly true in biotech, where virtually all the major technological breakthroughs—pharmaceuticals, diagnostics, etc.—have been developed by companies in the US or Europe. It will be important to put in place appropriate measures to ensure that the public interest is protected, and that profit motives do not supersede public good.

- Leverage existing repositories of research and intellectual property in industrialized countries, including unused corporate IP and government-funded labs conducting advanced research. Only a small fraction of patents filed in countries like the US are ever commercialized. While most of these are likely of no use in the global development context, it is possible that some of them hold the key to some of the breakthroughs listed in our study. However, because they may not have commercial value in the industrialized markets, such patents remain ‘shelved’.

- More accountable and creative structures for funding universities and other research institutions. As mentioned above, the main challenge with the way universities and academic research institutions are currently used in the technology-for-development context is the misalignment of incentives, and the lack of accountability to outcomes that can come with grant funding. Mechanisms like contracts (which can be terminated for non-delivery), combined with a shift in the nature of academic incentives (e.g., less emphasis on theoretical publications, and a greater emphasis on measurable development outcomes), can unlock a very valuable source of practical R&D.

To create sustainable businesses for deploying the technologies, work closely with the private sector—not just from India and China, but also emerging economies across Africa

In recent years, the economies of several countries in sub-Saharan Africa have demonstrated sustained, strong growth. This growth has been accompanied by greater demand for all manner of goods and services, which companies from India, China and South Africa have been making aggressive investments to meet. A salient feature of this economic growth has been the emergence of successful local companies—led by local corporate leaders—which are achieving true ‘double-bottom-line’ results.
through efficient and sustainable business models. Countries like Kenya, Nigeria, Ghana and Rwanda are all becoming home to successful African companies which are aiming to expand their services to a larger number of consumers in their countries. While not always competitive against established multinationals, these companies are better positioned to provide effective solutions in their home markets, than are international NGOs. Even for products and services which do not lend themselves to purely profit-seeking models, such companies are well positioned to engage in public-private partnerships with their governments. Funders and technologists, alike, should make a much greater effort to find and partner with such companies.

As countries in the developing world have emerged into regional and global powers, there has been an increasing demand for accountability and pragmatism from the social sector. Unfortunately, the social sector—including the technology-for-development sector—has not kept up with these changes, and outdated philosophies and business models still persist as a legacy of the ‘aid’ mentality. We believe that achieving these technological breakthroughs and translating them to tangible impact will require a fundamental shift in the current incrementalist ‘appropriate technologies’ model, towards more ambitious and results-based approaches.

Next steps on the 50 Breakthroughs

This study aims to begin a robust and honest conversation about where and how technologies can make a real and sustainable difference to the lives of the billions living in poverty. To that end, our hope is to work with a broad range of organizations and individuals in the ecosystem, and create an ongoing ‘State of the Breakthroughs’ forum—a combination of online and physical discussions and events. We hope that such a forum will draw attention to innovative, impactful ideas that emerge, and that those ideas get funding as well as the right partnerships to take them to fruition.

We look forward to the conversation.
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