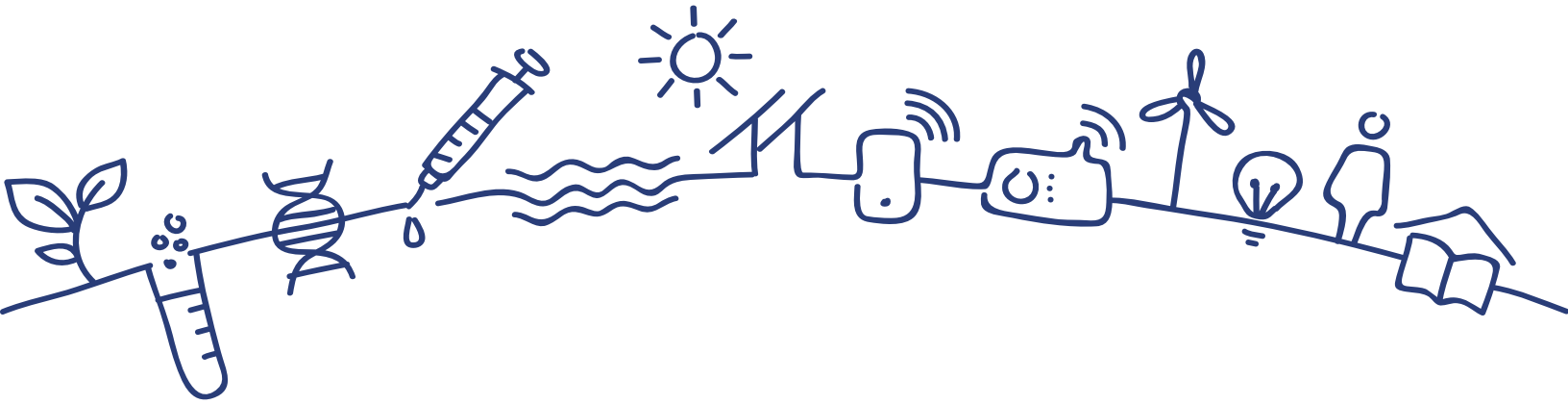
50 BREAKTHROUGHS

Critical scientific and technological advances needed for sustainable global development



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NOTES ON METHODOLOGY AND LAYOUT

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.

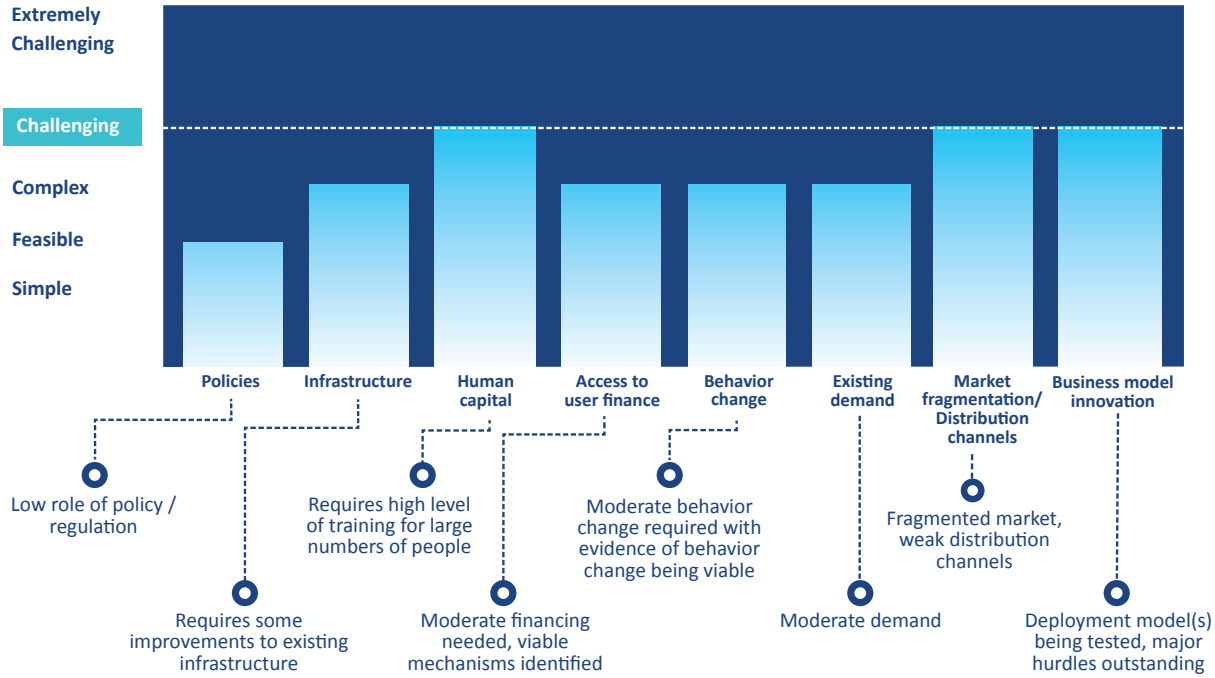
[1] A structured communication technique, originally developed as a systematic, interactive forecasting method which relies on a panel of experts who anonymously reply to questionnaires and subsequently receive feedback in the form of a statistical representation of the 'group response', after which 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 A

	Simple	Feasible	Complex	Challenging	Extremely Challenging
Policies	Minimal role of policy/regulation	Low role of policy/regulation	Regulated market with supportive policies	Highly regulated market with policy changes required	Highly regulated and controversial changes required
Infrastructure	Minimal need for infrastructure	Dependent on existing infrastructure	Requires some improvements to existing infrastructure	Requires moderate improvements to infrastructure	Requires major improvements to infrastructure
Human capital	Minimal need for human capital development	Low-moderate need for human capital development	Moderate need to train a limited number of people	Requires high level of training for large numbers of people	Requires national scale training programs
Access to user finance	Financing not required	Limited financing required	Moderate financing needed, viable mechanisms available	Significant financing required, limited mechanisms available	Significant financing required, no identified mechanism
Behavior change	No behavior change required	Minimal behavior change required	Moderate behavior change required with evidence of behavior change being viable	Major behavior change required, potentially on daily basis	Significant behavior change needed on daily basis, changes contrary to cultural norms
Existing demand	Strong existing demand	Existing demand	Moderate demand	Low demand, needs to be built	Extremely low demand or not a perceived need
Market fragmentation/ Distribution channels	Highly concentrated market or well defined channels	Fairly concentrated market and/or well defined channels	Moderate fragmentation of customers, under-developed channels	Fragmented market, weak distribution channels	Highly fragmented, challenging to reach customers
Business model innovation	Clear deployment models existing at scale	Deployment model in process of scaling	Deployment model(s) being tested	Deployment model(s) being tested, major hurdles outstanding	No identified deployment model, major hurdles identified

Exhibit A

Breakthrough – Difficulty of deployment



FOOD SECURITY AND AGRICULTURAL DEVELOPMENT

OVERVIEW

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[1] (**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

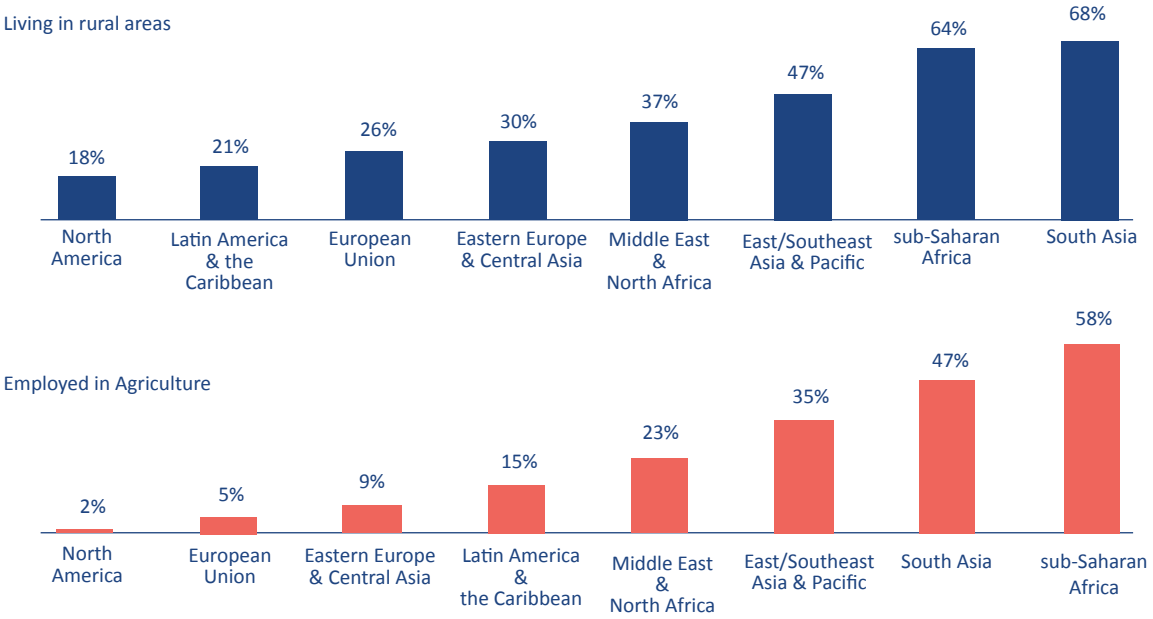


Exhibit 1: Most people in sub-Saharan Africa and South Asia live in rural areas. In addition, the majority of the labor force in these regions works in agriculture and related activities (World Bank, 2014).

[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

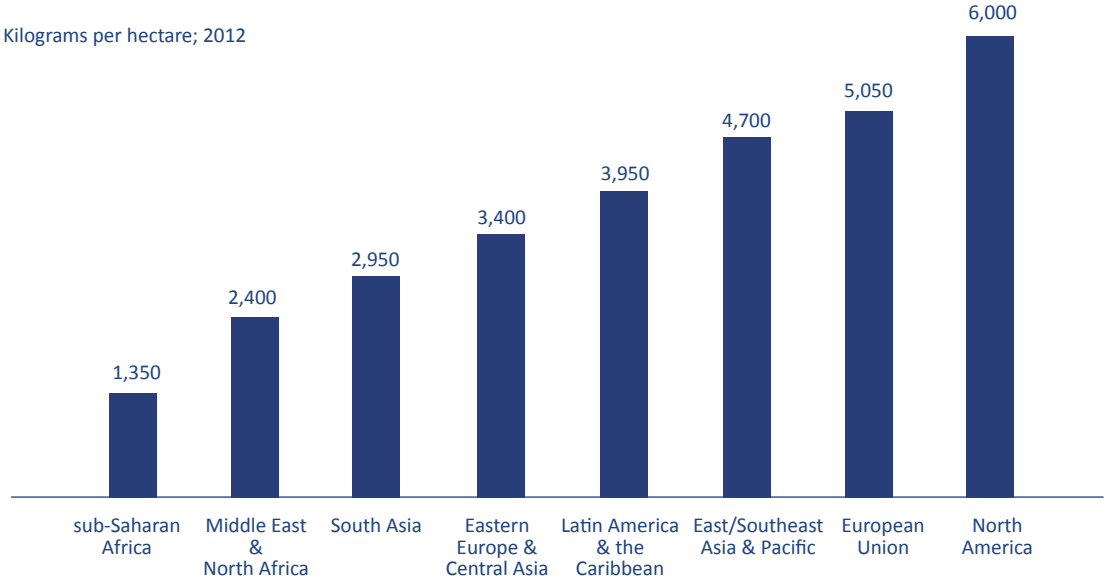


Exhibit 2: Cereal crop yield in sub-Saharan Africa is less than half of South Asia, and a fraction of that in other parts of the world. Yields for other agricultural commodities—cash crops, horticulture, livestock—also lag significantly behind (FAO, 2014) (World Bank, 2014).

Number of countries that are net importers vs. net exporters of food in each region

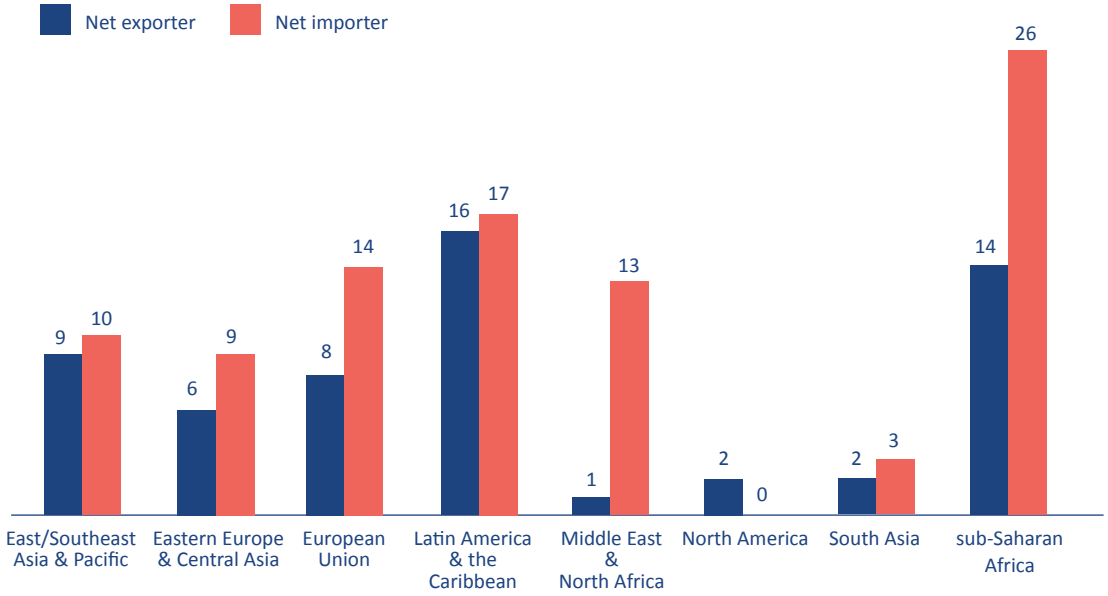


Exhibit 3: The majority of countries in sub-Saharan Africa and South Asia are net importers of food (World Bank, 2014) (FAO, 2014). While this is also true of all other regions, agriculture is neither the mainstay of their economies, nor the primary generator of employment.

Rates of undernourishment, in different regions of the world

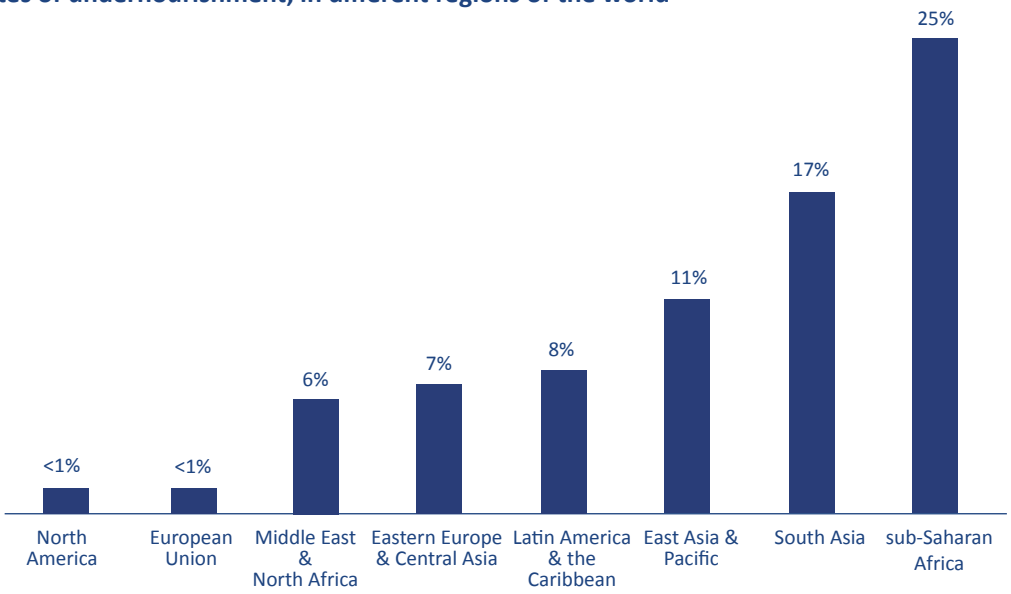


Exhibit 4: Based on daily caloric intake, 25% of the population in sub-Saharan Africa and 17% in South Asia are undernourished. This is a clear indicator of food insecurity in these regions (World Bank, 2014) (FAO, 2014).

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

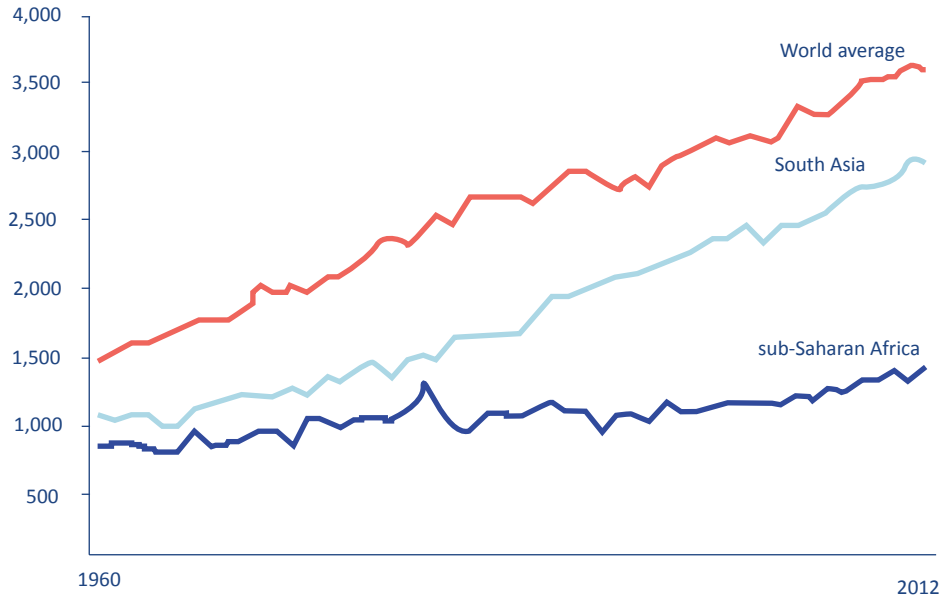


Exhibit 5: The Green Revolution led to dramatic increases in agricultural productivity in South Asia, to the extent that South Asia is approaching agricultural self-sufficiency. On the other hand, sub-Saharan Africa continues to lag far behind the world average.

Cereal production, yield and land usage in South Asia and sub-Saharan Africa, 1961 - 2009

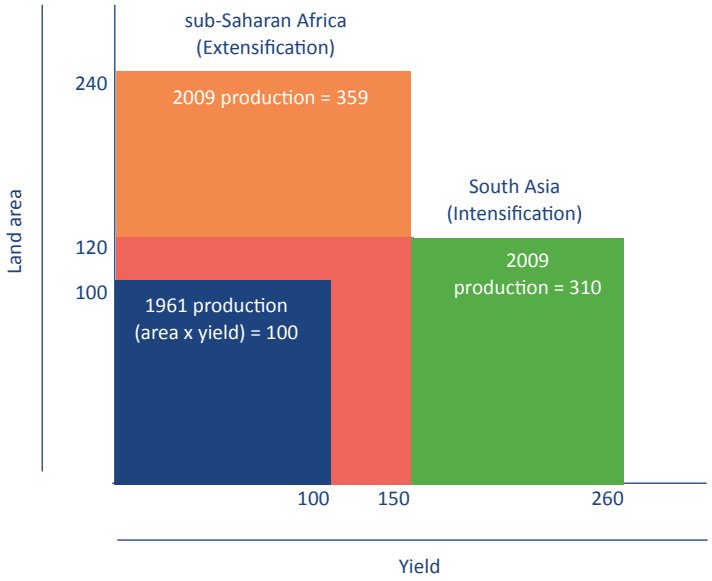


Exhibit 6: South Asian countries have increased agricultural yield dramatically over the past few decades using intensified agricultural practices. Compared with 1961, per hectare cereal yield in South Asia has increased by 165%, leading to a total output increase of 210%, with only a small increase 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

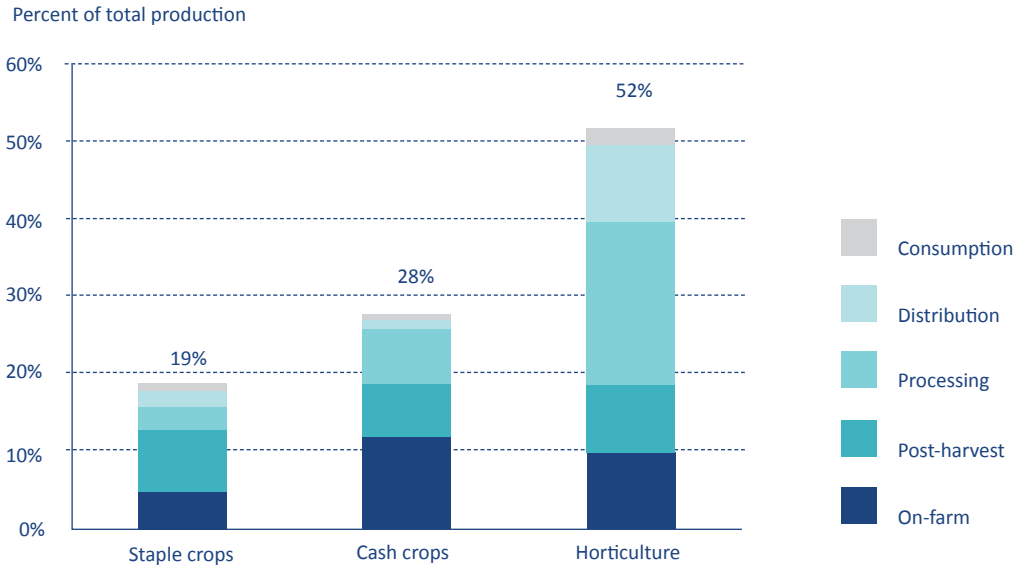


Exhibit 7: Smallholder farmers in sub-Saharan Africa lose a substantial portion of their produce, even before the food is ready to be consumed. The primary reason for the losses is the lack of appropriate technologies for handling, storage and transportation (FAO, 2011).

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

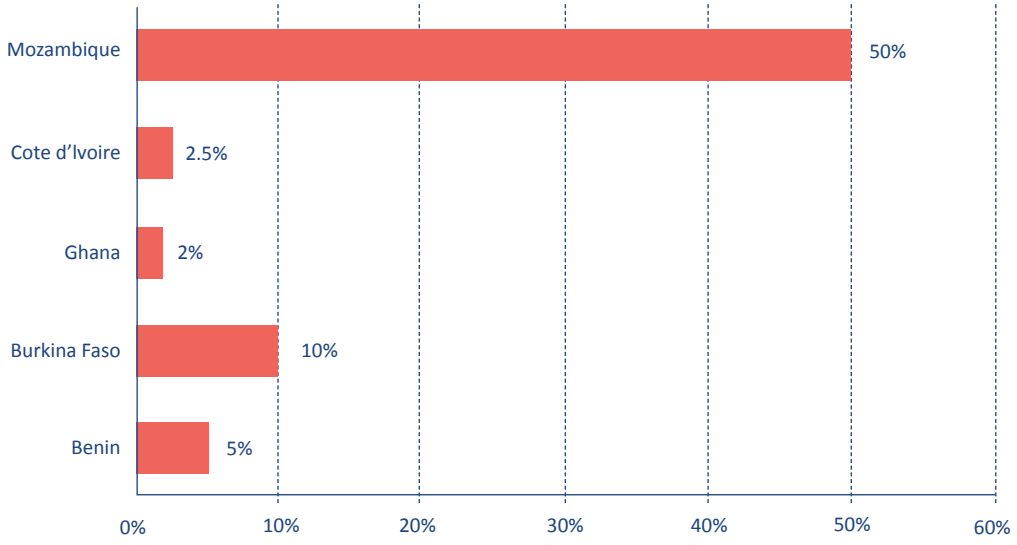


Exhibit 8: Cashews have to be processed before they are consumed. The dearth of cashew processing factories means that most of the cashews grown in Africa are shipped elsewhere for processing.

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.

Distribution of women's economic activities

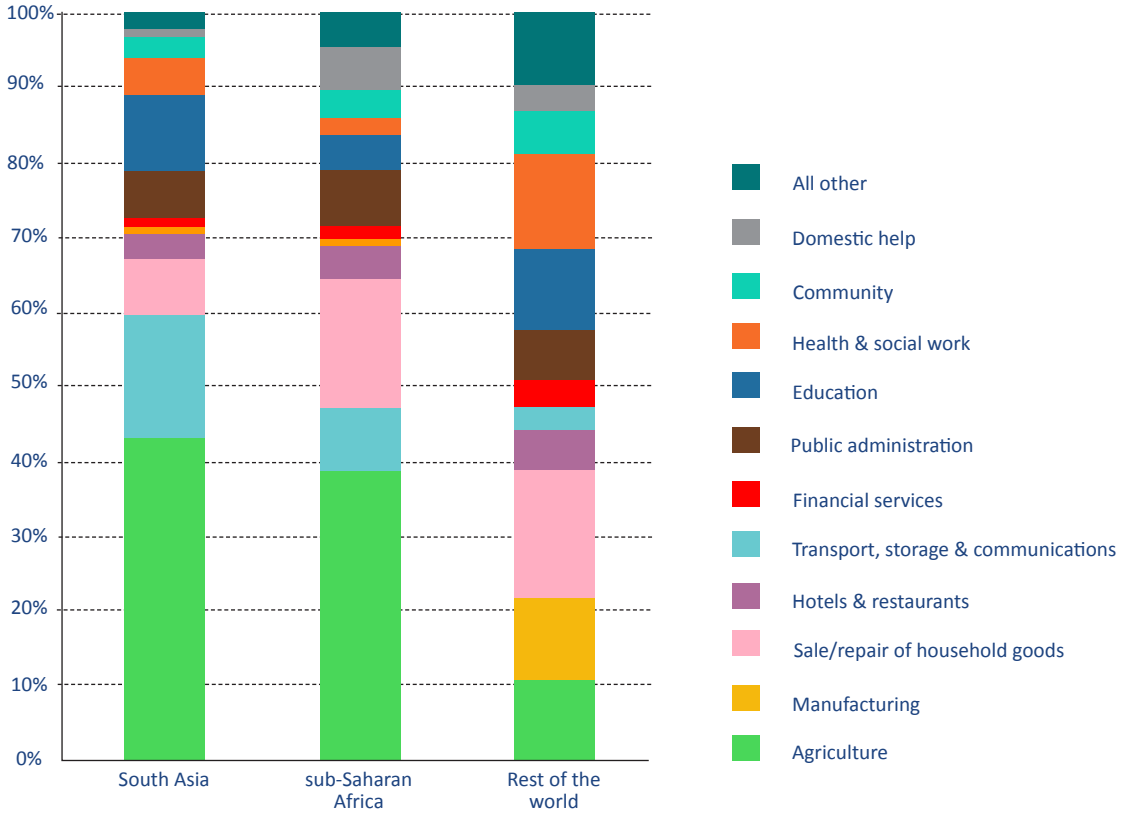


Exhibit 9: In South Asia and sub-Saharan Africa, agriculture constitutes the single largest type of economic activity performed by women.

Share of agricultural work performed by women across 10 low and middle income countries

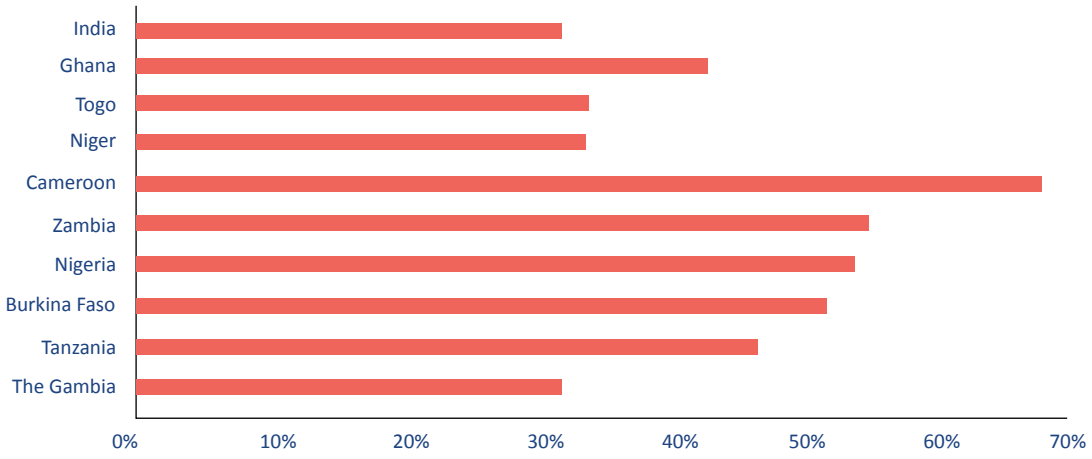


Exhibit 10: Women contribute to a substantial portion of total agricultural labor, ranging from 32% in India, to almost 70% in Cameroon.

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).

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS FOR FOOD SECURITY AND AGRICULTURAL DEVELOPMENT

1. **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.

2. **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.

3. **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.

4. **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.

5. **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.

11 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.

12 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.

13 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.

14 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.

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
- A low cost precision irrigation application system, ideally combining fertilizers with irrigation Portable sensors for estimating depth of shallow groundwater

FAO

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

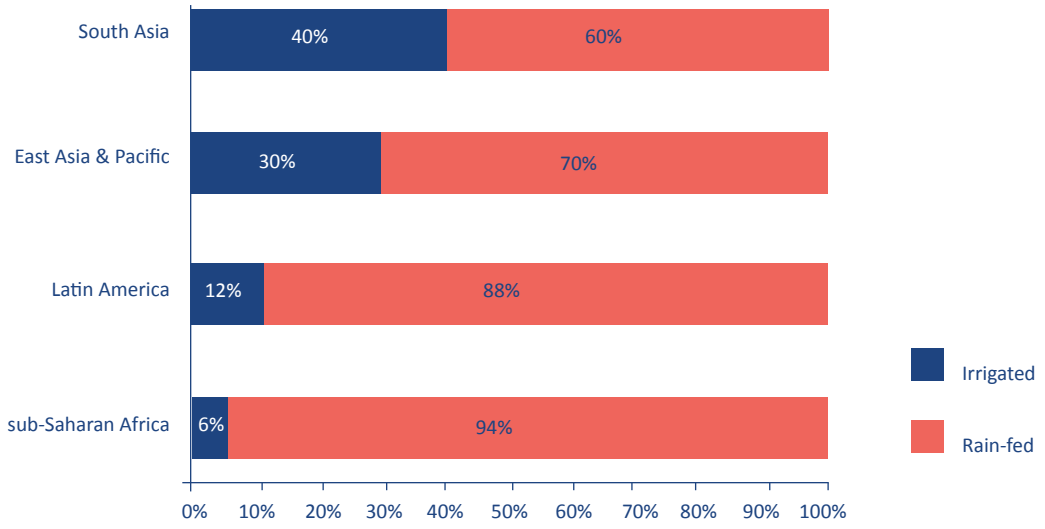


Exhibit 1: Most of the agricultural land in most developing countries is rain-fed. This is especially true for sub-Saharan Africa.

[1] With the exception of Bangladesh and Indian states like Orissa, which were not deeply involved in the Green Revolution.

Rainfall and cereal yields in Burkina Faso

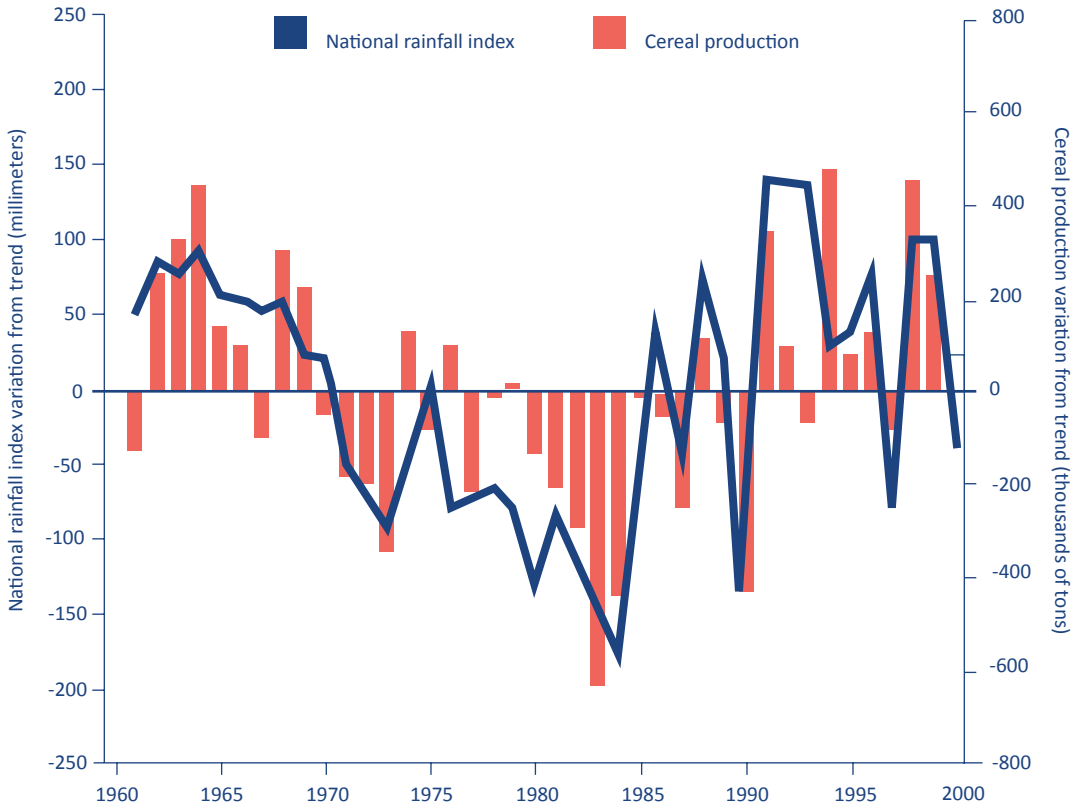


Exhibit 2: Cereal production in Africa is closely linked to rainfall, as shown in this study from Burkina Faso (Molden, 2007).

1 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

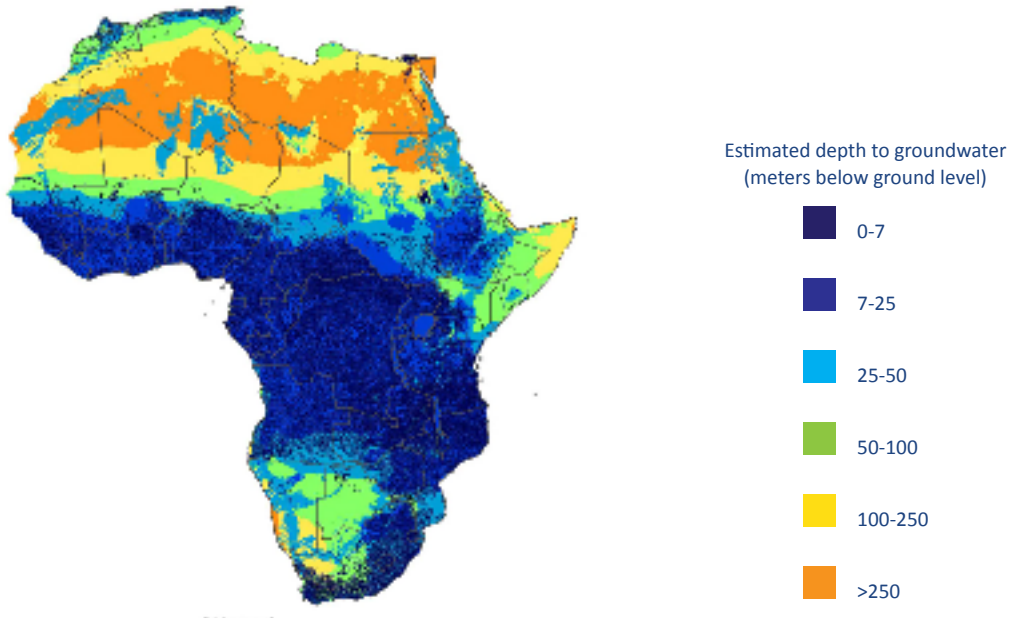


Exhibit 3: Current data suggests that there is substantial unutilized groundwater through much of sub-Saharan Africa (British Geological Survey, 2014).

Water scarcity around the world

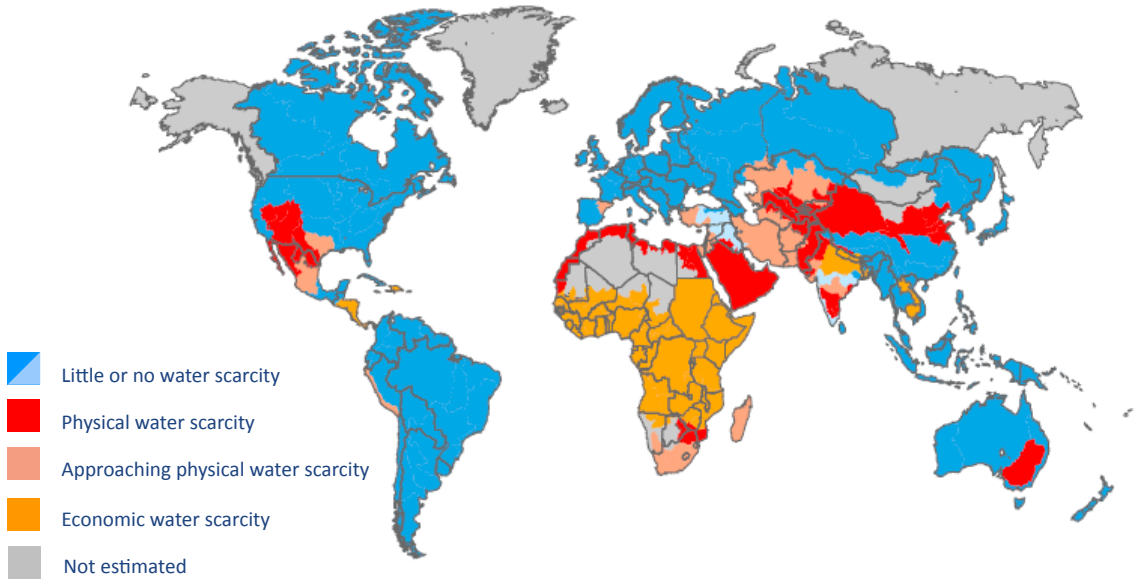


Exhibit 4: Most of sub-Saharan Africa is considered to be facing 'economic water scarcity' because the majority of the population cannot afford the pumps and other equipment to access available water. By contrast, parts of the world that do not have adequate water present, are considered to be facing 'physical water scarcity' (IWMI, 2007).

2 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

Steps	Levels of sophistication			
	Basic	Limited	Medium-scale	Large-scale, sophisticated
Capture	Small hand-dug well ($50-$200)	Borehole ($300-$1,000)	Deep borehole or small dam ($1,000-$3,000)	Community dam (> $0.5 million)
Lift	Hand-carried by bucket ($0)	Treadle pump, hand pump or rope pump ($50-$100)	Small motorized pump, or animal drawn pump ($100-$150)	Large motorized pump (>$1,000)
Storage	Drum or small pond ($50-$200)	Artificial pond ($300-$1,000)	Small reservoir or groundwater recharge ($1,000-$3,000)	Large reservoir or community dam (> $0.5 million). Note: this can be the same as the reservoir used for capture.
Distribution	Furrow ($0)	Ditch, small canal, or basic hose ($10)	Small network of pipes or canals ($500-$2,000)	Extensive network of pipes or canals (> $2,500)
Application	Pour/furrow ($0)	Hose, or drip/ trickle kit ($10-$25)	Automated drip, single sprinkler, or sprinkler system ($500-$2,000)	Pivots or large mobile sprinklers (>$ 2,500)

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.

Cost per meter of a 150 meter borehole in Ethiopia

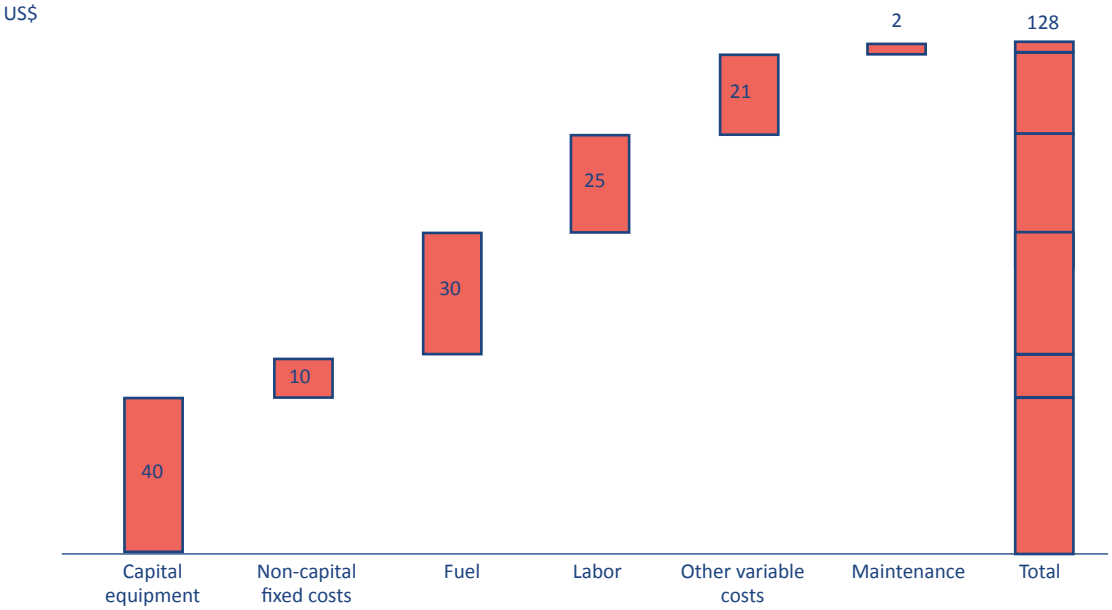


Exhibit 5: Digging a 150 meter borehole costs roughly $130 per meter. About 75% of this is expense for capital equipment, fuel, and labor (Rural Water Supply Network, 2006).

3 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.

4 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.

5 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.

6 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.

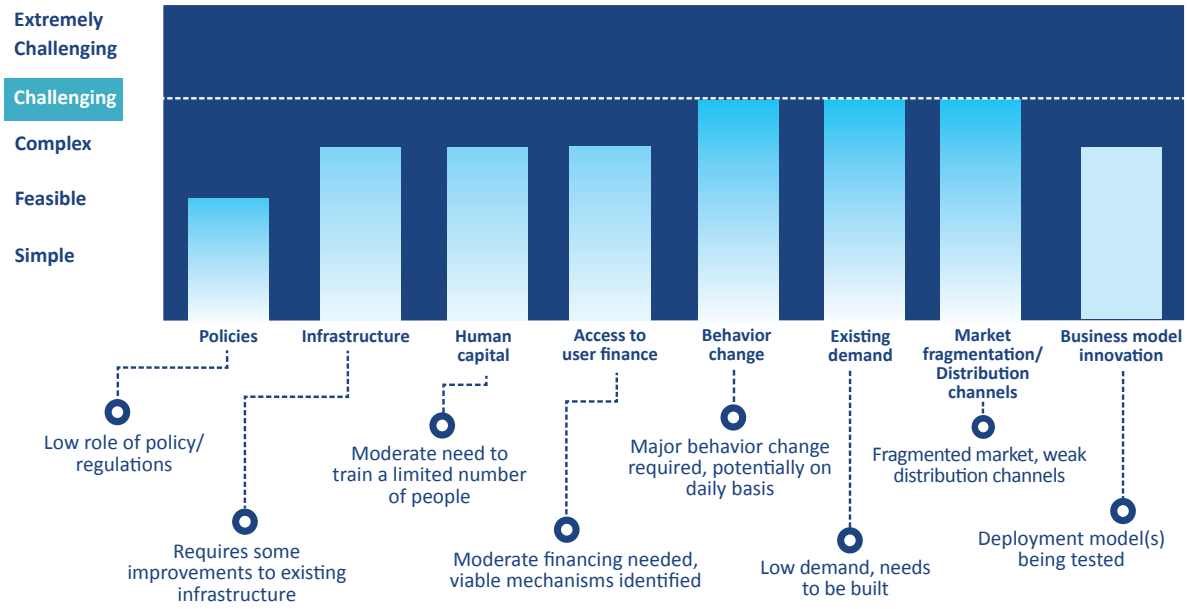
Low cost drilling technologies for shallow groundwater, which reduce the cost to under $100 per farmer

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



Breakthrough 2

Low cost, easy-to-construct rainwater storage repositories where harvested rainwater can be stored for several months without contamination

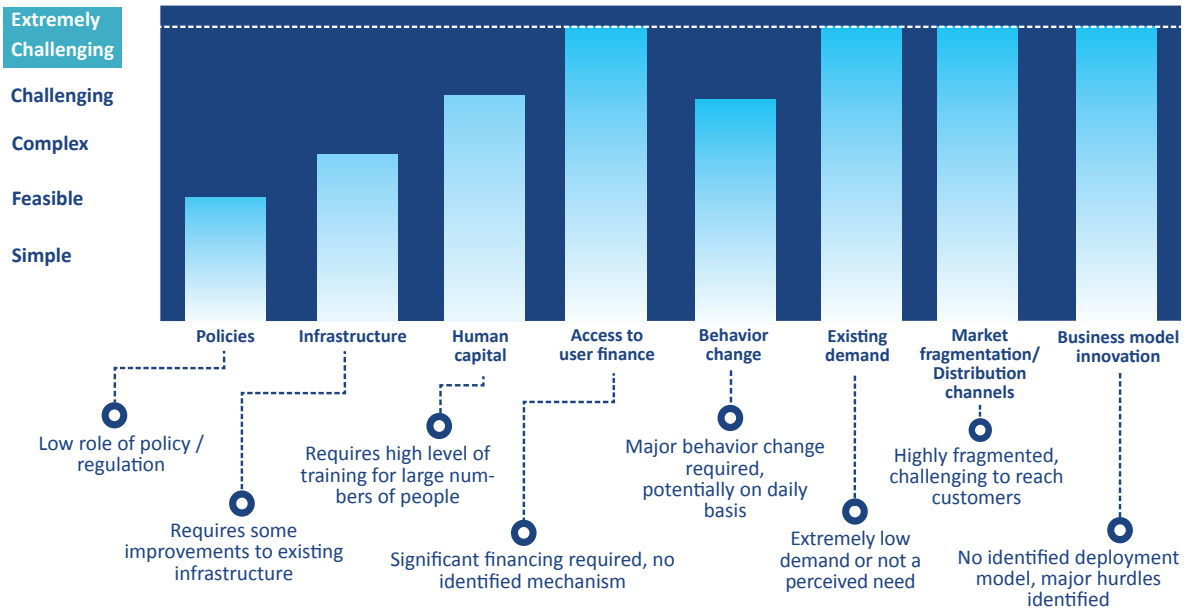
A feasible mechanism to capture and store rainwater for several months at a time, can prevent runoff-related losses, and create shallow groundwater reserves. There is considerable research on the artificial recharging of groundwater (Government of India, 2007), but most techniques (e.g., percolation 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.

Breakthrough 2 – Difficulty of deployment



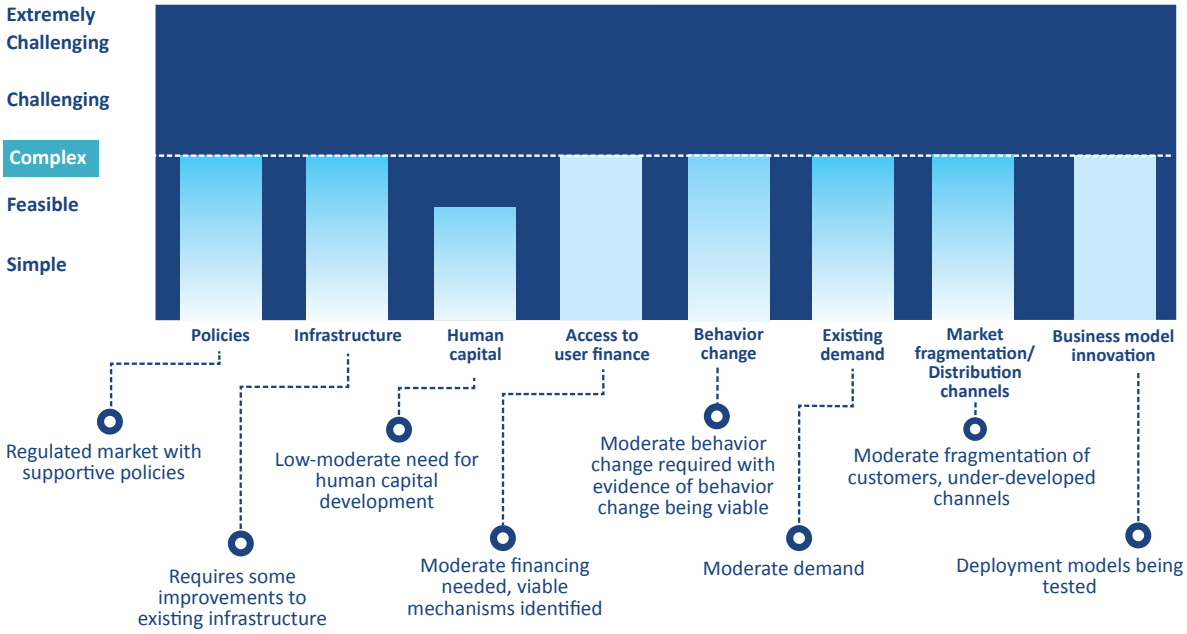
Breakthrough 3

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.

Breakthrough 3 – Difficulty of deployment



Breakthrough 4

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.

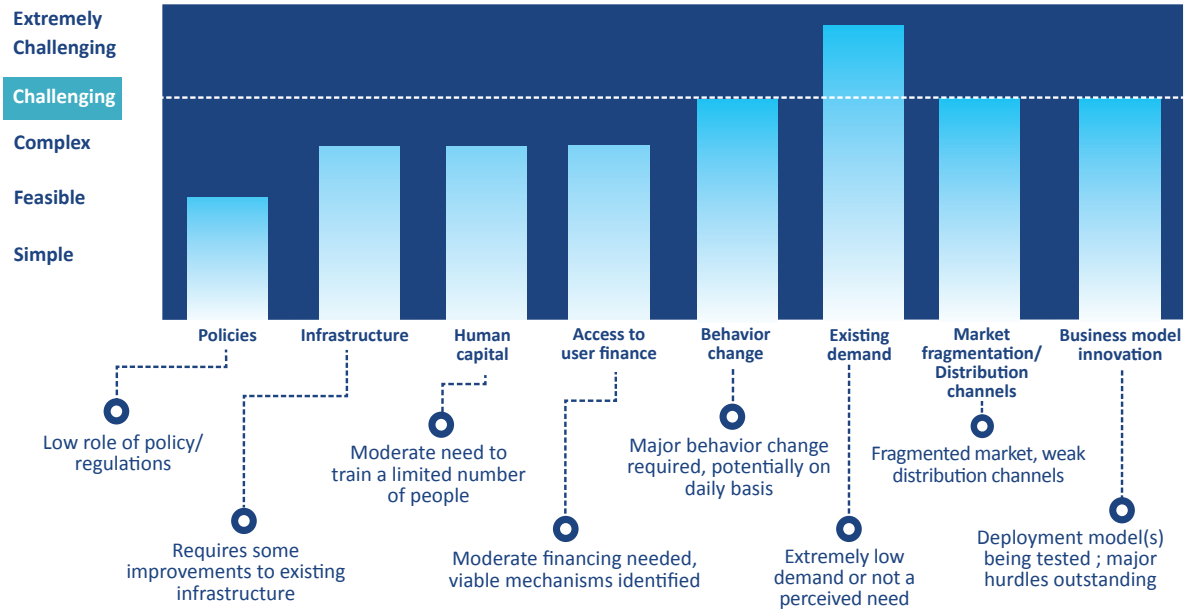
As discussed in other sections of this report, fertilizer overuse is a major problem, with overall efficiency of about 50% for nitrogen, less than 10% for phosphorous, and about 40% for potassium (Baligar, Fageria, & He, 2001). The rest of the applied fertilizer is unavailable to the plants and is wasted 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



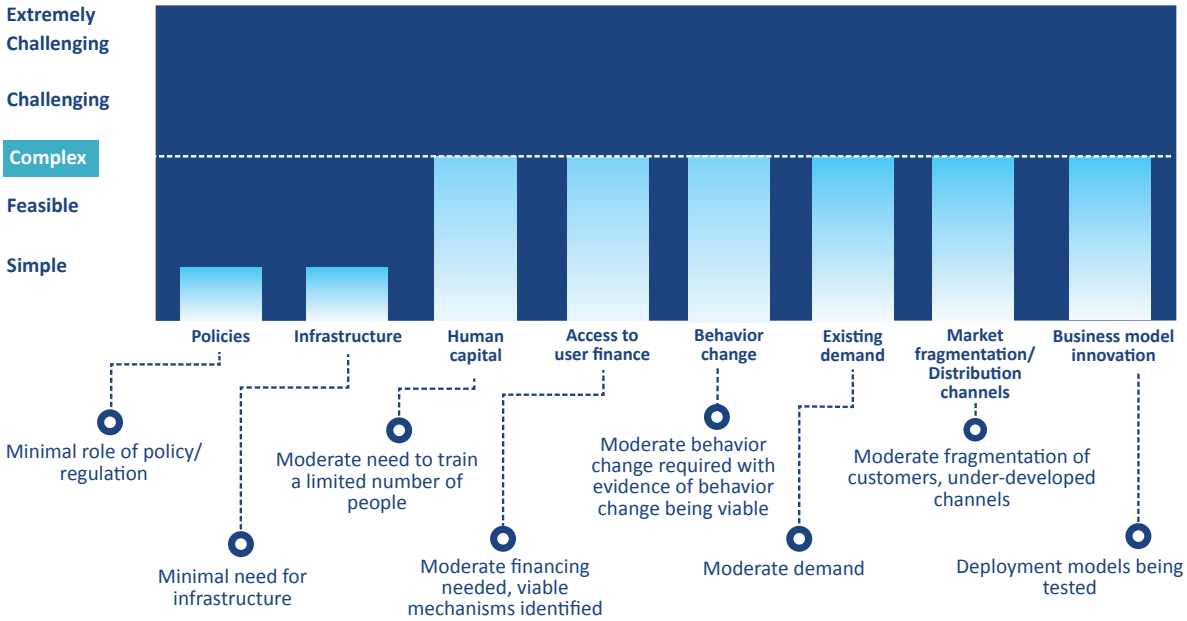
Breakthrough 5

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



FERTILIZER AND PLANT NUTRIENTS[1]

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.[2] 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

[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 (NH_3) or nitrate (NO_3). 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.

Sources of the 3 key soil nutrients, and how they are lost

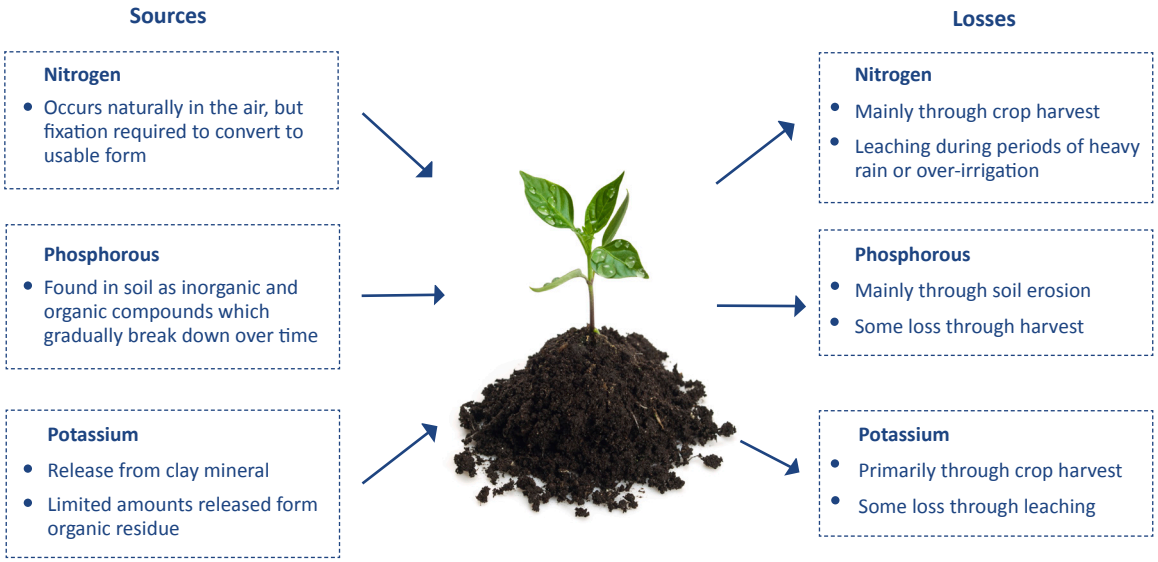


Exhibit 1: Three nutrients are essential for agriculture, all of which occur naturally. However, intensive agricultural cycles cause rapid depletion of these nutrients from the soil (Silva & Uchida, 2000).

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 rhibozome 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.

1 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

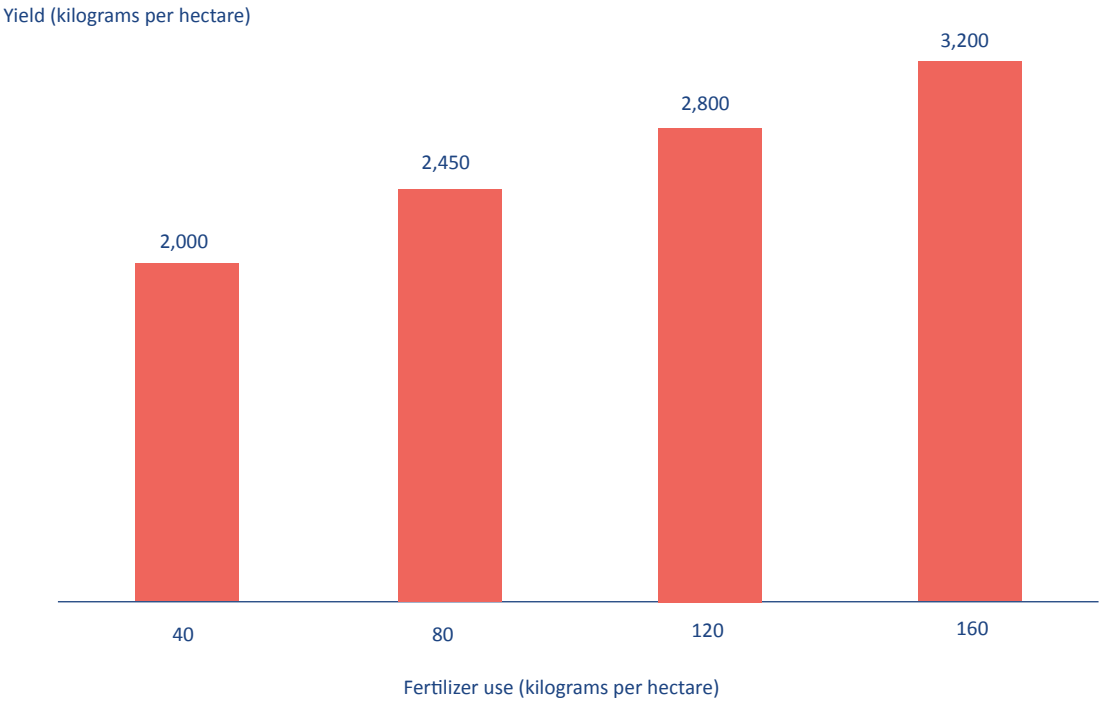


Exhibit 2: Fertilizer use directly leads to yield increases, as shown in this study of maize (Pandey, Maranville, & Admou, 2000). However, depending on the type of crop, the condition of the soil and other factors, there is a diminishing return to adding fertilizer after a certain point.

Fertilizer use for some staple crops in sub-Saharan Africa compared with other parts of the world

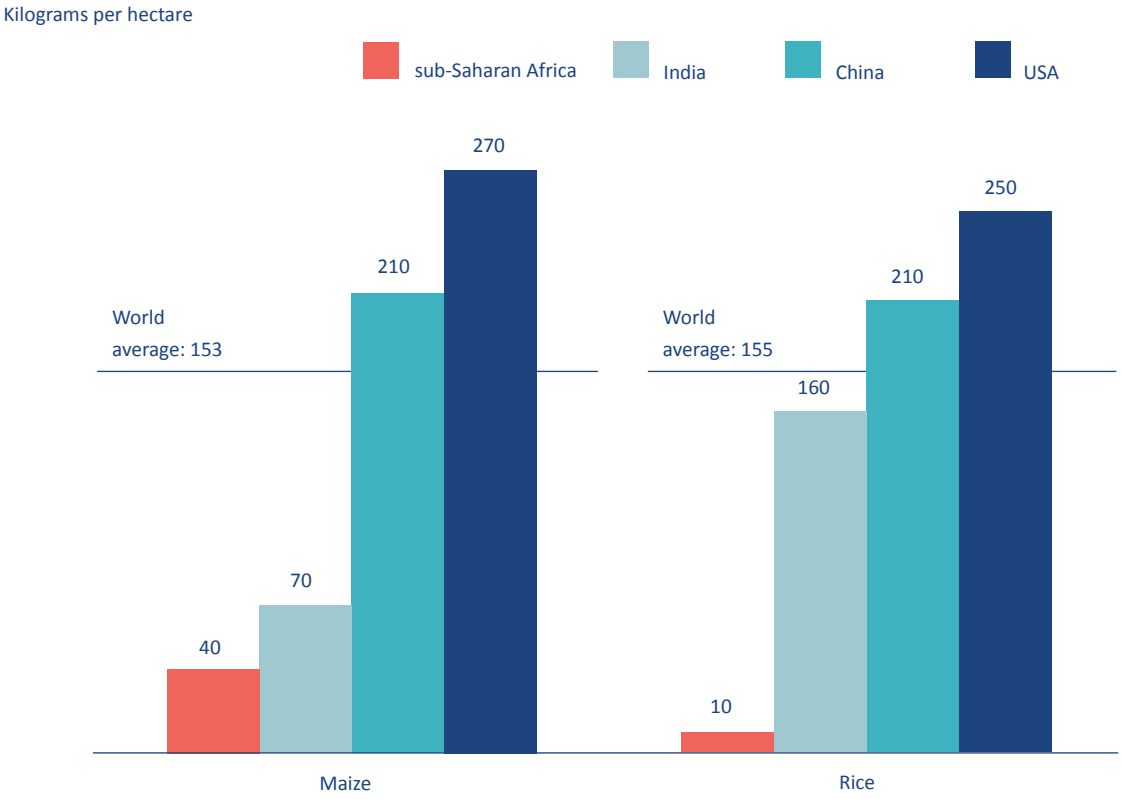


Exhibit 3: Fertilizer use in sub-Saharan Africa is a fraction of that in other parts of the world (FAO, 2009).

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

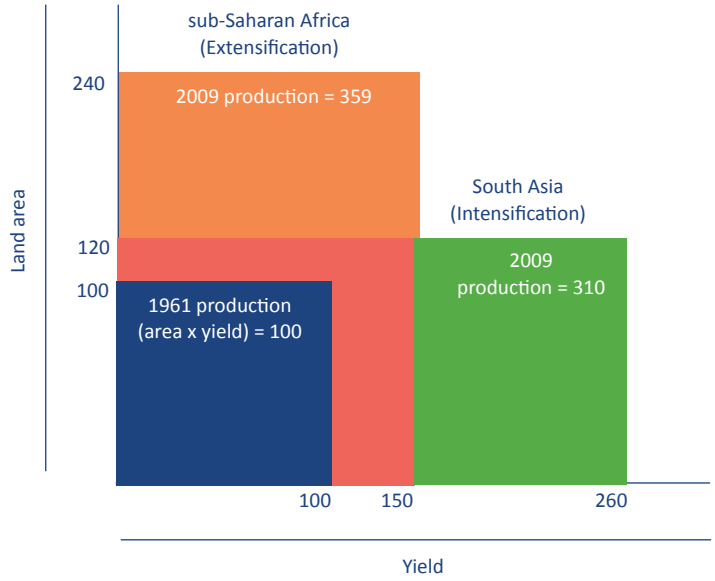


Exhibit 4: Synthetic fertilizers, a critical component of intensified agriculture, have been a key difference between agricultural development in South Asia and sub-Saharan Africa. Compared to 1961, per-hectare cereal yield in South Asia has increased by 165%, for total output increase of 210%, with 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).

2 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).

Nitrogen balances in maize farming systems in different parts of the world

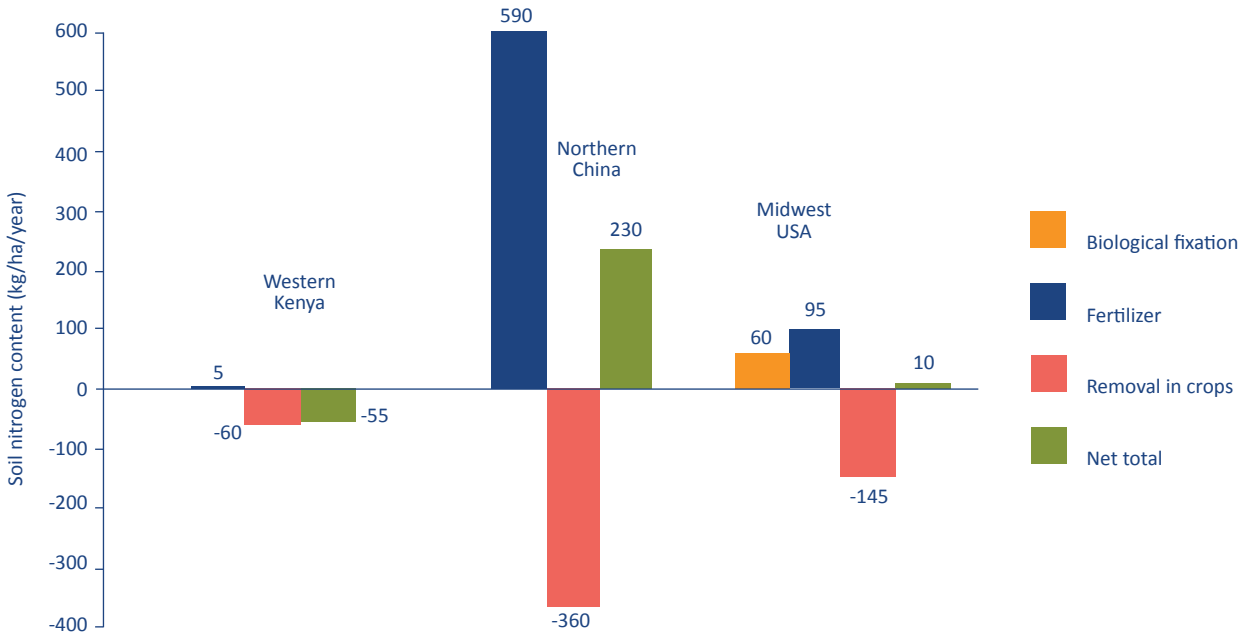


Exhibit 5: Soil nutrient losses in Africa are higher compared with most other parts of the world where much more fertilizer is used to replenish nutrient-depleted soil during crop growth and post-harvest (Vitousek, et al., 2009).

Soil nutrient losses in Africa

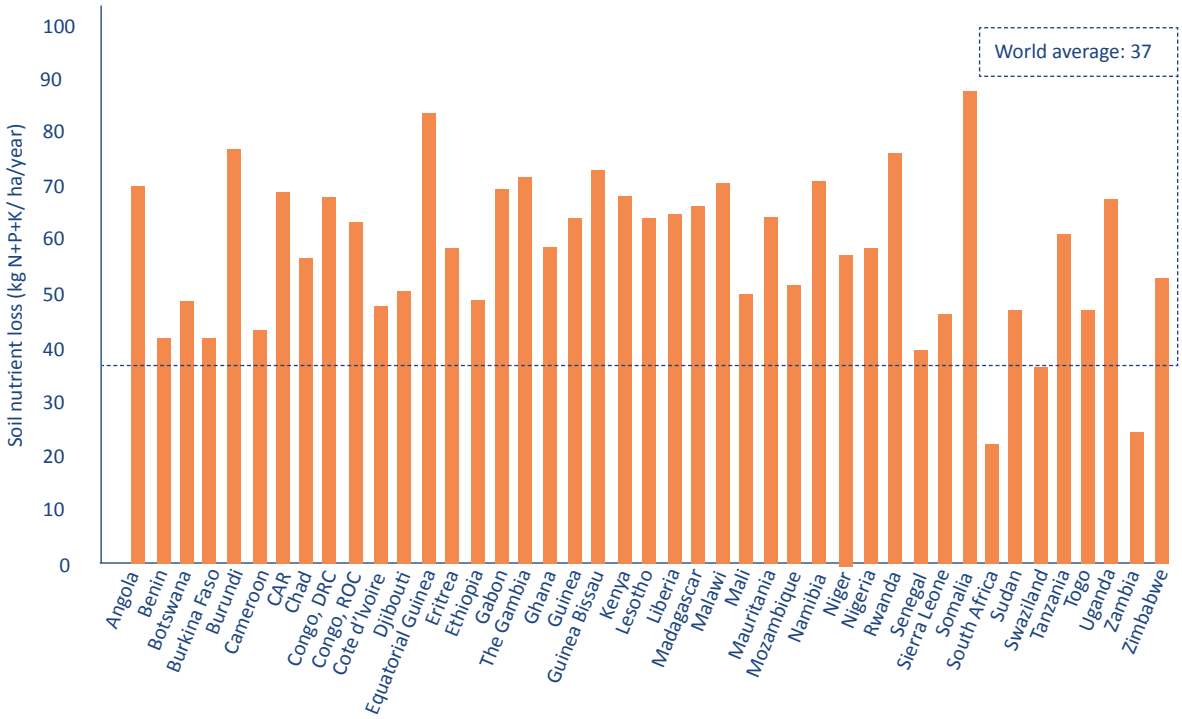


Exhibit 6: The problem of nutrient mining is common across sub-Saharan Africa; 85% of African farmland has nutrient mining rates of more than 30 kg per hectare per year and 40% had rates greater than 60 kg per hectare per year (Henao & Baanante, 2006).

3 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**).

Fertilizer production: Global vs. sub-Saharan Africa

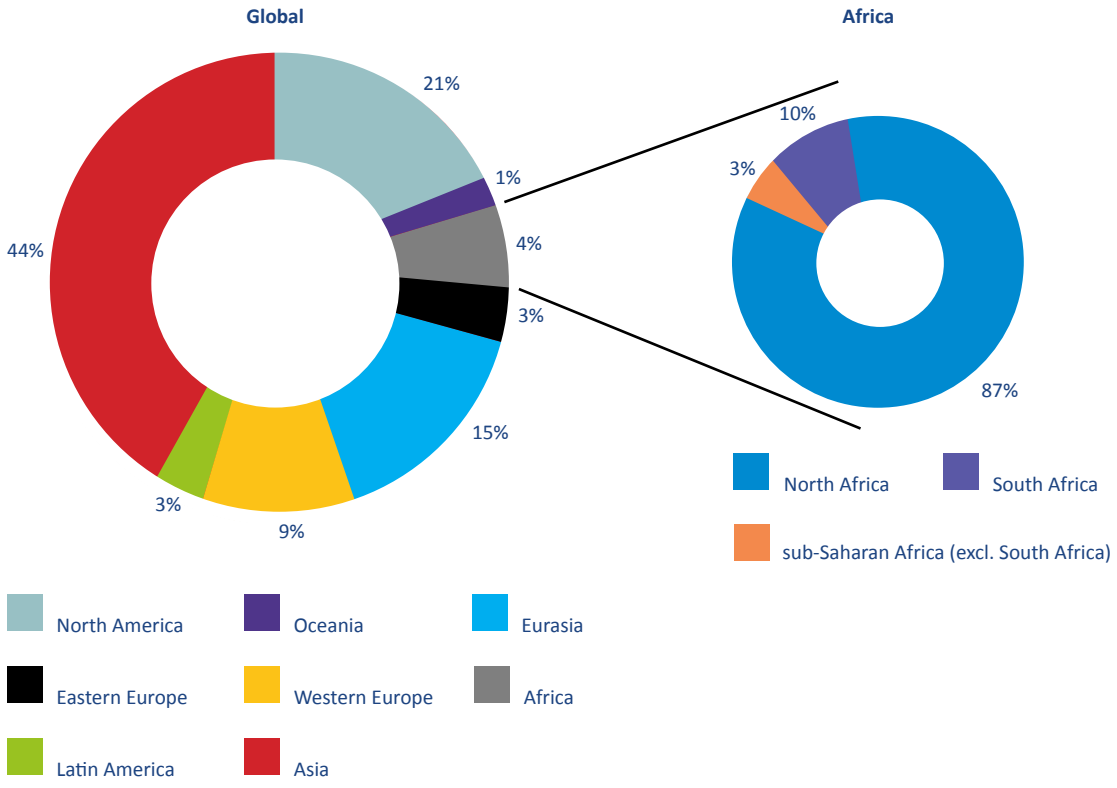


Exhibit 7: Barely 0.1% of the world's synthetic fertilizer is produced in sub-Saharan Africa (excluding South Africa). All of Africa accounts for 4% of global production, most of which is from North Africa, with South Africa accounting for most of the remaining.

End user cost of fertilizer in the USA vs. in sub-Saharan Africa

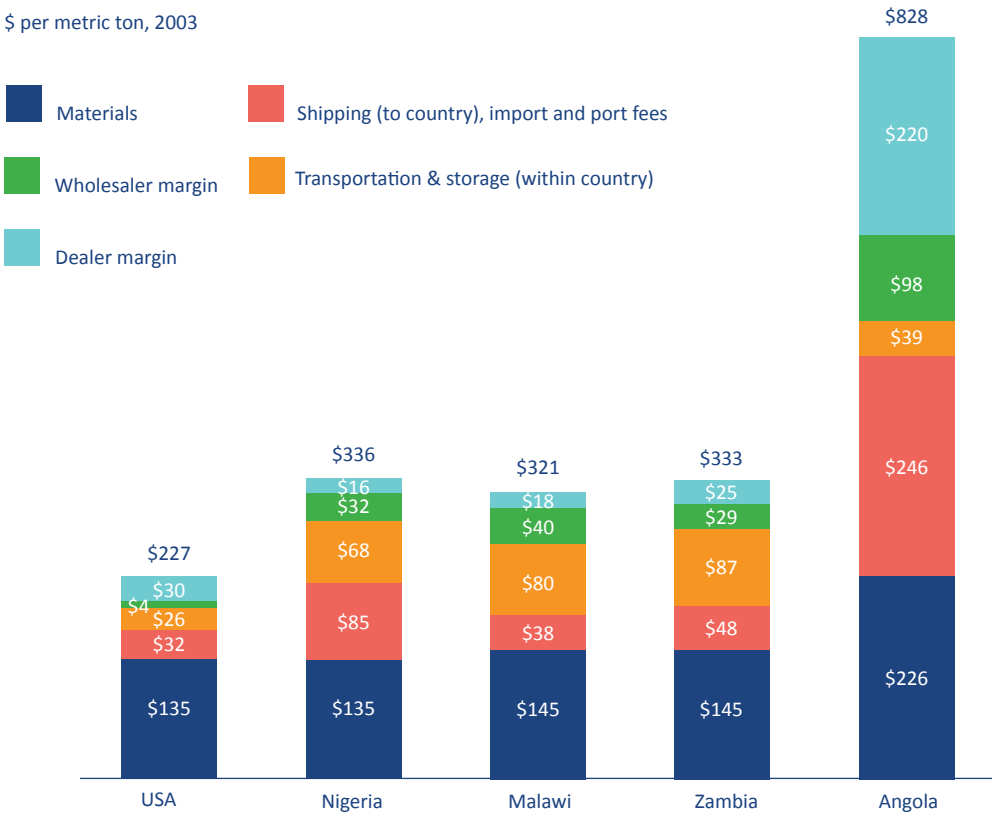
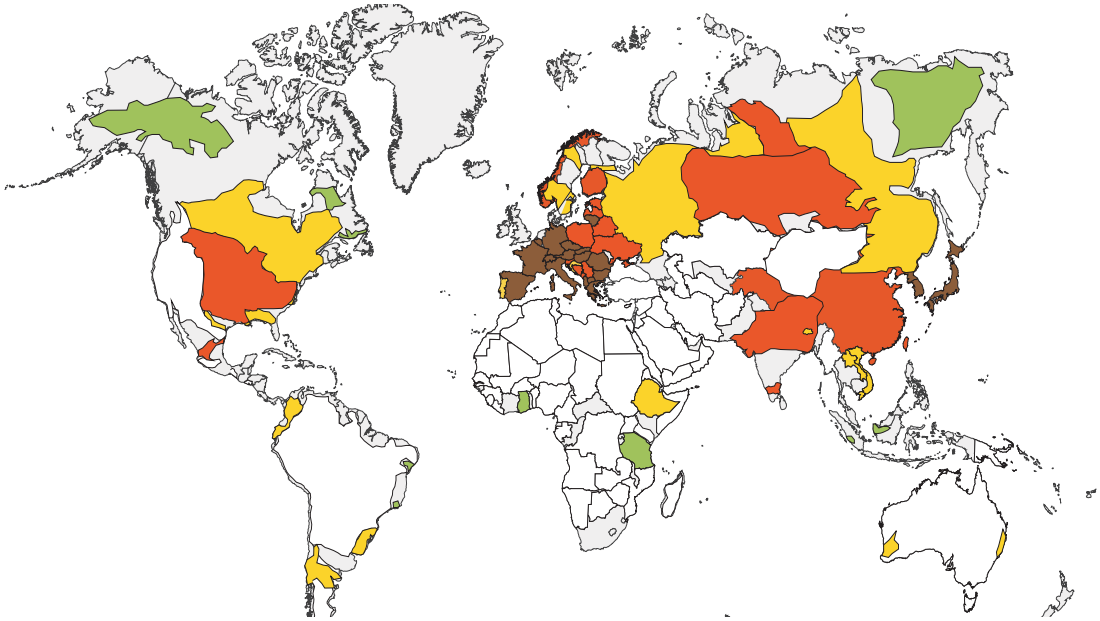


Exhibit 8: The high cost of shipping (to the country) and transportation (within the country) for most African countries has led to a significantly higher market price of fertilizer in Africa than markets like the USA. The market price varies somewhat even between different African countries (World Bank, 2007).

4 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.

Global map of nitrogen runoffs



Percent increase in nitrogen transport to river mouth

<1% 1-50% 50-75% 75-300% 300-500% >500%

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.

5 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.

6 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.[4]

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[5] (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)[6] (**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

[4] 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.

[5] 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

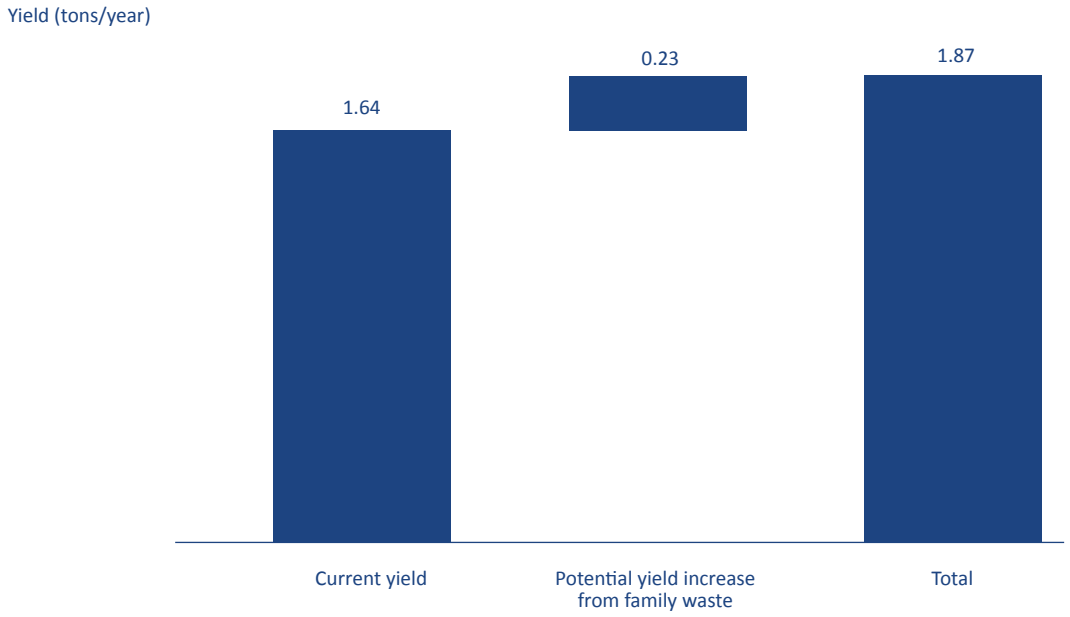


Exhibit 10: If appropriately processed, the fertilizer made from the waste (feces and urine) generated by 3 adults in a smallholder farming family can provide a modest boost to total crop yield; it can potentially increase yield on a 1 hectare maize farm in Kenya by 14% (from 1.6 tons to 1.9 tons). Higher 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)

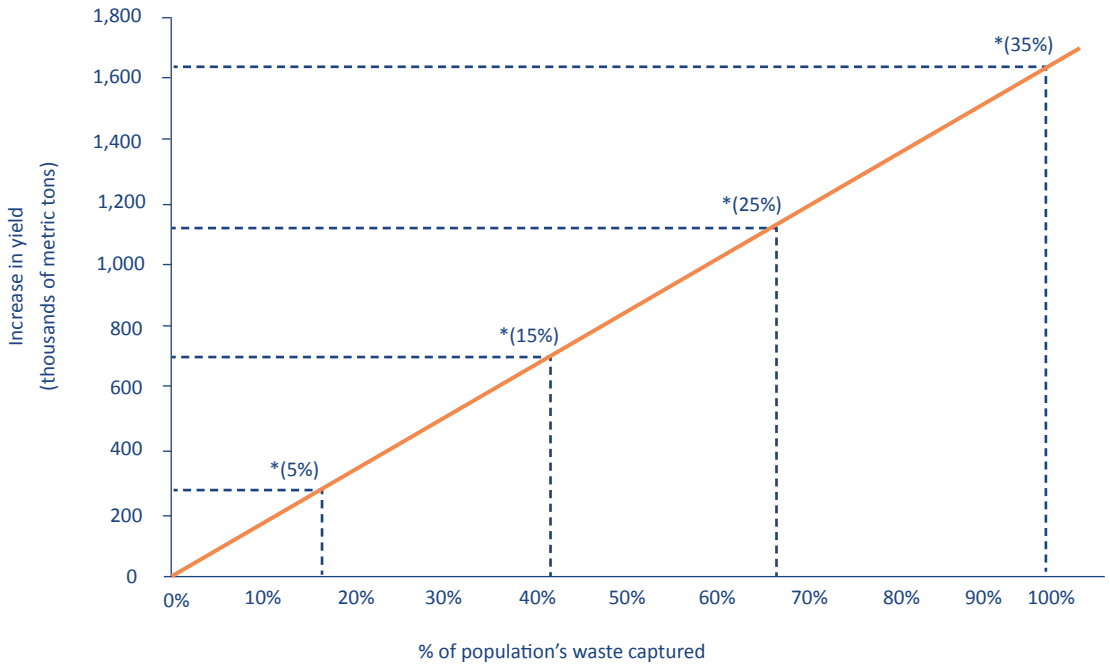


Exhibit 11: If 100% of the human waste in Kenya is composted and used as fertilizer, it will increase cereal production by about 40%. Given the poor sanitation infrastructure in a country like Kenya, it is unlikely to be a major source of fertilizer there. However, it can be a promising source of fertilizer 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).

4 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.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

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.

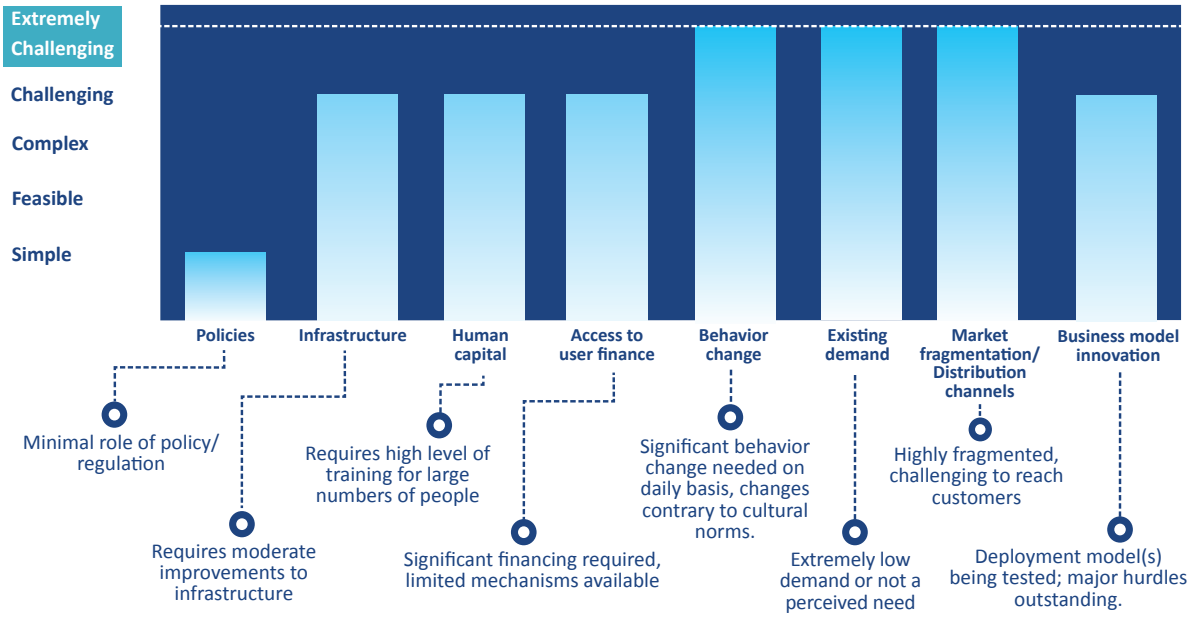
New methods for nitrogen fixation and producing other fertilizer components, instead of the energy-intensive and capital-intensive methods used currently

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



Breakthrough 2

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.

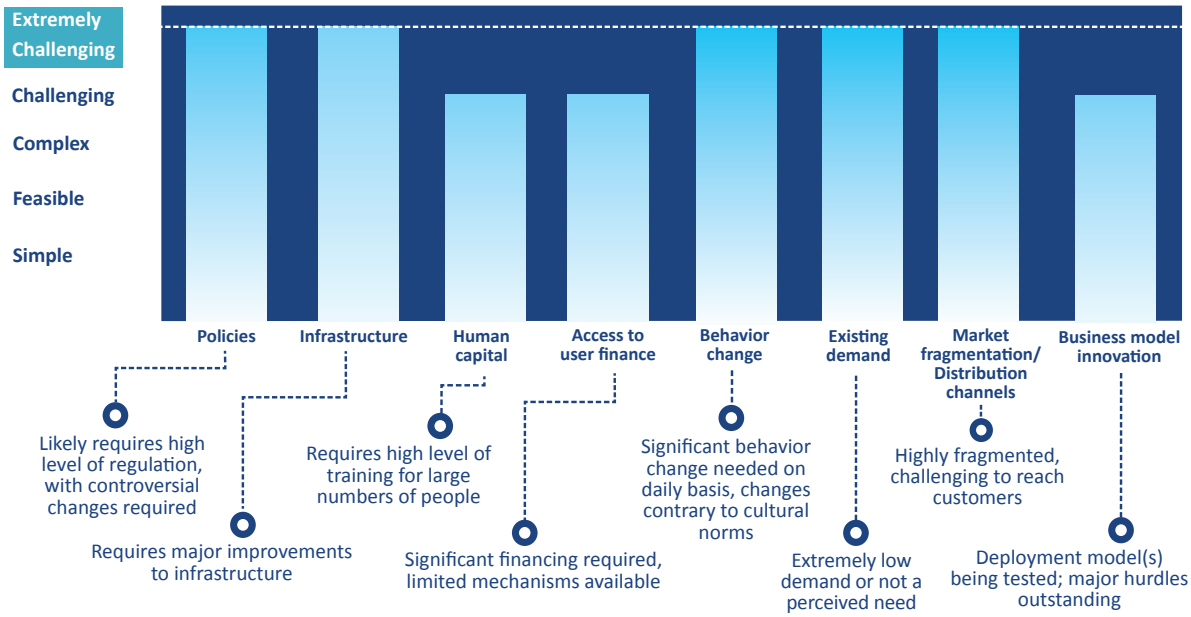
Using human waste to make fertilizer presents its own set of challenges. Collecting human waste safely for converting it to fertilizer can help tackle the spread of diarrheal diseases—mostly caused by the spread of fecal pathogens—that are one of the biggest drivers of childhood mortality. The process 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



Breakthrough 3

A low cost, point-of-use kit to evaluate soil nutrient content, and recommend tailored use of fertilizers for specific crops

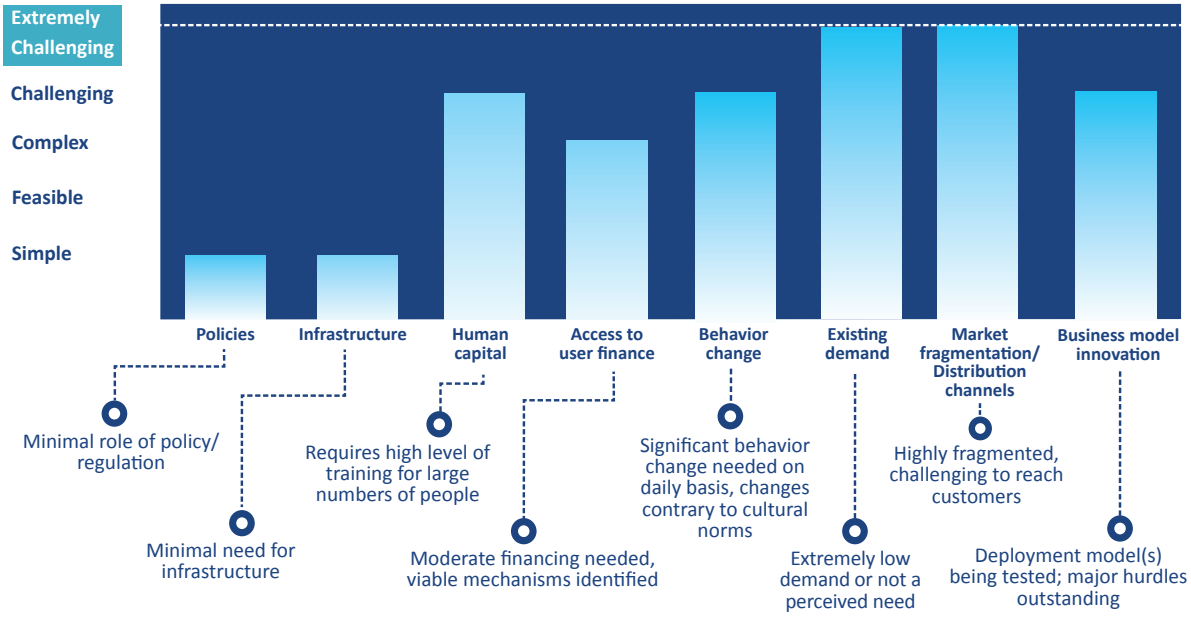
Understanding exactly how much fertilizer to apply, and at what stage of the plant's lifecycle, is very critical for maximizing returns on the farmers' investment. Smallholder farmers in Africa rely on advice from knowledgeable peers (e.g., farmer cooperative leaders) or from extension workers. A low 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



Breakthrough 4

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 phosphorous, 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.

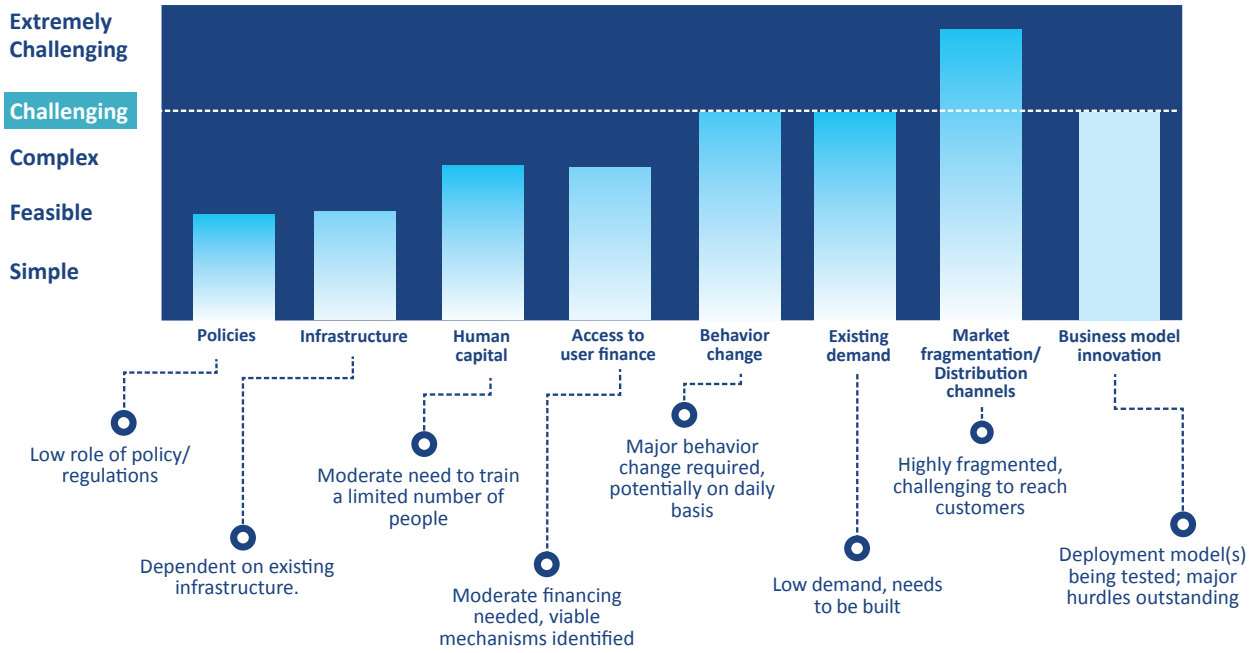
A low cost, robust, scalable technology is needed to precisely meter and distribute plant nutrients and/or other inputs. This would allow farmers to apply the right amounts of fertilizer (not too much and not too little), at the right time, to maximize economic returns and reduce nutrient loss. This breakthrough would be strongly leveraged by low cost soil nutrient analysis and low cost precision irrigation methods (identified as breakthroughs 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).

Breakthrough 4 – Difficulty of deployment



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

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.

Yield losses from various biotic stresses

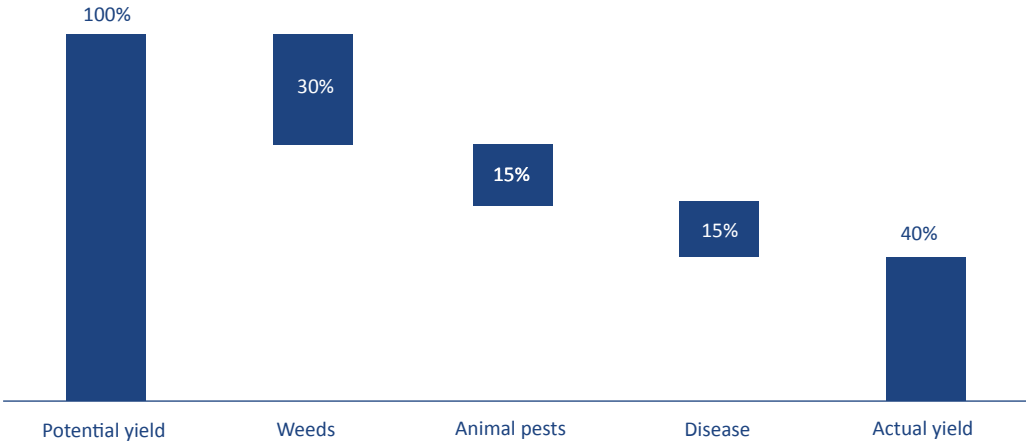


Exhibit 1: Based on a representative study of biotic stresses on cereal crops in sub-Saharan Africa, weeds constitute the largest driver of losses, followed by pests and diseases caused by a range of pathogens. Collectively, these stresses can reduce potential yield by as much as 60%.

1 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

damage. 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 CO_2 emissions (Chaplota, 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[1]) 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

[1] GMOs are discussed in greater detail the chapter on Sustainable Agriculture.

takes up to 400 person-hours of manual weeding time (Shetto & Kwiligwa, 1990). Importantly, by the time the weeds become visible above ground, their roots have already done the damage to the crops by competing for scarce soil nutrients and moisture. Missing the optimal weeding time by even a single week can reduce yield by up to 33%. In effect, there is no affordable, reliable mechanism available for smallholder farmers (especially in Africa) to avoid losses due to weeds.

2 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

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

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 vetver 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.

3 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.

5 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.

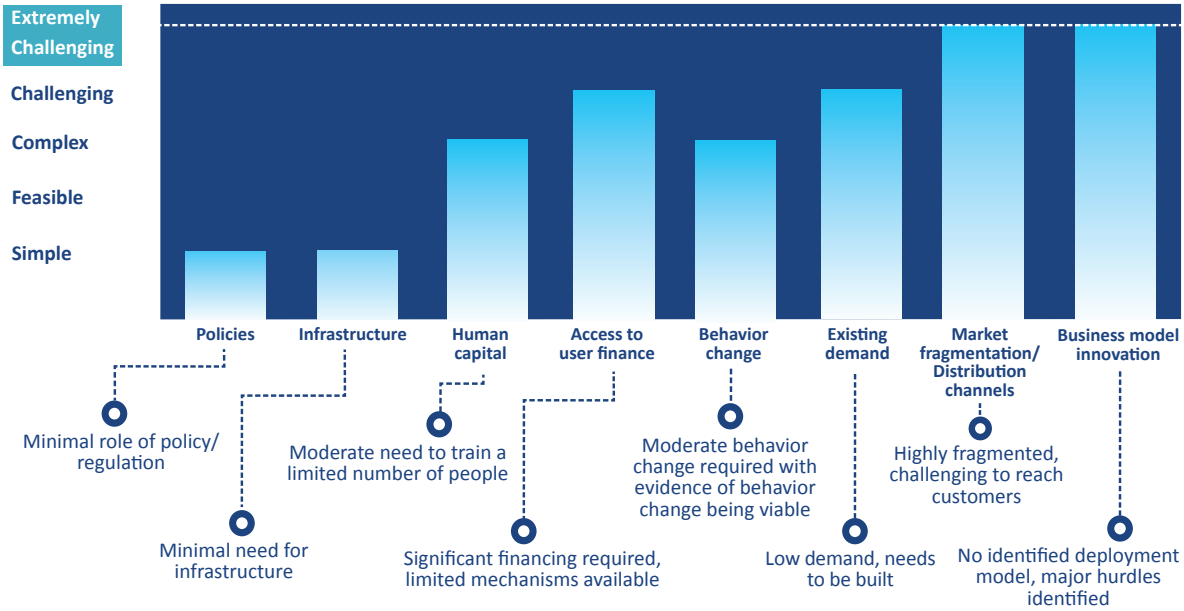
A low cost (under $50) tilling machine

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



Breakthrough 2

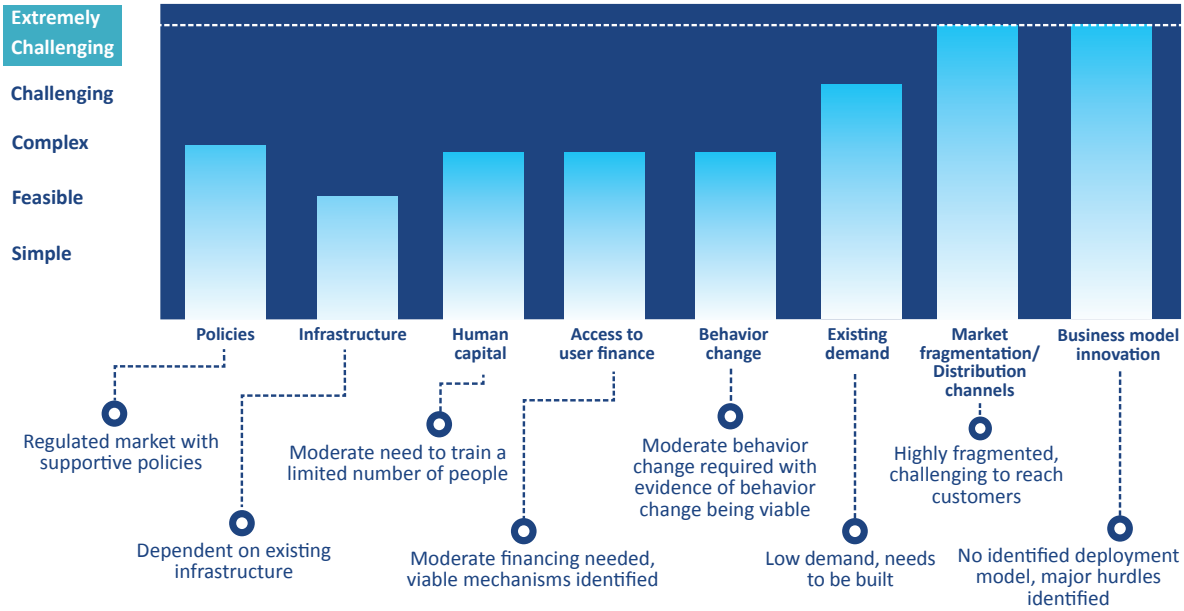
Herbicides or other affordable mechanisms to control weeds, ideally ones that are more environmentally friendly than herbicides currently on the market

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 2 – Difficulty of deployment



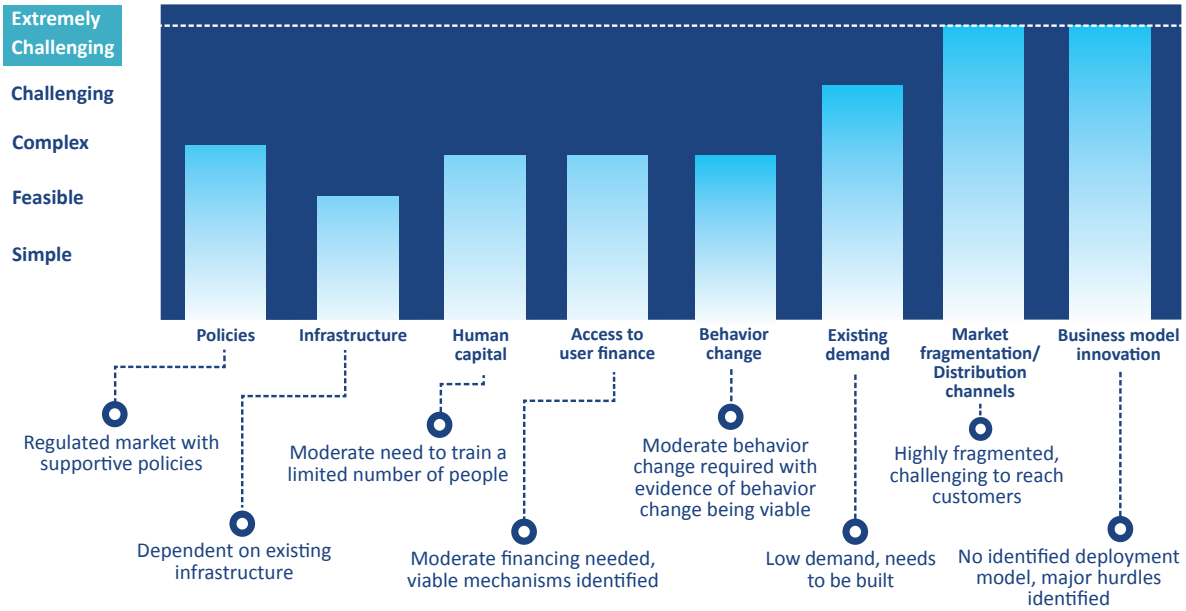
Breakthrough 3

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



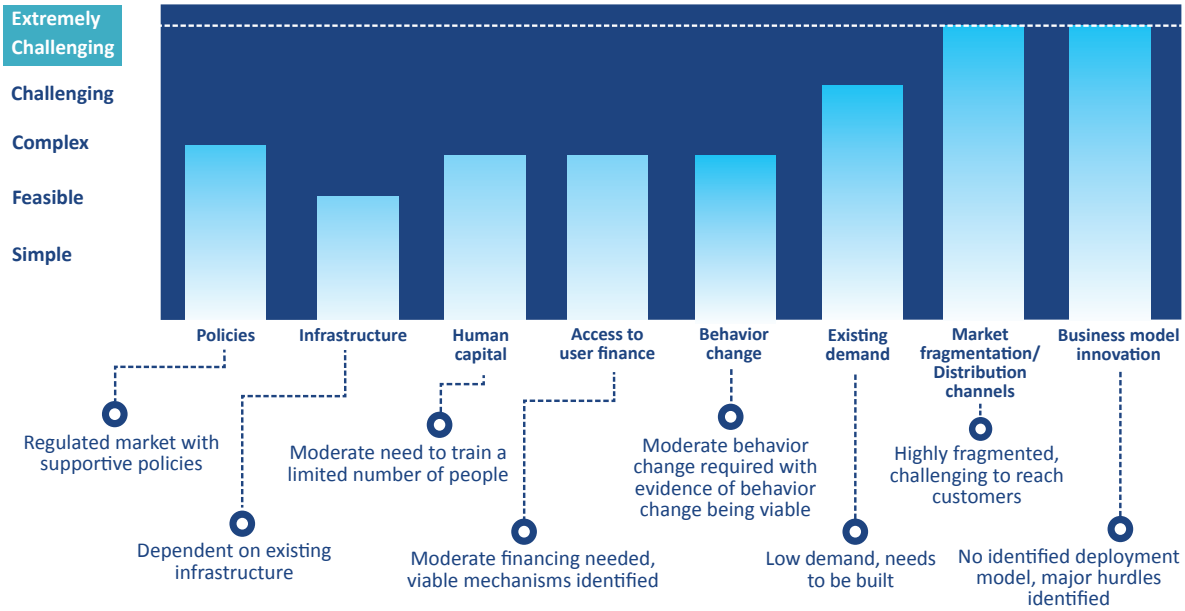
Breakthrough 4

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



POST-HARVEST HANDLING AND STORAGE

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

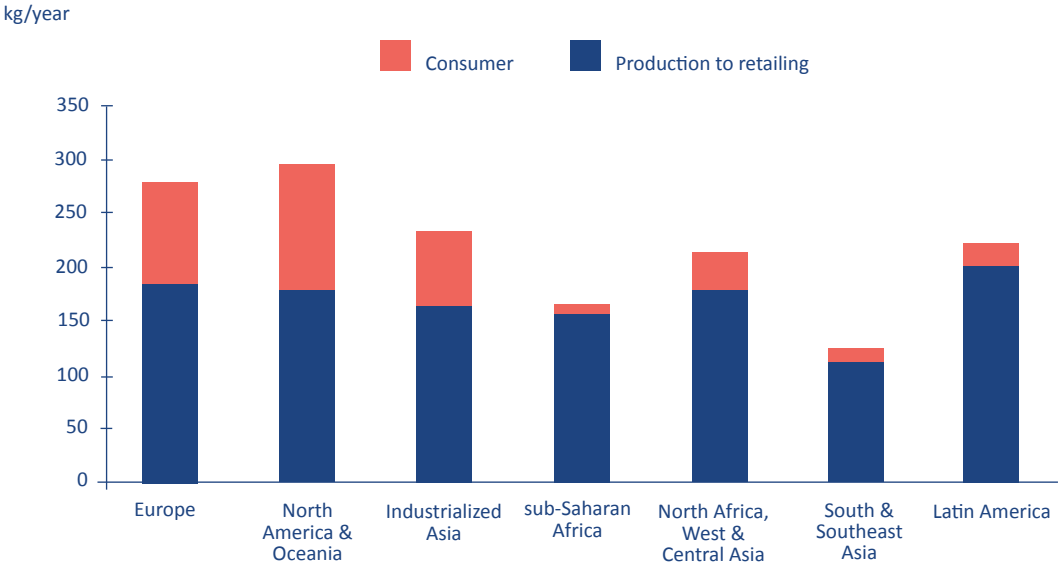


Exhibit 1: While food is wasted or lost in every part of the world, most of the losses in sub-Saharan Africa and South Asia occur before it reaches the consumer (FAO, 2011).

[1] Note that this exhibit from FAO combines data from South Asia and Southeast Asia.

1 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).

2 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

dearth of local processing facilities for most cash crops produced in sub-Saharan Africa, which means that dealers and other intermediaries representing foreign buyers usually wield significant bargaining power in timing and price of purchase. Given the high premium placed on the quality of cash crops, sub-par produce can be devastating for farmers. Not only will such produce fetch lower prices, but crops like coffee cannot be consumed by a farmer's household as a source of calories, resulting in not just economic loss but also food insecurity. Most post-harvest losses of cash crops occur on the farm, because farmers do not have an adequate understanding of, or tools to employ, optimal—often crop-specific—practices for harvesting and handling the produce. This risk of loss, combined with the absence of appropriate storage facilities and the urgent need for income, often forces farmers to sell their produce early, at below-market prices (as low as 30-50% of peak prices) (World Bank, 2011) (Gockel, et al., 2009). The problems specific to cash crops are detailed below.

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 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 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

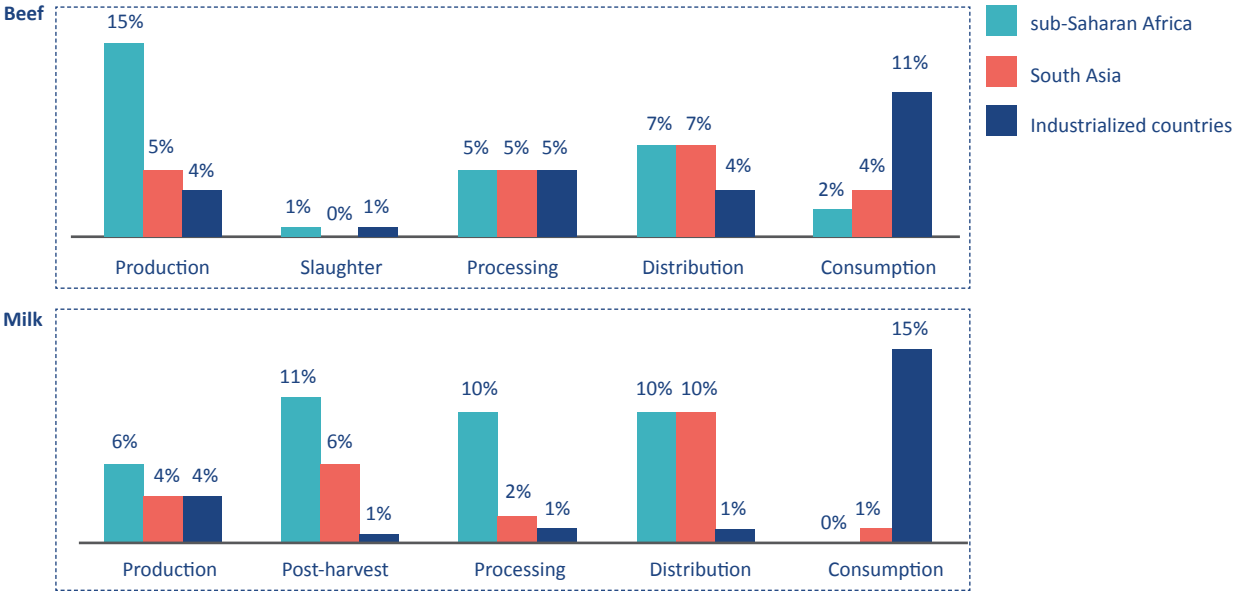


Exhibit 3: The most significant losses in beef (and other meat products) occur in the production phase due to animal death from diseases or other causes. For milk, on the other hand, greater losses occur post-production, due to the absence of processing and storage infrastructure en route to the market.

Temperature sensitivity of various livestock products

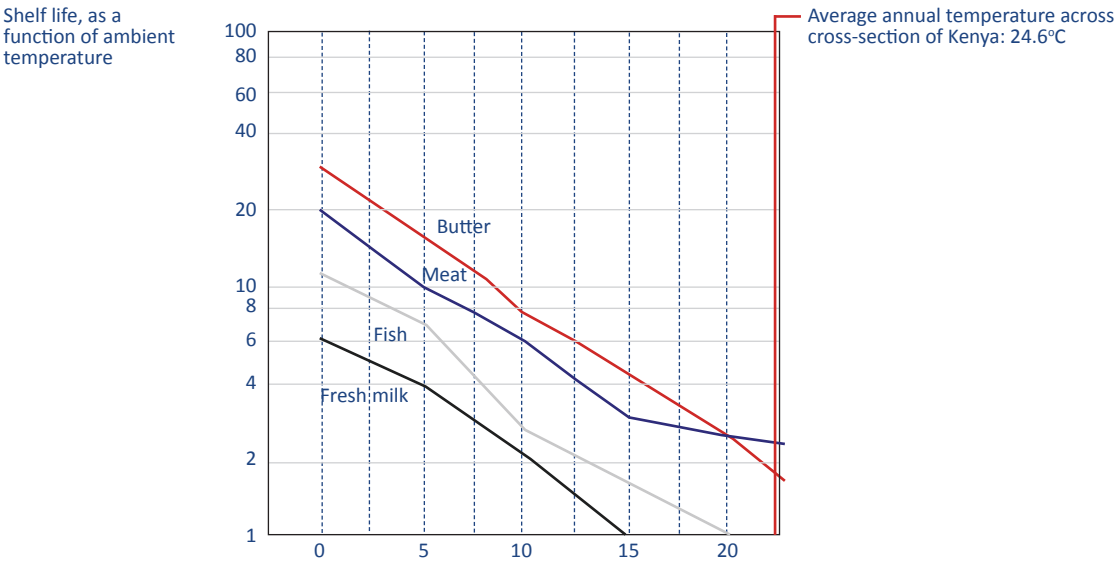


Exhibit 4: Livestock products such as milk, fish, meat and butter, are highly temperature-sensitive. They need to be stored well below the average temperatures common to most tropical countries (Practical Action, 2012). Only 14% of the rural population in Africa has access to electricity, and only 3-4% 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.

7 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

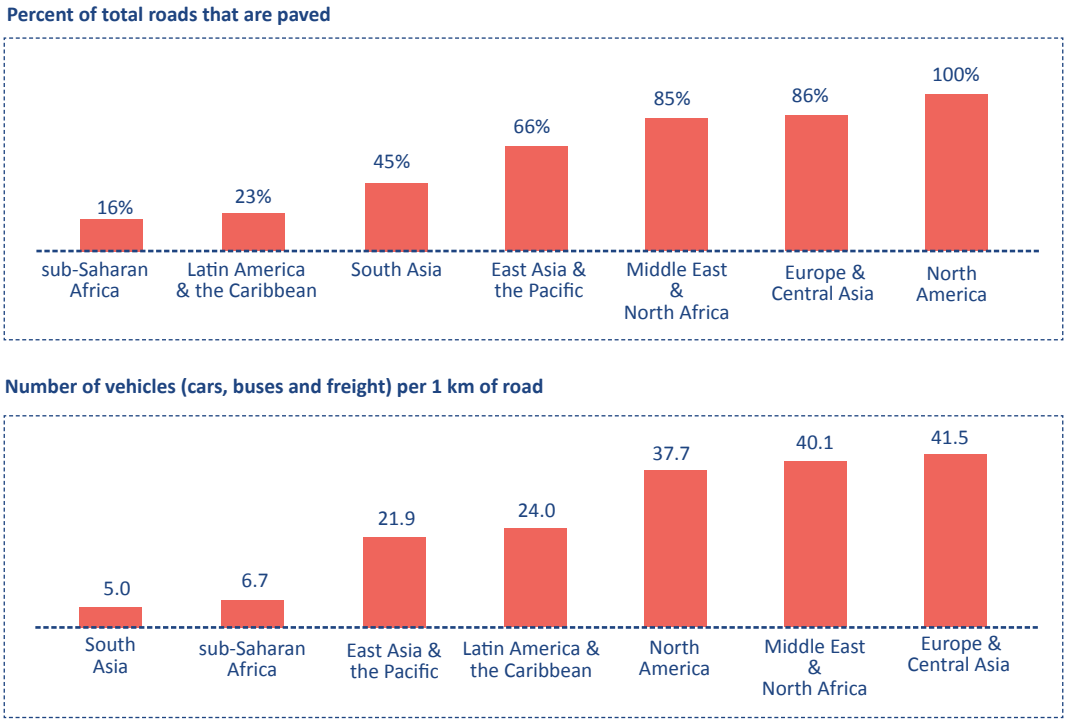


Exhibit 5: Smallholder farmers in Africa do not have any realistic means of transporting their produce to markets far from where they live. Only 16% of the roads are paved, and there is a serious dearth of automobiles for transport.

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.

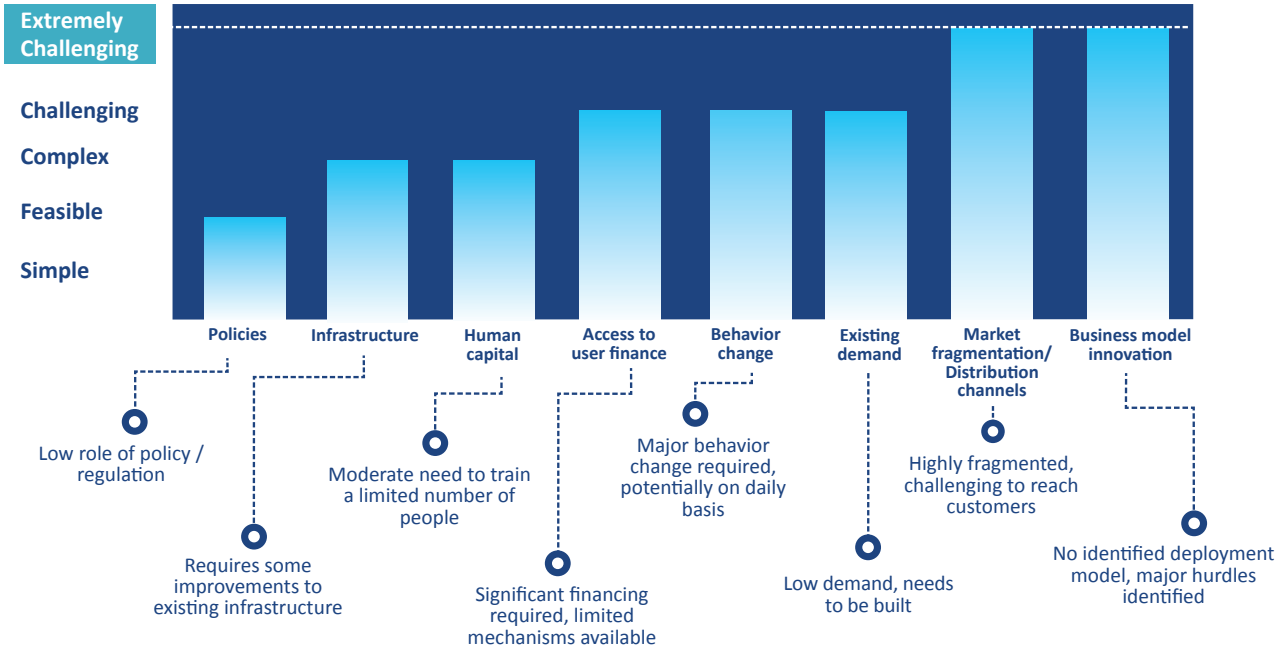
Easy-to-install, low cost structures for long-term grain storage

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



Breakthrough 2

Affordable (under $50) off-grid refrigeration for smallholder farmers and small agribusinesses

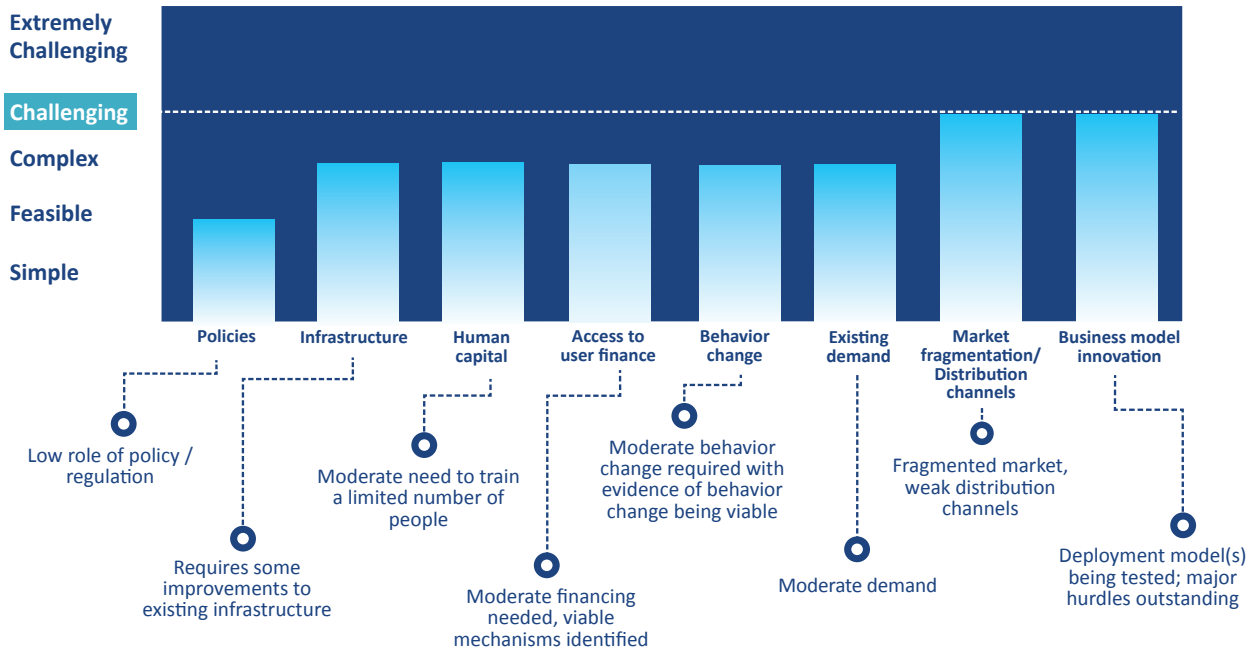
Horticulture products like fruits and vegetables are highly sensitive to temperature, and the lack of refrigeration dramatically reduces their shelf life, especially in tropical climates. While there are some inexpensive refrigerators available in emerging markets like India and China, they still cost 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.

Breakthrough 2 – Difficulty of deployment



Breakthrough 3

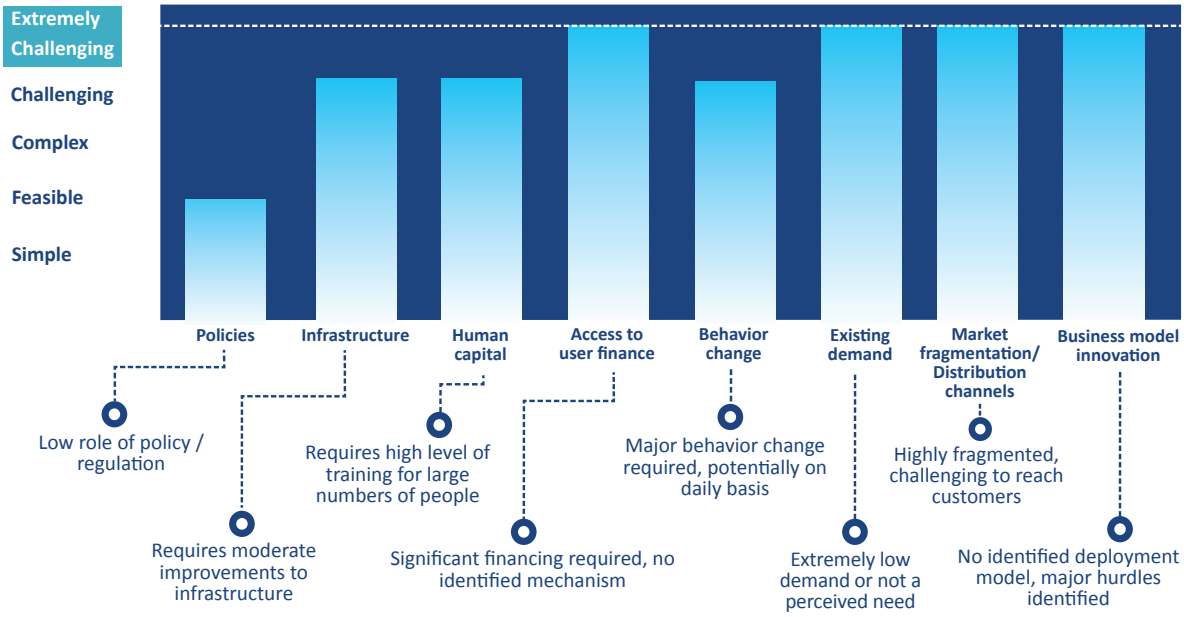
Low cost (under $5,000) refrigerated vehicles, sturdy enough for unpaved roads in rural areas.

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



EXTENSION SERVICES

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

Provider type

- Government
- NGO (with fee-for-service)
- NGO (free service)
- Private value chain partner
- Private fee-for-service
- Farmer organization
- Community member
- Universities or research institutions

Content type

- Inputs usage
- Plant management
- Livestock rearing
- Post-harvest processing
- Market information
- Weather information
- Farming business training
- Natural resource management

Channel

- In-person, verbal
- In-person, demonstration
- Train-the-trainer
- Peer-to-peer sharing
- Two-way ICT (Internet or mobile)
- One-way ICT (radio, video)
- Written/print

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

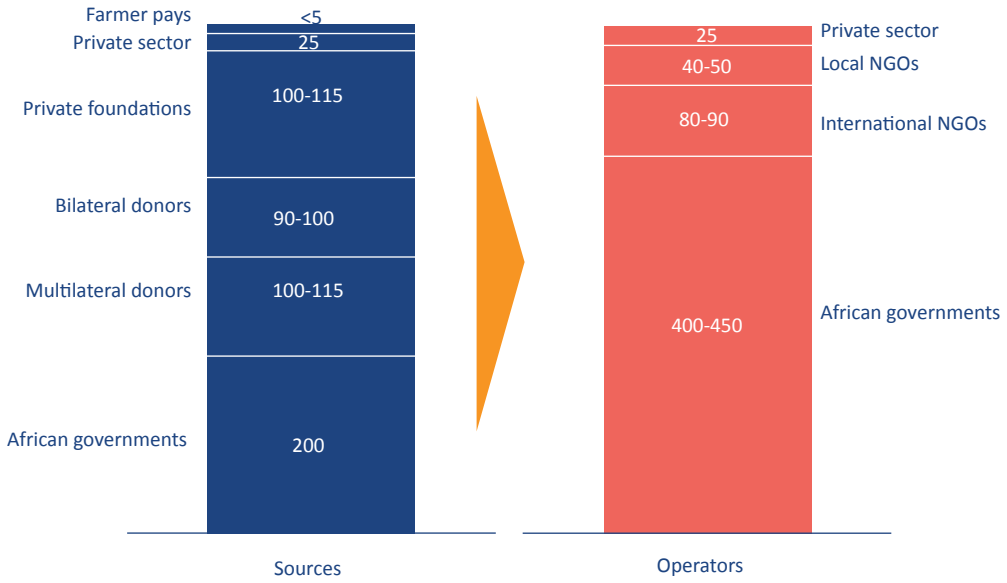


Exhibit 2: About 80% of the extension services for farmers in Africa are provided by their governments, with most the remainder of the services provided by NGOs. Private providers account for a very small portion of the services. About one-third of the funds for these services come from the local governments. Multilateral, bilateral and private philanthropic donors account for the bulk of funds.

1 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).

2 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

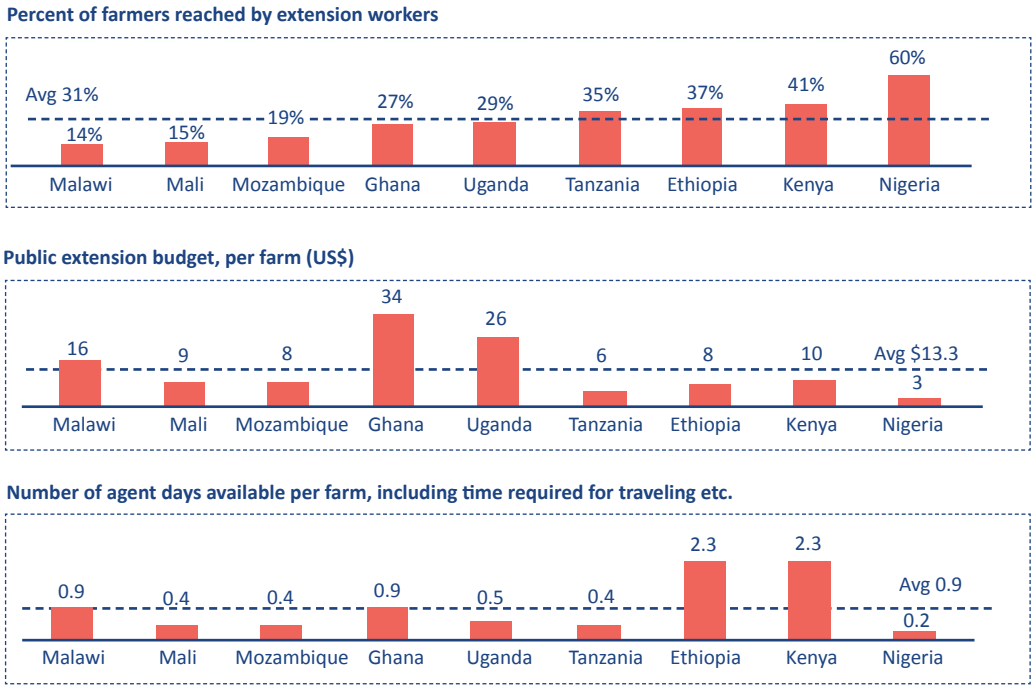


Exhibit 3: A very small percentage of African farmers—barely 30% across a sample of countries—are reached by extension workers. With an annual extension budget of $13 per farm, and average availability of less than 1 day per extension agent per farm, few farmers receive any quality advice. This is particularly true since the predominant mode of extension is travel-and-visitation.

3 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

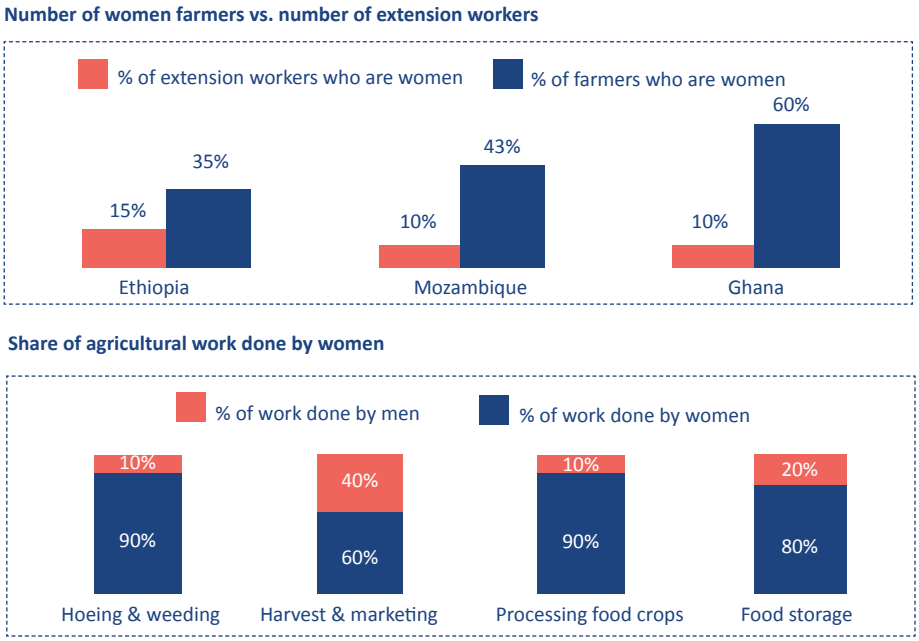


Exhibit 4: Even though a substantial portion—in many countries, more than half—of agricultural work is done by women, extension agents are primarily men. As a result, the quality of extension support received by women does not address the needs and constraints of women farmers.

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.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

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.

Breakthrough 1

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:

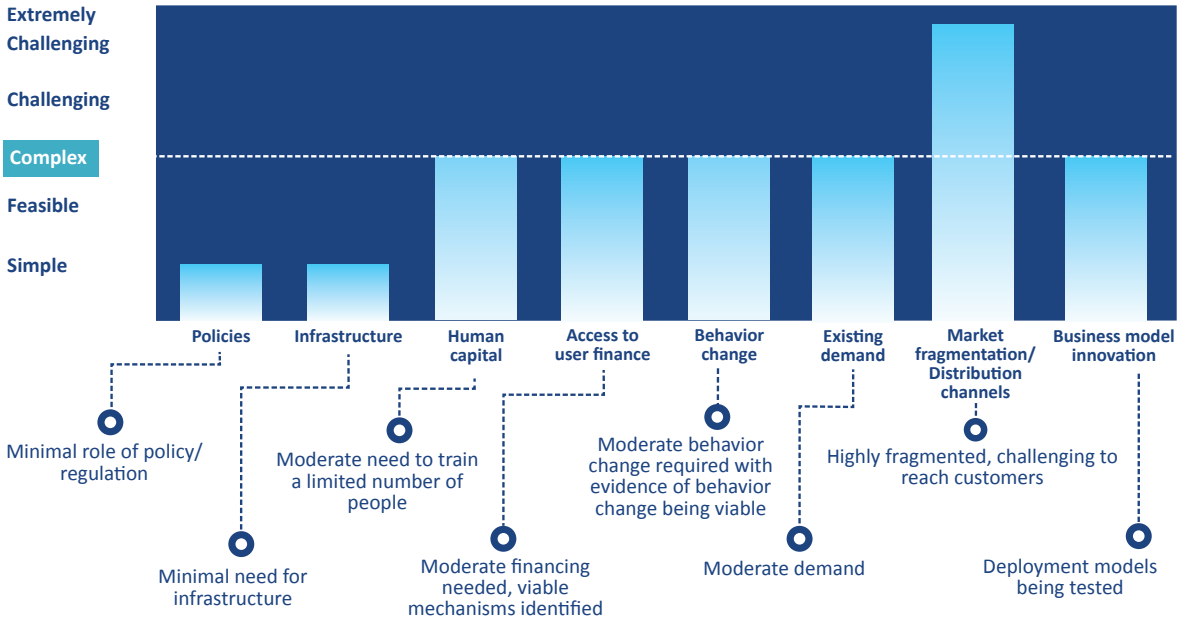
- Testing crops for particular, common pathogens and providing information about appropriate remedies. If combined with the provision of appropriate remedies, such a tool can help prevent potentially devastating losses for farmers.
- Diagnosing livestock at the point-of-care for particular diseases, 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

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.

1 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

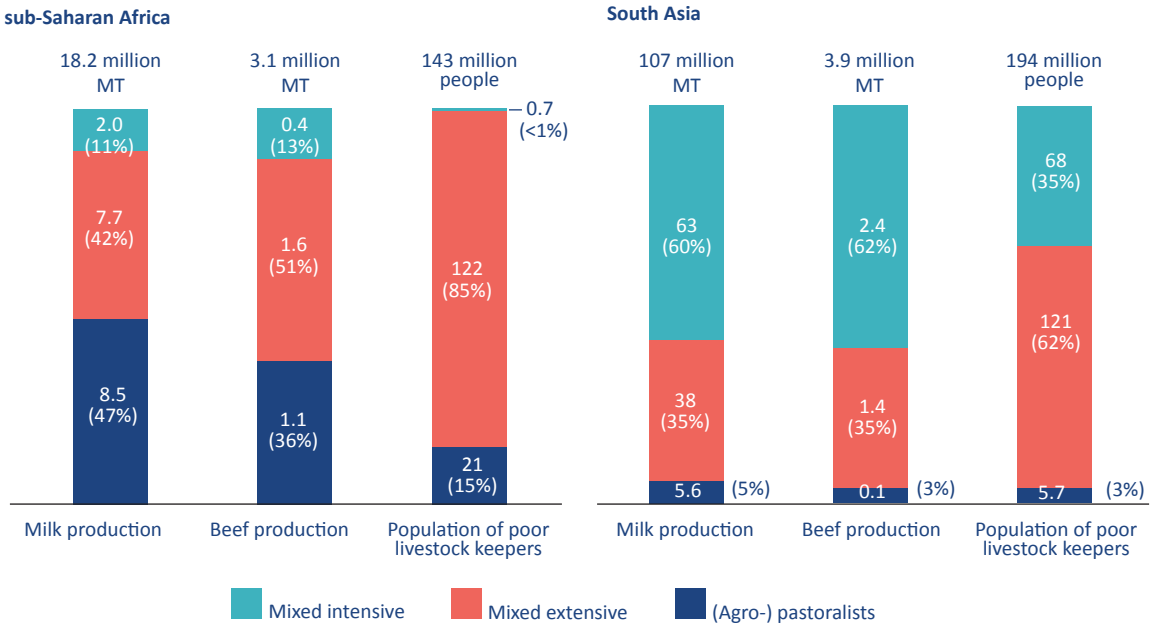


Exhibit 1: There are 3 major forms of livestock production: extensive mixed crop-livestock farming is the most common both in sub-Saharan Africa and South Asia. Agro-pastoral and pastoral farming is primarily an African phenomenon, and mixed intensive farming is common in South Asia. Currently, mixed extensive systems are the most prevalent in both regions.

Livestock production systems across various agroclimatic zones

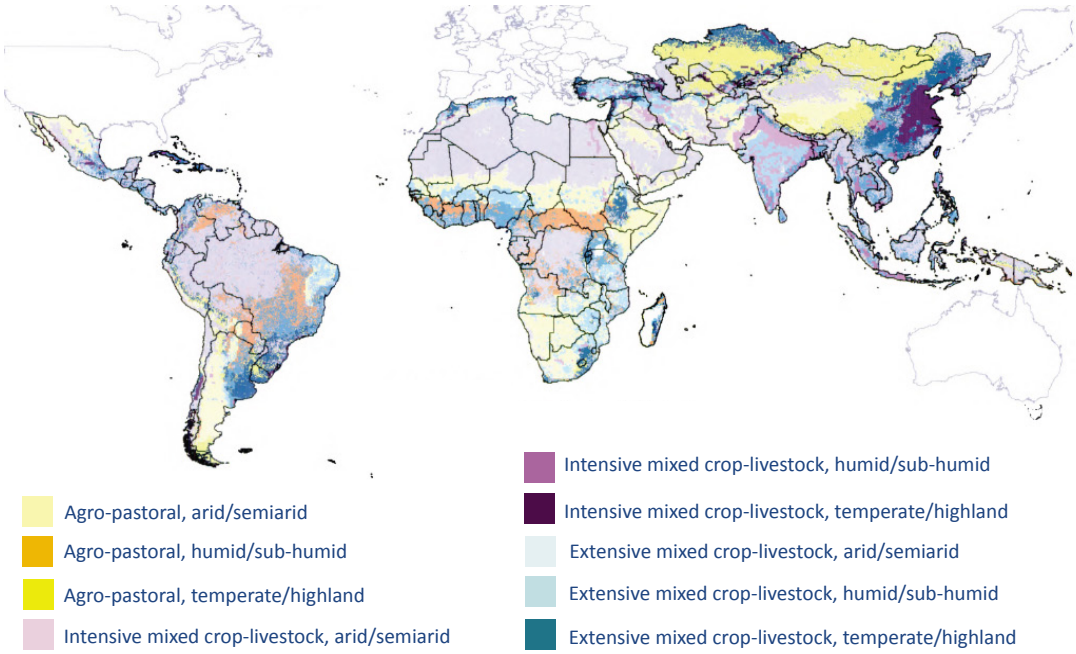


Exhibit 2: Livestock production practices and output are heavily influenced by agroclimatic zones (Thornton, et al., 2002).

2 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

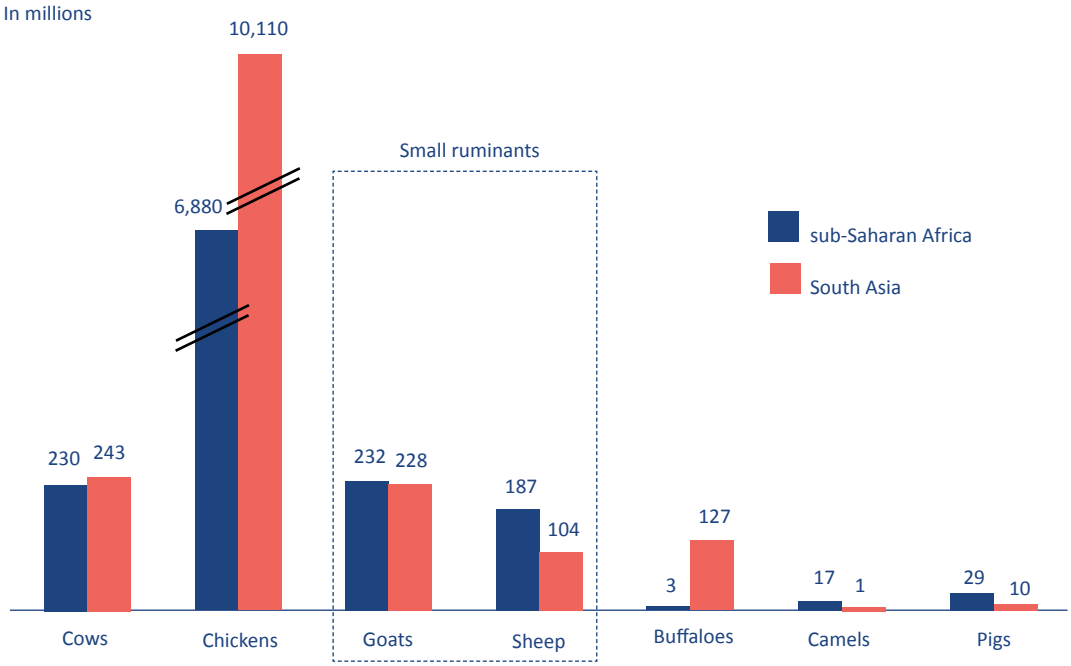


Exhibit 3: Livestock in South Asia and sub-Saharan Africa is dominated by cattle, chickens and small ruminants. Water buffaloes are kept primarily in South Asia.

3 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

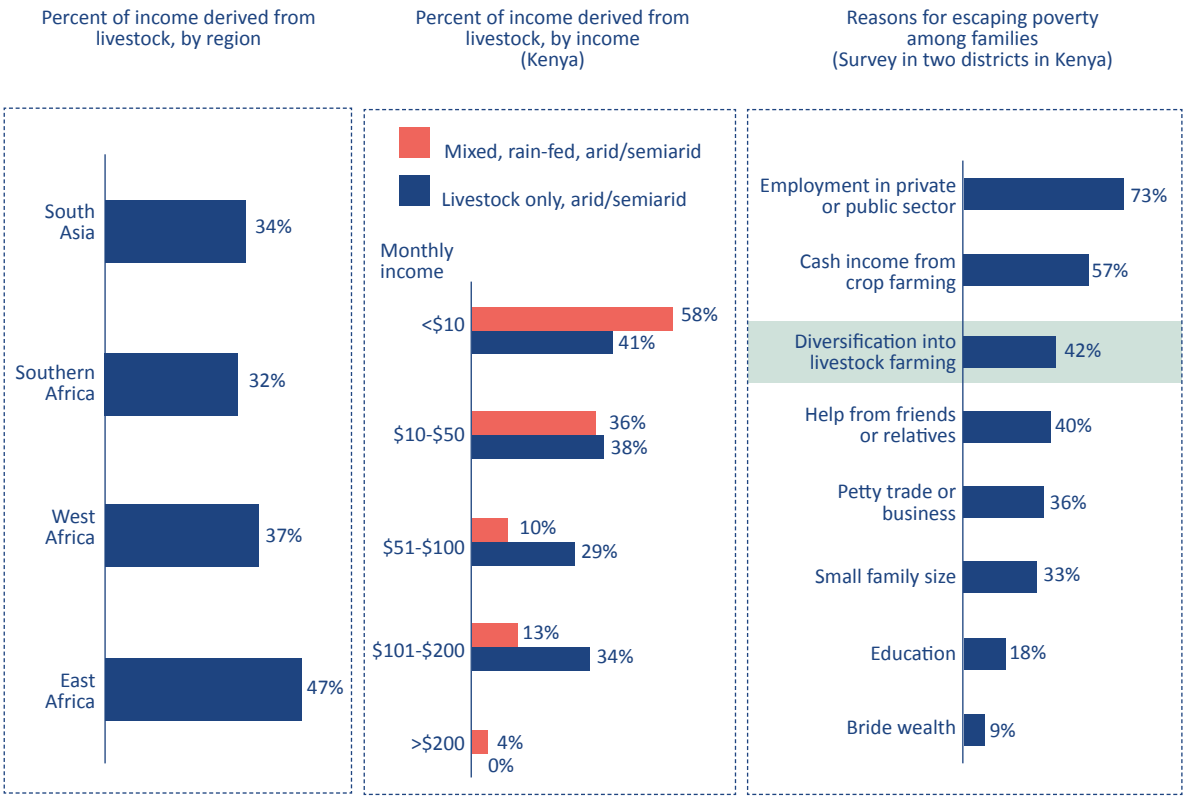


Exhibit 4: Livestock is a major source of income for smallholder farmers, and accounts for 30-50% of total income for farmers in different parts of sub-Saharan Africa and South Asia. Income from livestock is particularly important for lower income farmers,[1] a greater portion of whose overall income 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

[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).

4 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,[2] 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 is 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

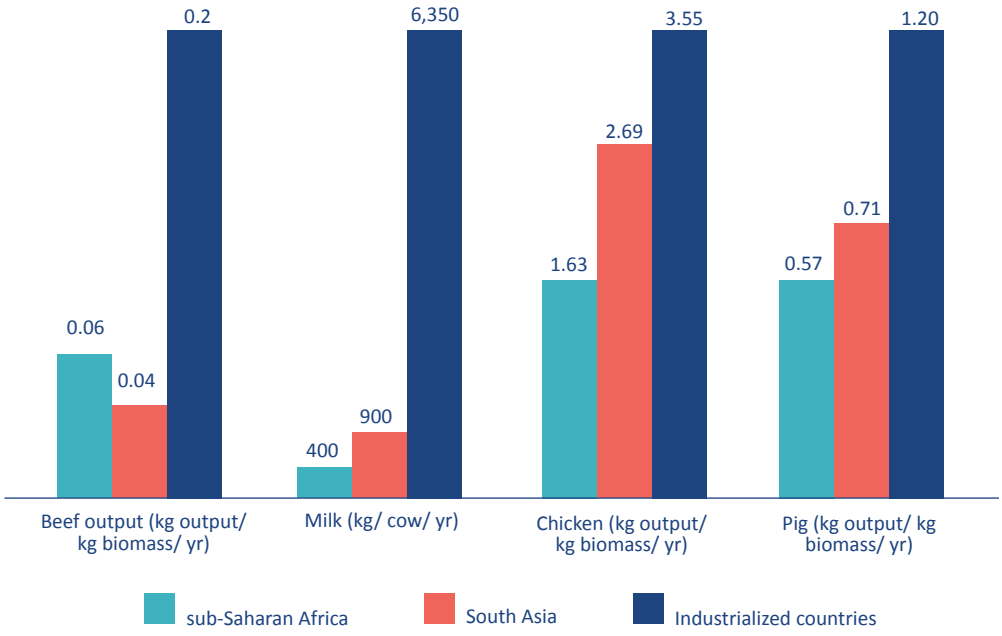


Exhibit 5: Livestock output in sub-Saharan Africa and South Asia is a fraction of that in industrialized countries. Beef and milk output, in particular, lag far behind (FAO, 2006).

[2] 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

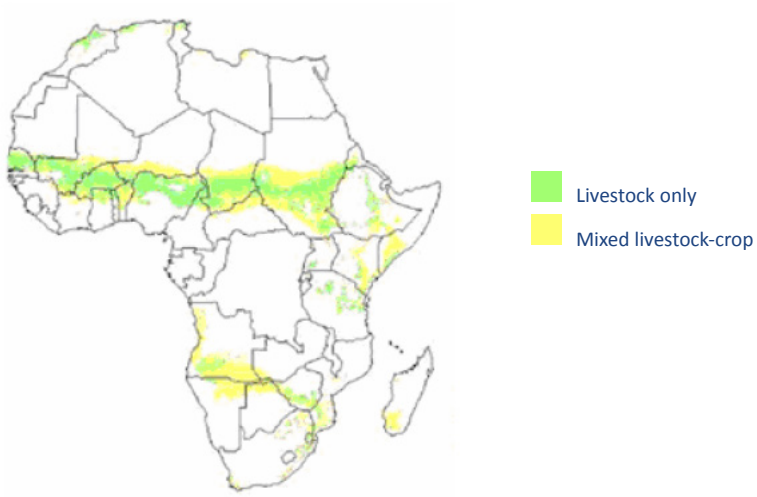


Exhibit 6: A large portion of the agro-pastoral, pastoral and extensive mixed-crop systems in sub-Saharan Africa are facing serious threats due to environmental degradation (current and projected). These stresses deplete the already meager food and water sources for livestock (Thornton, et al., 2002) (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

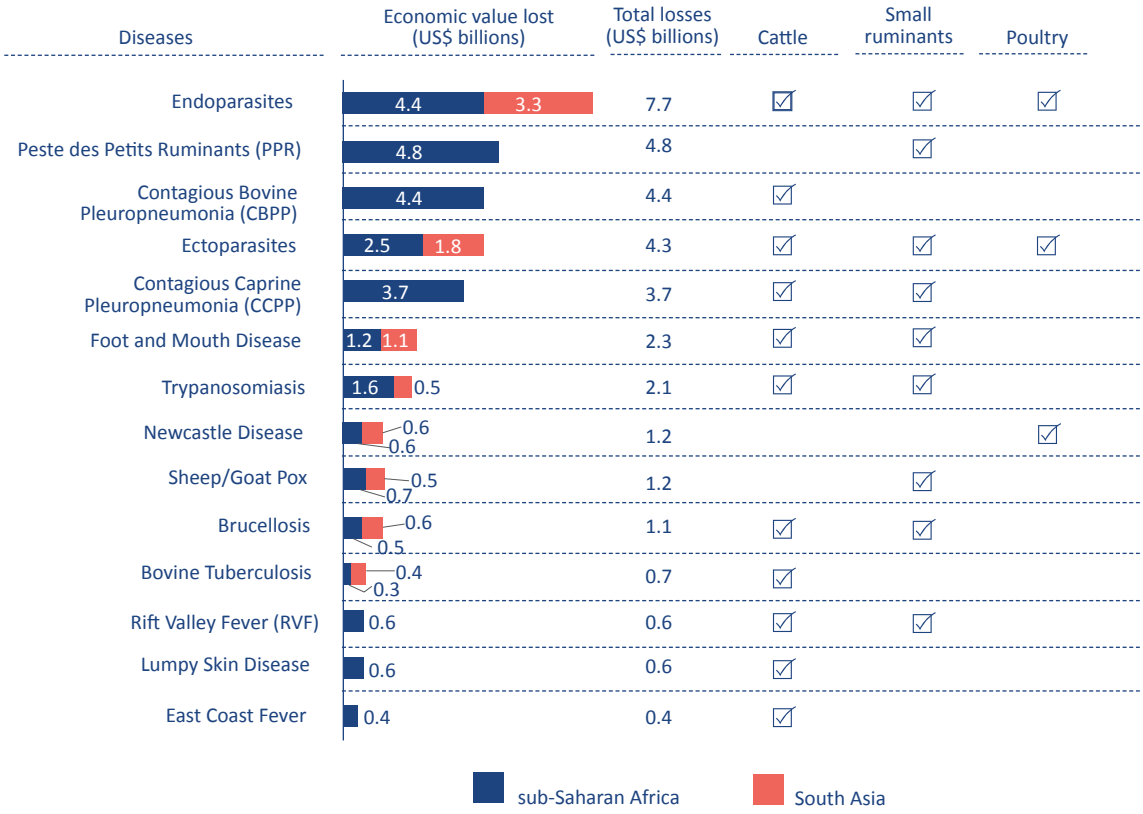


Exhibit 7: Fourteen livestock diseases collectively cause US$33.5 billion in losses to smallholder farmers in sub-Saharan Africa and South Asia. In sub-Saharan Africa, these diseases kill a quarter of livestock animals owned by low income farmers.

Genetics: Genetic improvement through cross-breeding

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

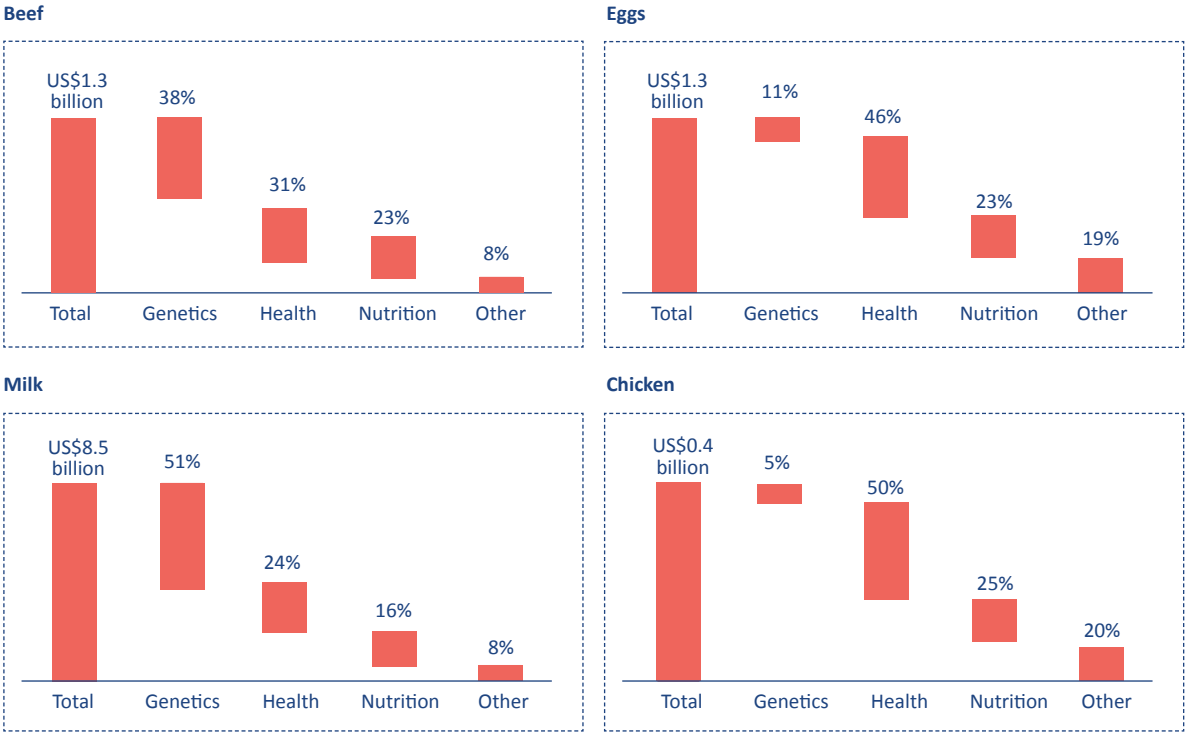


Exhibit 8: Improvements in animal genetics are the single largest driver of productivity for cattle products (beef and milk). Improvements to animal health (through both vaccines and treatment) can also have significant impact. For poultry (chicken meat and eggs), the primary driver is improvement in 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).

5 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

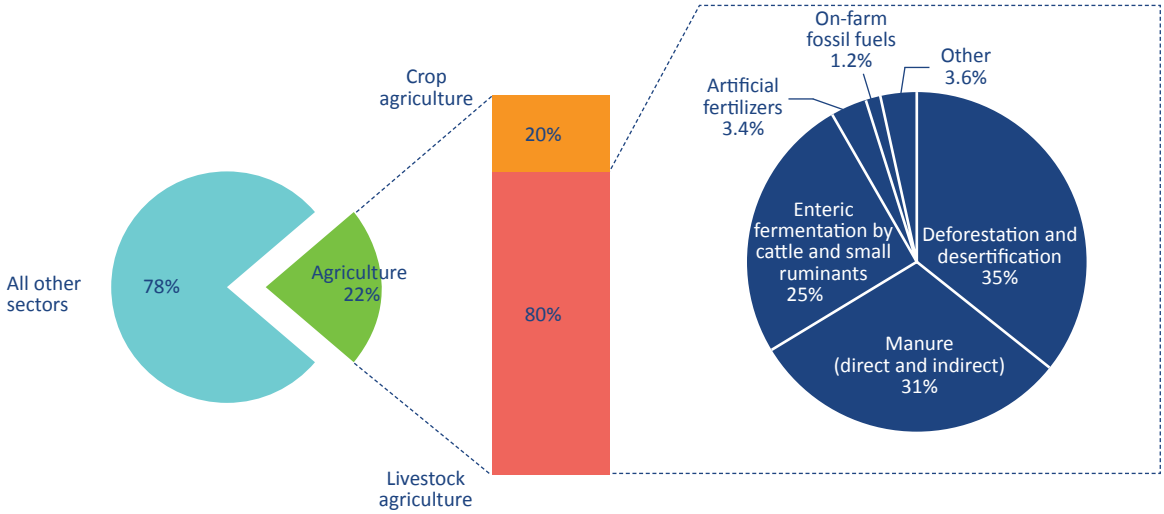


Exhibit 9: Agriculture accounts for 22% of all greenhouse gas emissions, and 80% of the agriculture-related emissions—18% of all GHG emissions—are from livestock rearing. While this predominantly comes from industrialized countries, desertification and deforestation are a major concern in parts of sub-Saharan Africa and South Asia.

KEY CHALLENGES[3]

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.

[3] 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.

3 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.

Waste in various stages of the livestock product value

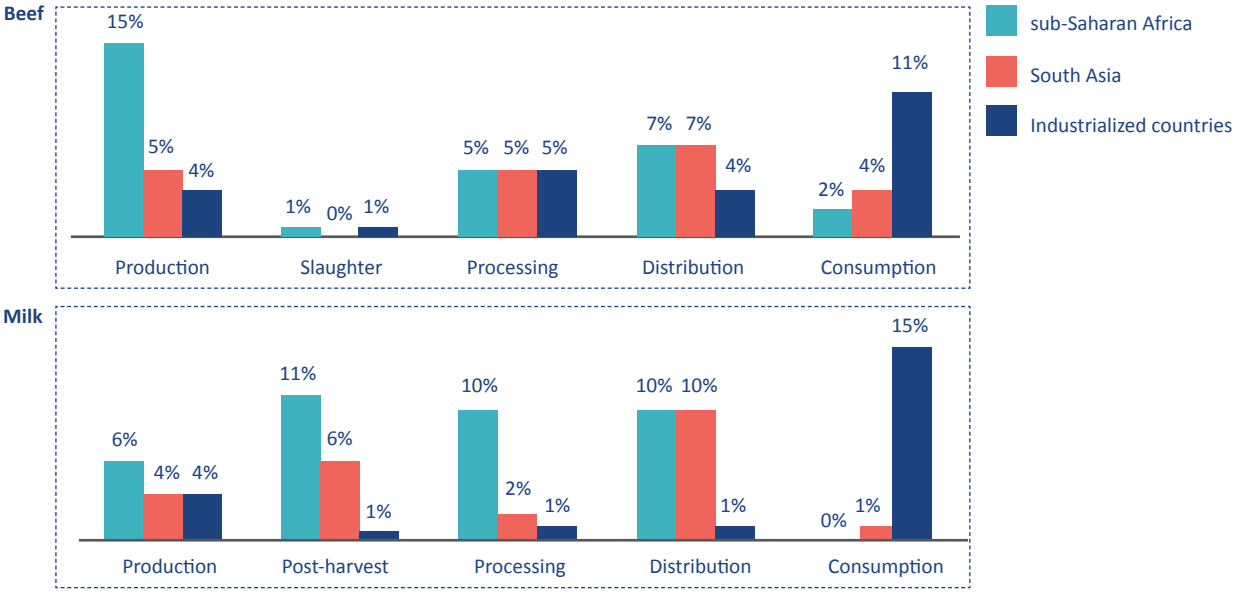


Exhibit 10: The most significant losses in beef (and other meat products) occur in the production phase due to animal death from diseases or other causes. For milk, on the other hand, greater losses occur post-production, due to the absence of processing and storage infrastructure en route to the market.

Temperature sensitivity of various livestock products

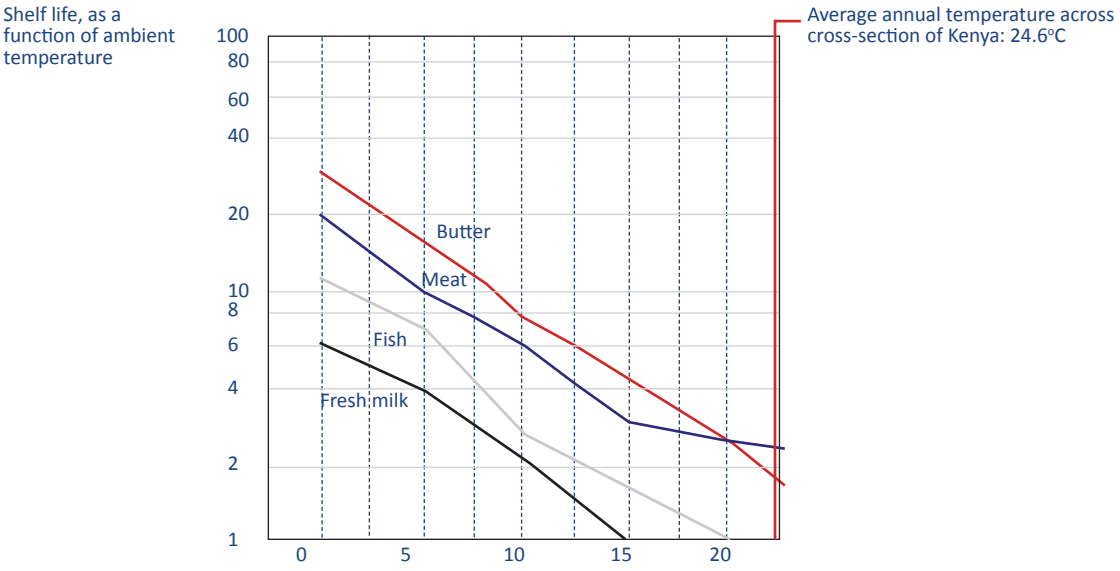


Exhibit 11: Livestock products such as milk, fish, meat and butter, are highly temperature-sensitive. They need to be stored well below the average temperatures common to most tropical countries (Practical Action, 2012). Only 14% of the rural population in Africa has access to electricity, and only 3-4% 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.

4 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

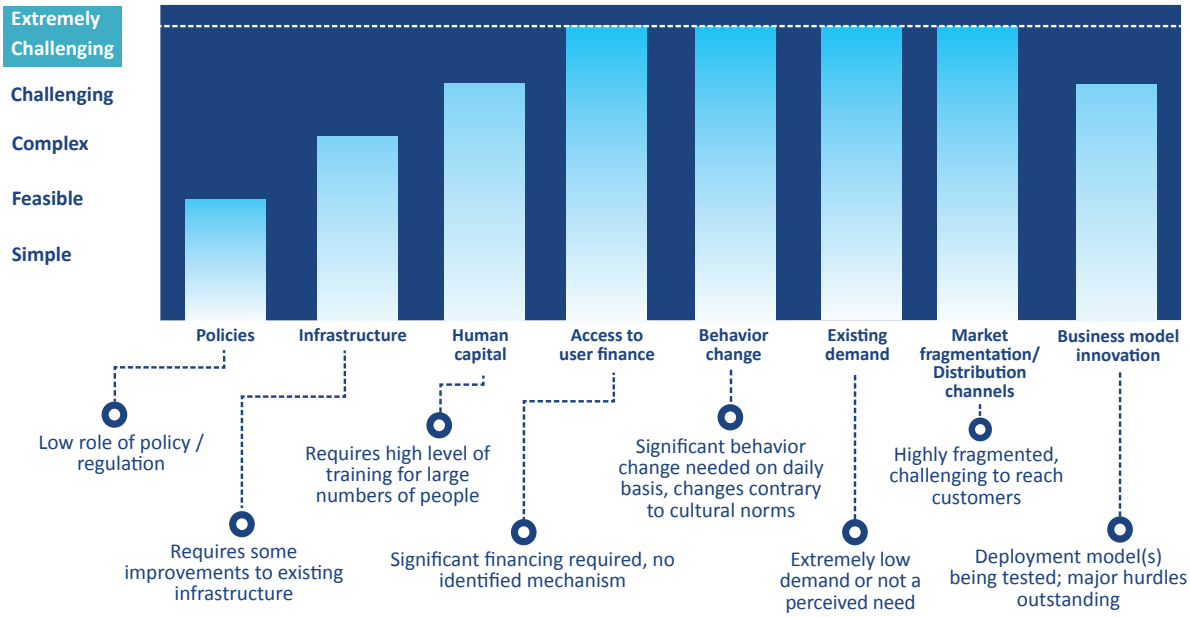
Farmers, and the few service providers they usually have access to, are typically not able to diagnose a sick animal. This prevents them from seeking timely treatment, even it were available. More importantly, it keeps farmers from preventing the disease from spreading to the rest of the herd. A simple low cost stall-side[4] 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.

Breakthrough 1 – Difficulty of deployment



Breakthrough 2

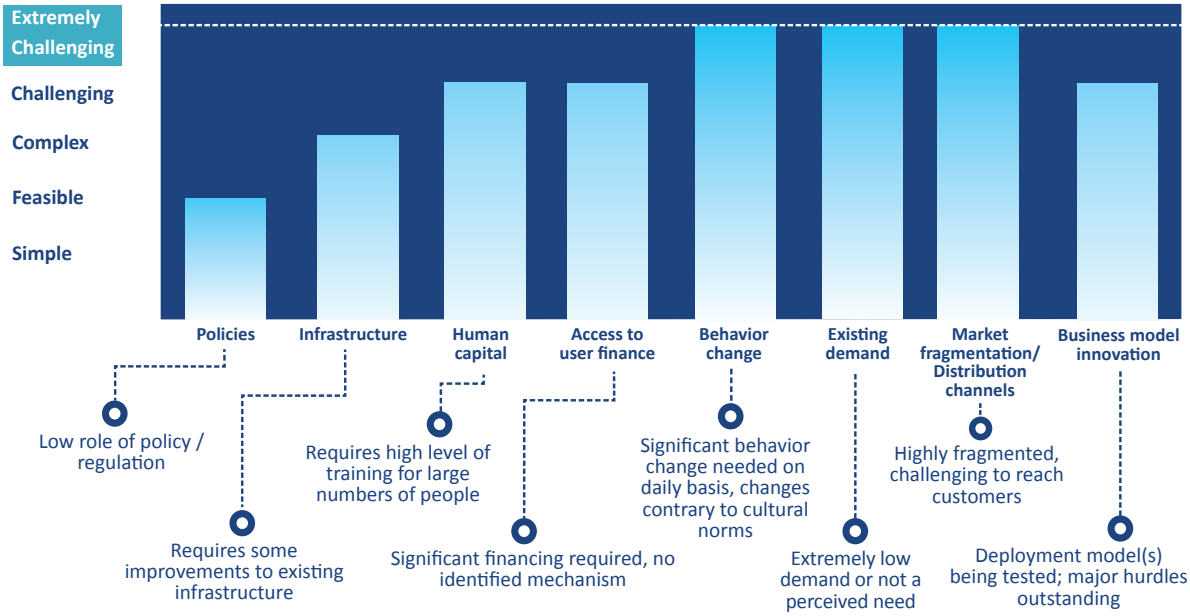
A low cost mechanism to preserve animal semen (including new methods to produce liquid nitrogen, or alternatives to liquid nitrogen)

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



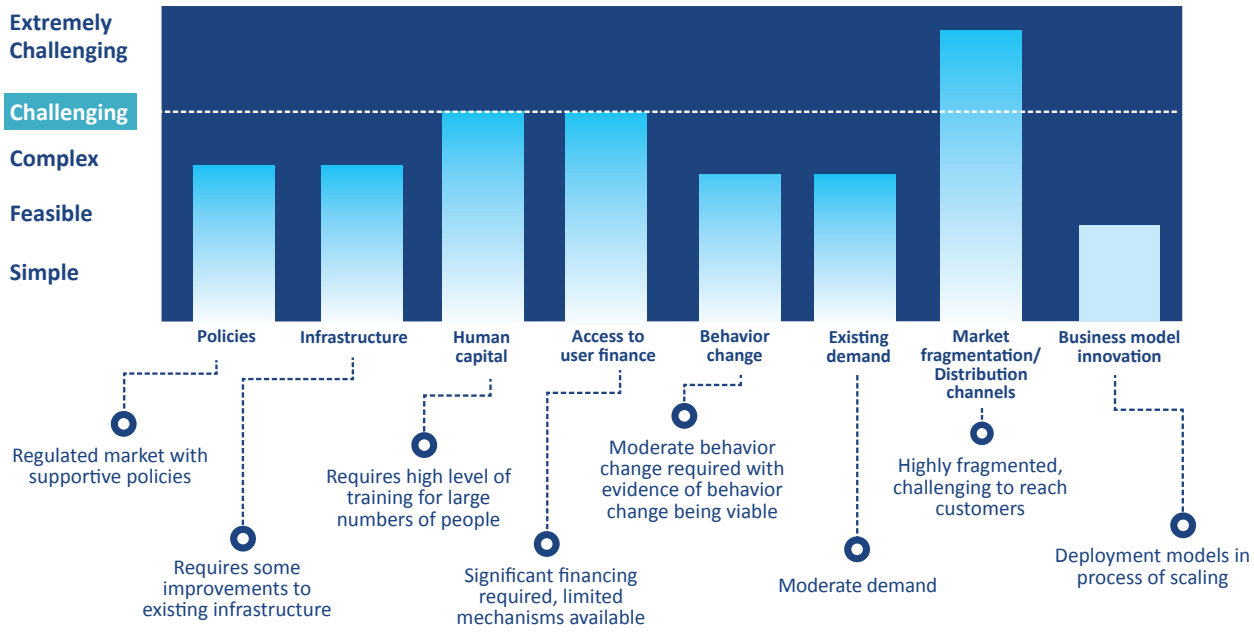
Breakthrough 3

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 thermosensitive 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.

Breakthrough 3 – Difficulty of deployment

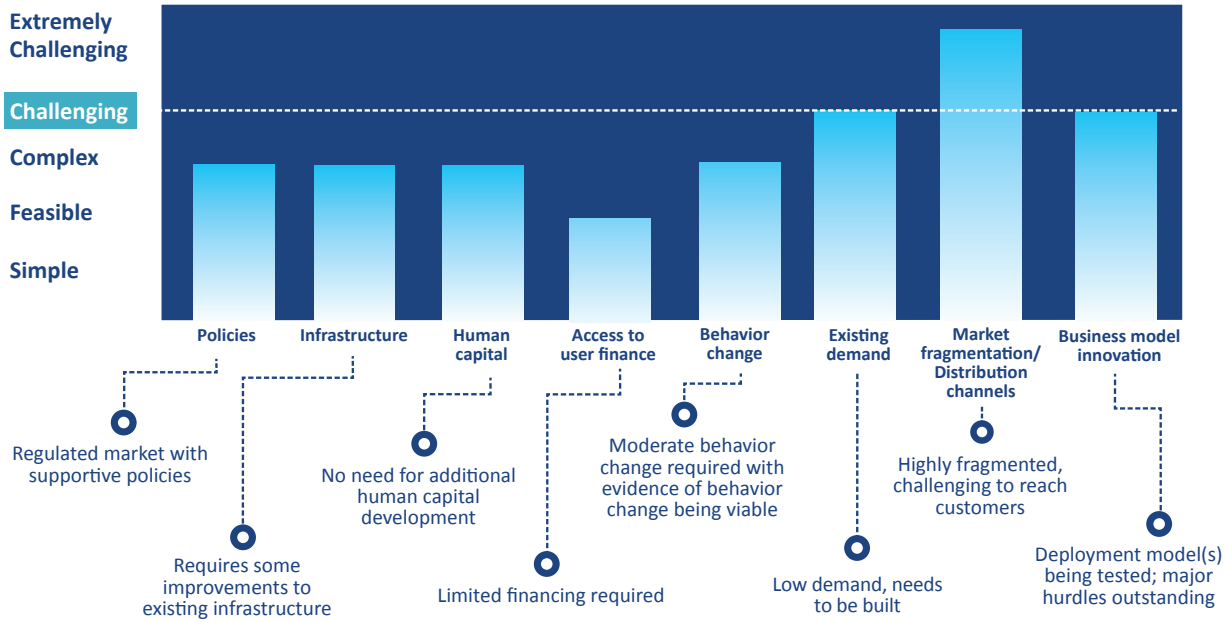


Breakthrough 4

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.

Breakthrough 4 – Difficulty of deployment

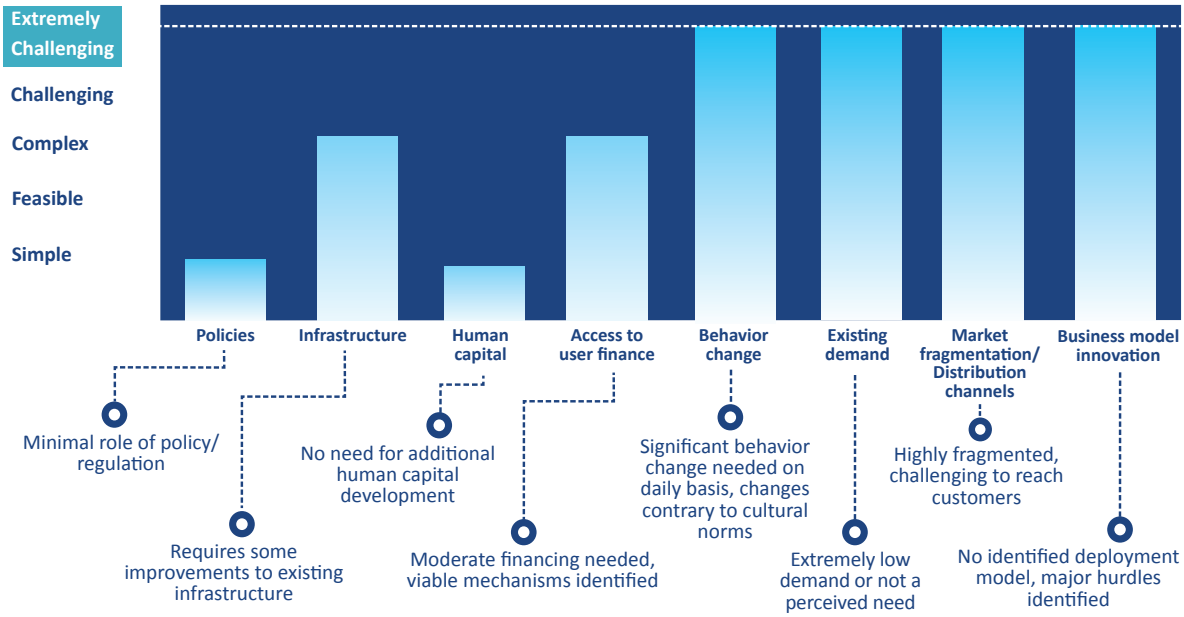


Breakthrough 5

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., pelletizing 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.

Breakthrough 5 – Difficulty of deployment



Breakthrough 6

Affordable (under $50) off-grid refrigeration for smallholder farmers and small agribusinesses

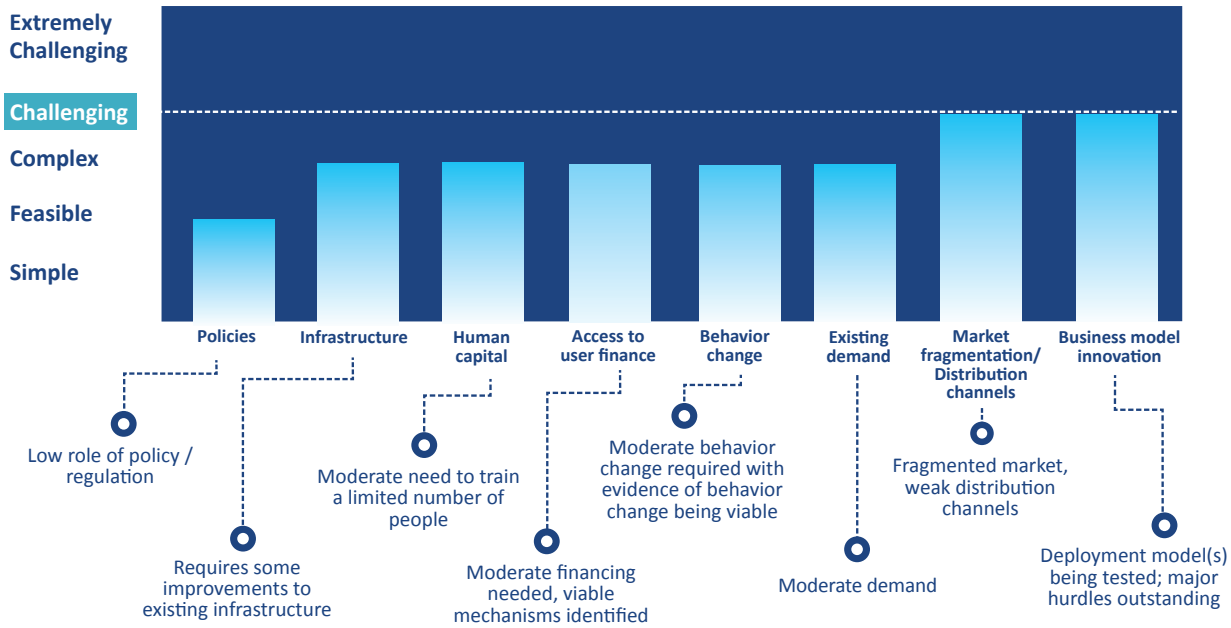
Horticulture products like fruits and vegetables are highly sensitive to temperature, and the lack of refrigeration dramatically reduces their shelf life, especially in tropical climates. While there are some inexpensive refrigerators available in emerging markets like India and China, they still cost 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.

Breakthrough 6 – Difficulty of deployment



Breakthrough 7

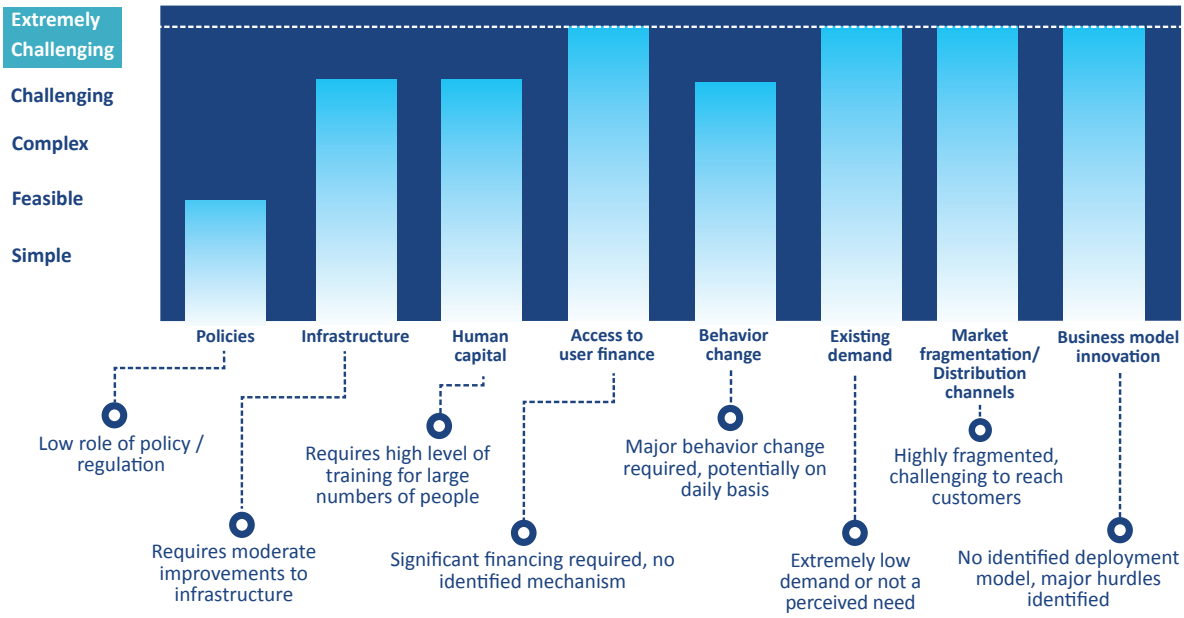
Low cost (under $5,000) refrigerated vehicles, sturdy enough for unpaved roads in rural areas.

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 7 – Difficulty of deployment



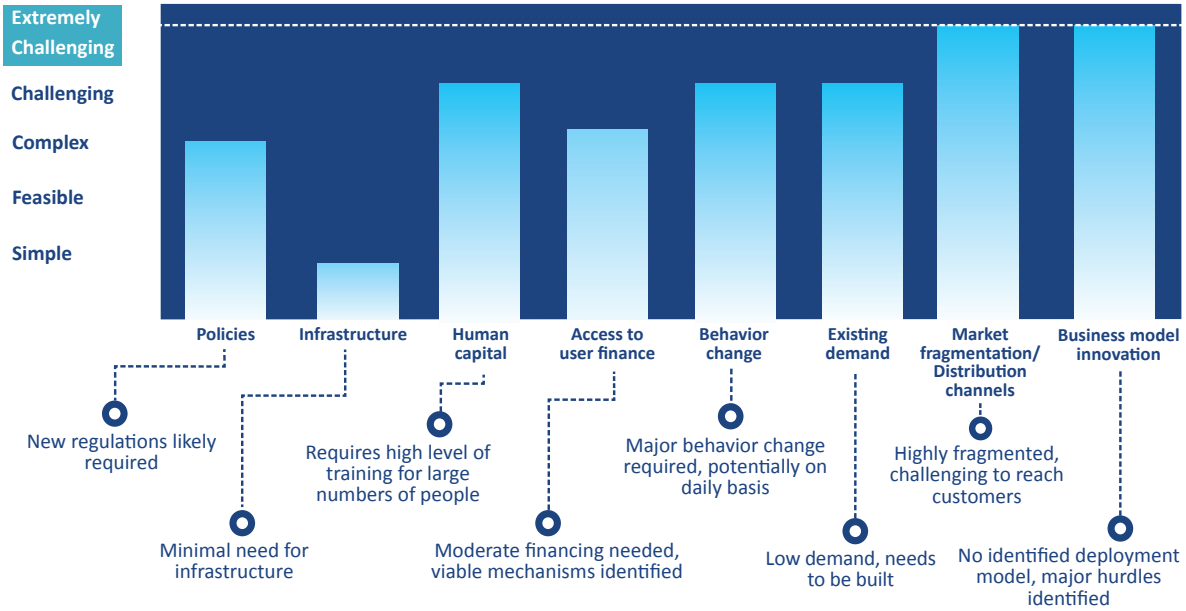
Breakthrough 8

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



SUSTAINABLE AGRICULTURE

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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[1]

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.

[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.

Maize output and cost across 4 major agricultural systems

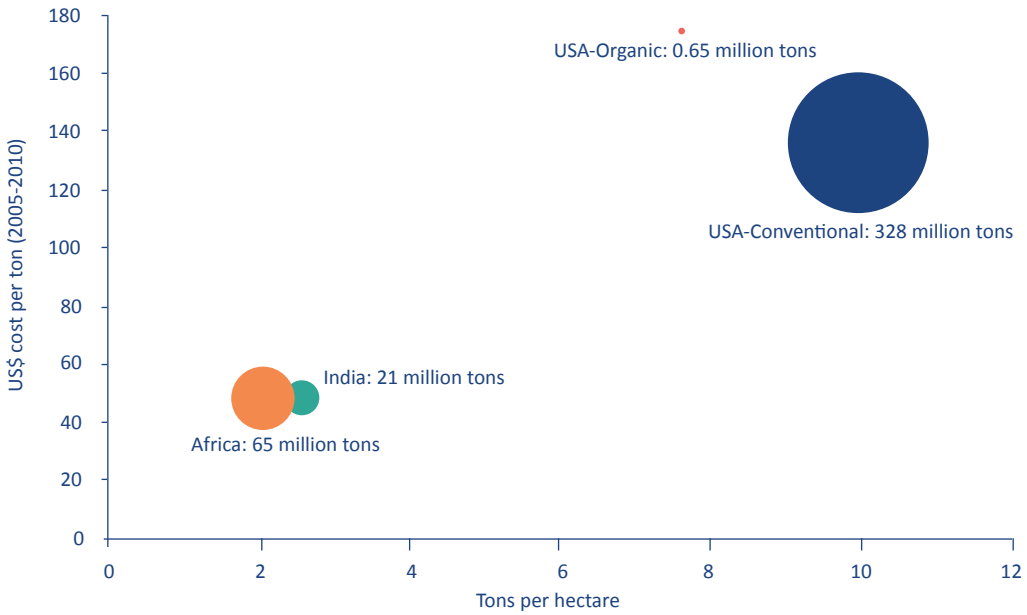

Exhibit 1: This exhibit illustrates the differences between 4 major agricultural production systems, using the example of maize. The US conventional system is the most prolific, producing 328 million tons annually. However, it also has a significant environmental footprint. Smallholder systems in Africa 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

Agricultural system	Typical sustainability challenges					
	Groundwater depletion	Water dead zones	Soil erosion	Deforestation	Chemical pollutants	Soil nutrient mining
Large-scale industrial (US-Conventional)	High	High	Medium	Low	High	Low
Green Revolution intensive (India)	High	High	High	Low	High	Low
Resource-constrained smallholder (sub-Saharan Africa)	Low	Low	High	High	Low	High
High-cost organic (US Organic)	Medium	Low	Medium	Low	Low	Low

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.

1 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.

Historical and projected global human population

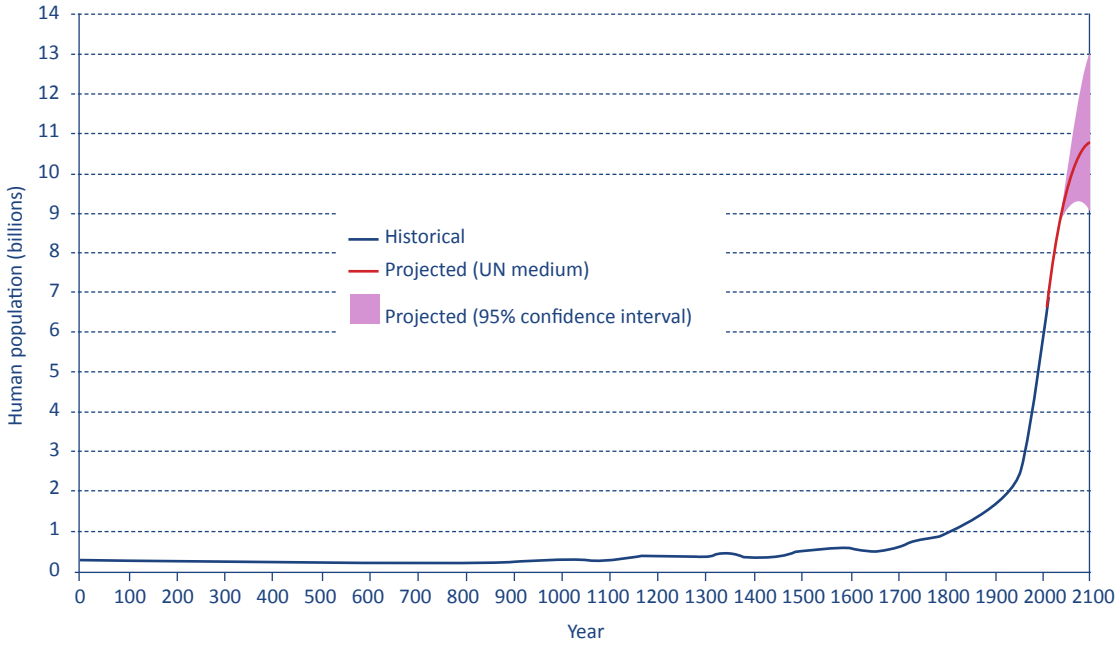

Exhibit 2: Global human population was relatively stable for much of the past 2 millennia, with fewer than 1 billion individuals until the year 1800. Population has increased markedly since then, and especially since 1950. Future population is projected to increase to 10.9 billion (95% confidence interval: 9.0 to 13.2 billion) people by 2100.

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).[4]

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).

[4] It should be noted that UN population projections are extrapolations of current demographics based on estimated future fertility rates, and implicitly assume that adequate sustenance will be available for the resulting populations. These projections are not based on certainty of how many people may be adequately fed with the resources available; rather, this is left as a challenge for the international agricultural development community.

Historical and projected global population and food production, 1960 - 2050

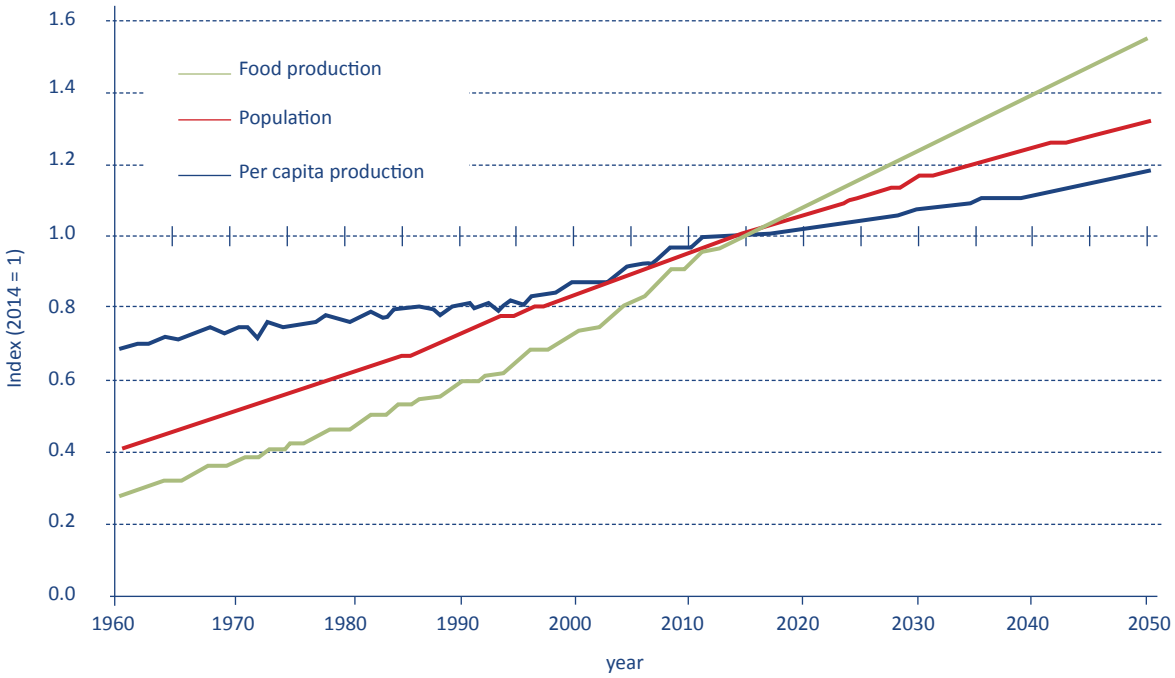

Exhibit 3: Total food production requirements are determined not just by total human population but also per capita food demand. Both have risen substantially since 1960, and are projected to continue rising through 2050 and beyond.

2 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).

Cereal production, yield and land usage in South Asia and sub-Saharan Africa, 1961 - 2009

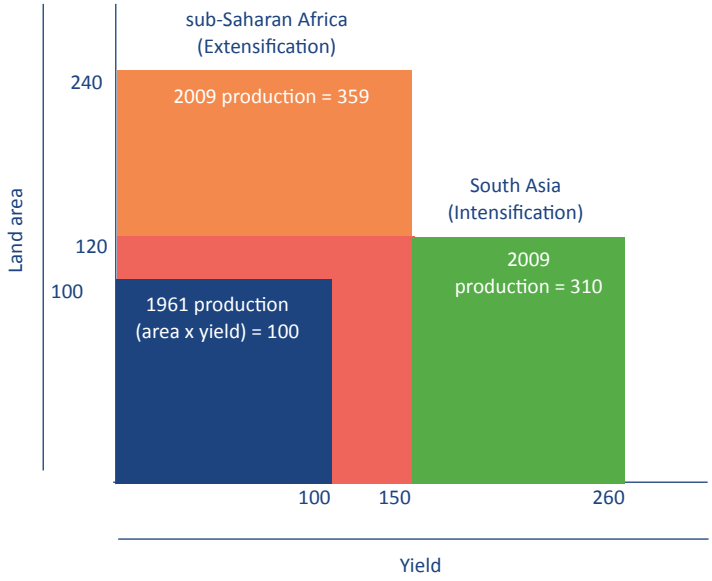

Exhibit 4: South Asian countries have increased agricultural yield dramatically over the past few decades using intensified agricultural practices. Compared with 1961, per hectare cereal yield in South Asia has increased by 165%, leading to a total output increase of 210%, with only a small increase 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.

Historical and projected sources of crop production increases

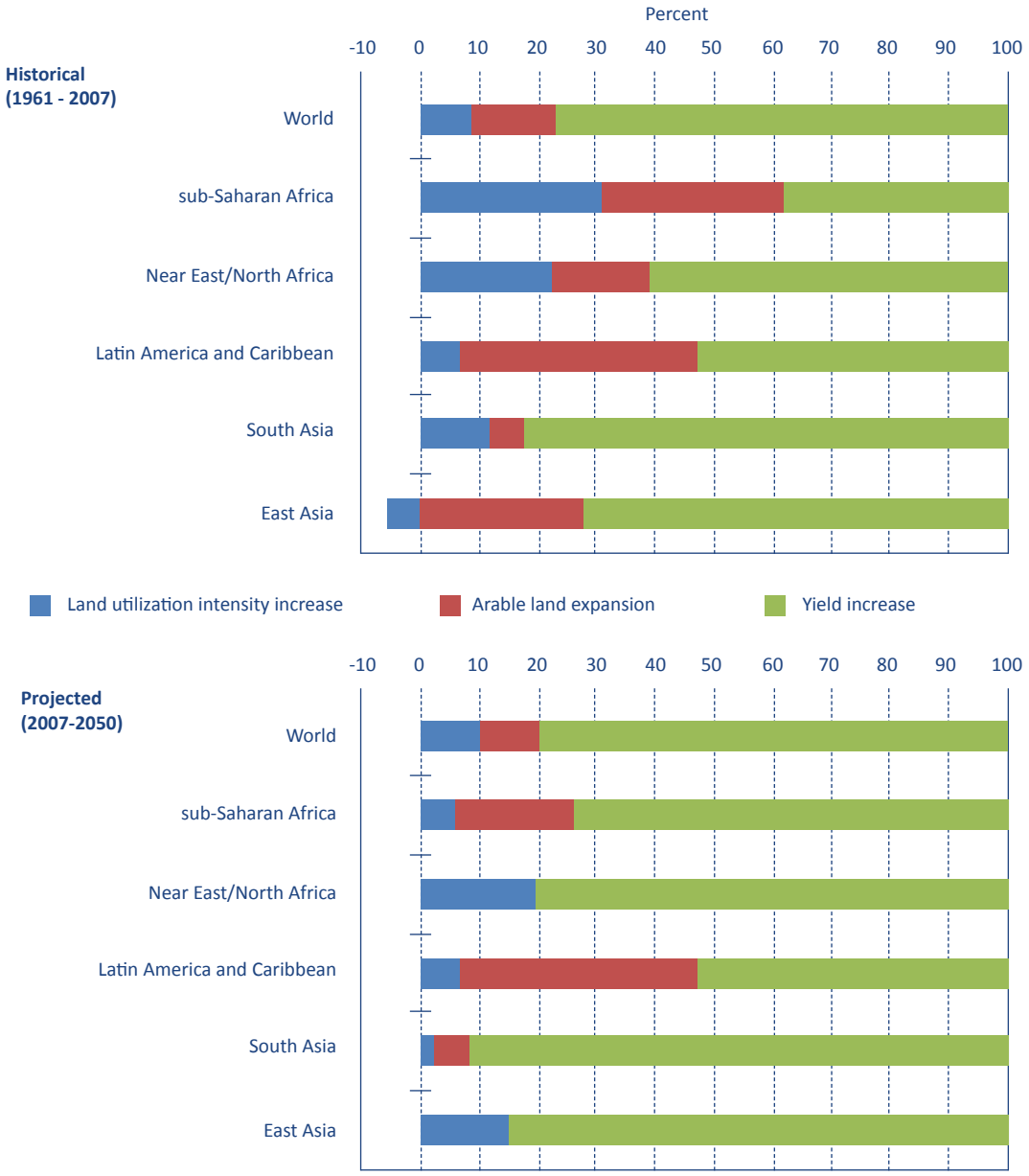

Exhibit 5: Crop production can be increased by extensification (expanding the area of farmland) or by intensification (getting bigger or more frequent harvests from existing farmland). Agricultural intensification can come from increasing yield, which gives more food per harvest, or by increasing land 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).

3 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).

Arable cropland in use in different regions (past and projected)

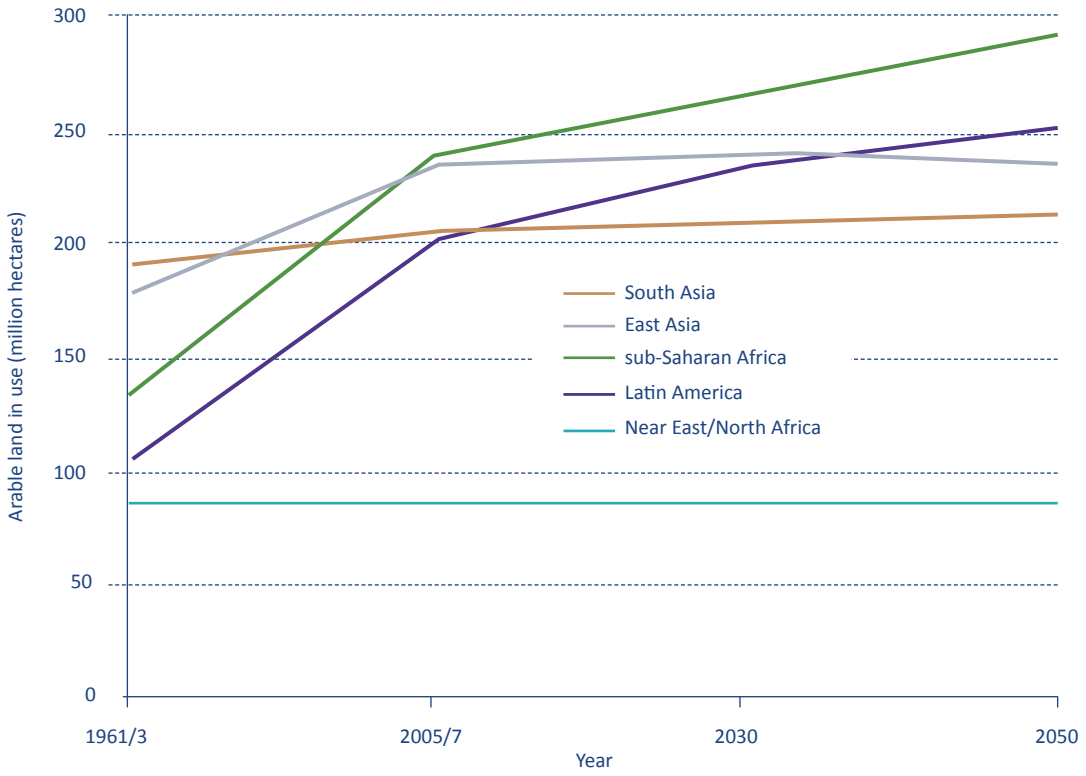

Exhibit 6: The area of arable cropland in use has increased substantially since the 1960s in sub-Saharan Africa and Latin America, with smaller increases in Asia. Arable cropland area is expected to continue to increase modestly through 2050 in sub-Saharan Africa and Latin America. Very little future 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 km² 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 km² 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

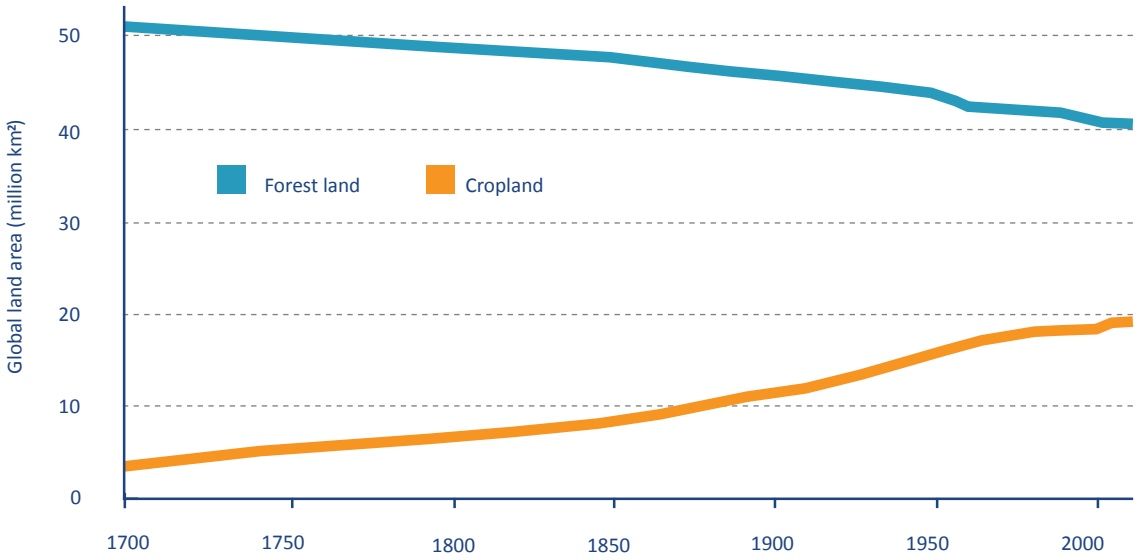

Exhibit 7: Over the last 3 centuries, humans have converted about 10 million km² of forest land to other uses, and have turned about 15 million km² of land into agricultural cropland. During the same period, natural grassland area has decreased, and pasture land area has increased (not shown in figure).

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

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

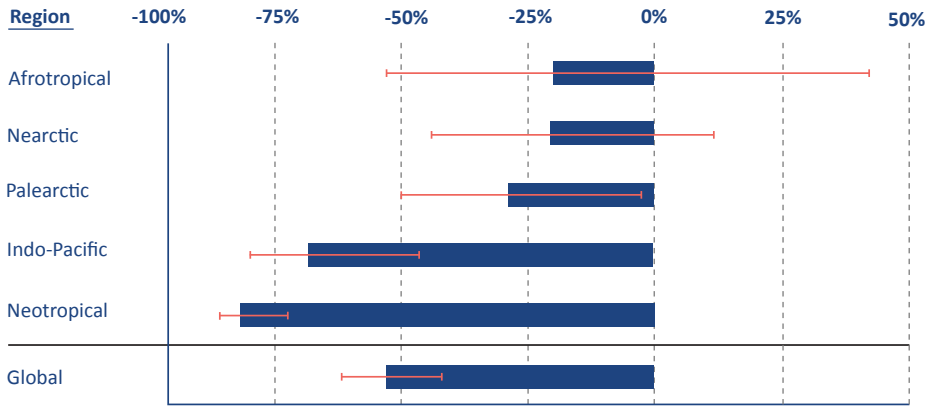

Exhibit 8: Regional and global biodiversity has generally decreased in recent decades, as estimated by WWF's Living Planet Index, based on wild populations of vertebrate animals between 1970 and 2010. Error bars represent 95% confidence limits. The 5 regions are biogeographic realms, where terrestrial 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

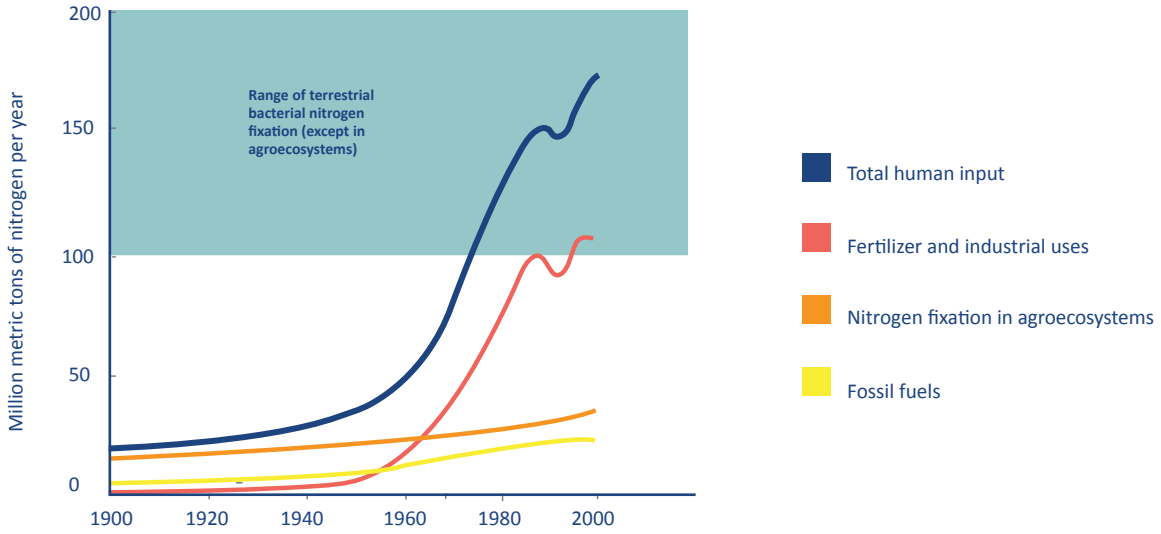

Exhibit 9: Human production of reactive nitrogen has increased substantially during the last 50 years, and now occurs at the same rate as it does in all natural land ecosystems put together. Most of this increase is due to fertilizer production using the Haber-Bosch process.

Another important plant nutrient is the chemical element phosphorous, 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).

Sources of phosphorous fertilizer since 1800

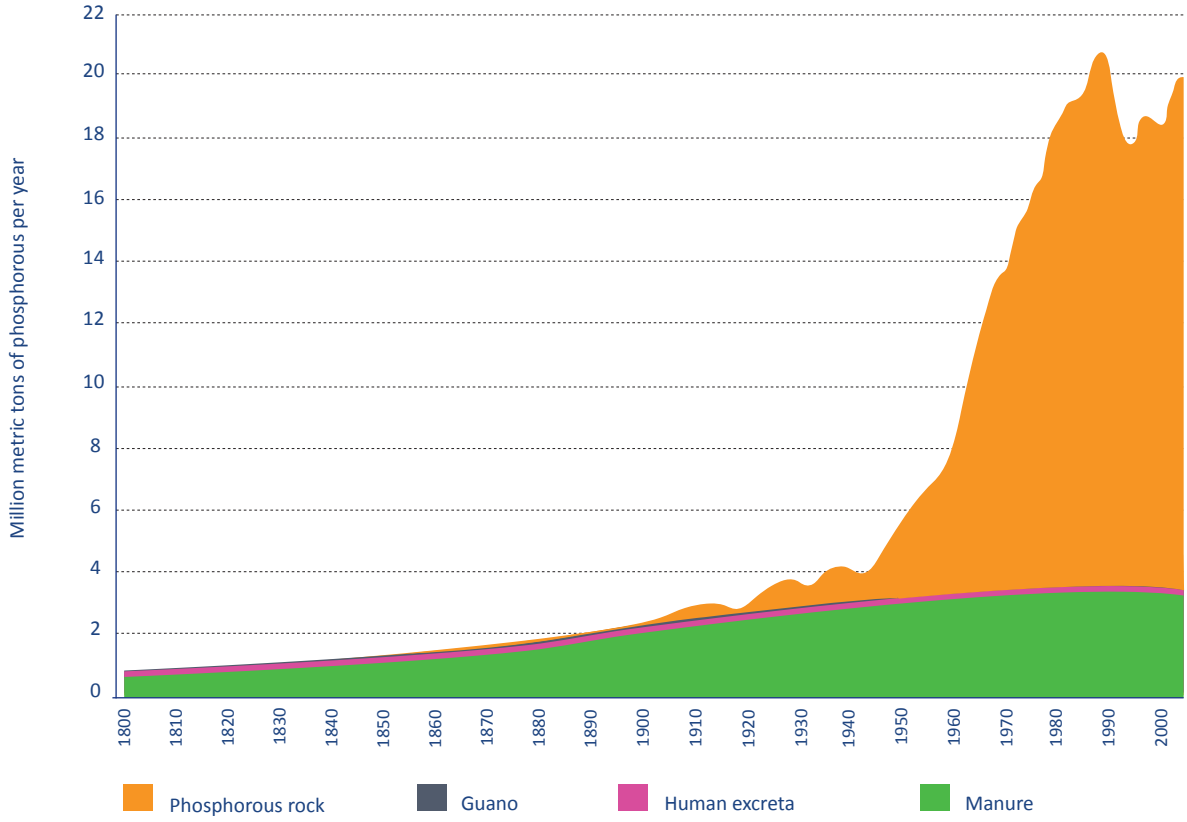

Exhibit 10: Mining of phosphate rock expanded considerably after 1950, and is now the dominant source of phosphorous fertilizer used in agriculture.

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.

Increase in nitrogen runoff leading to aquatic dead zones

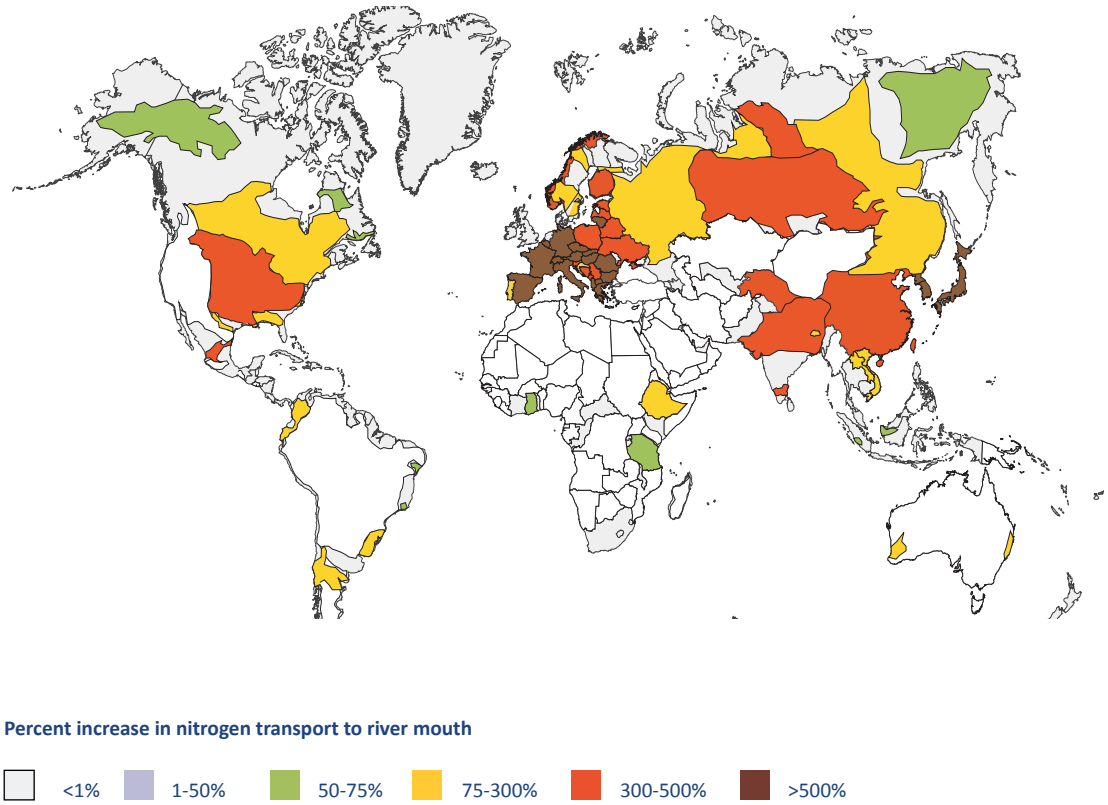

Exhibit 11: Reactive nitrogen flows in many river systems have increased dramatically in recent decades—primarily due to fertilizer runoff from agricultural lands—especially evident in Europe, Asia and North America. This has led to 'dead zones' in waterways.

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.

Sources of water used globally for irrigation, 1960 to 2000

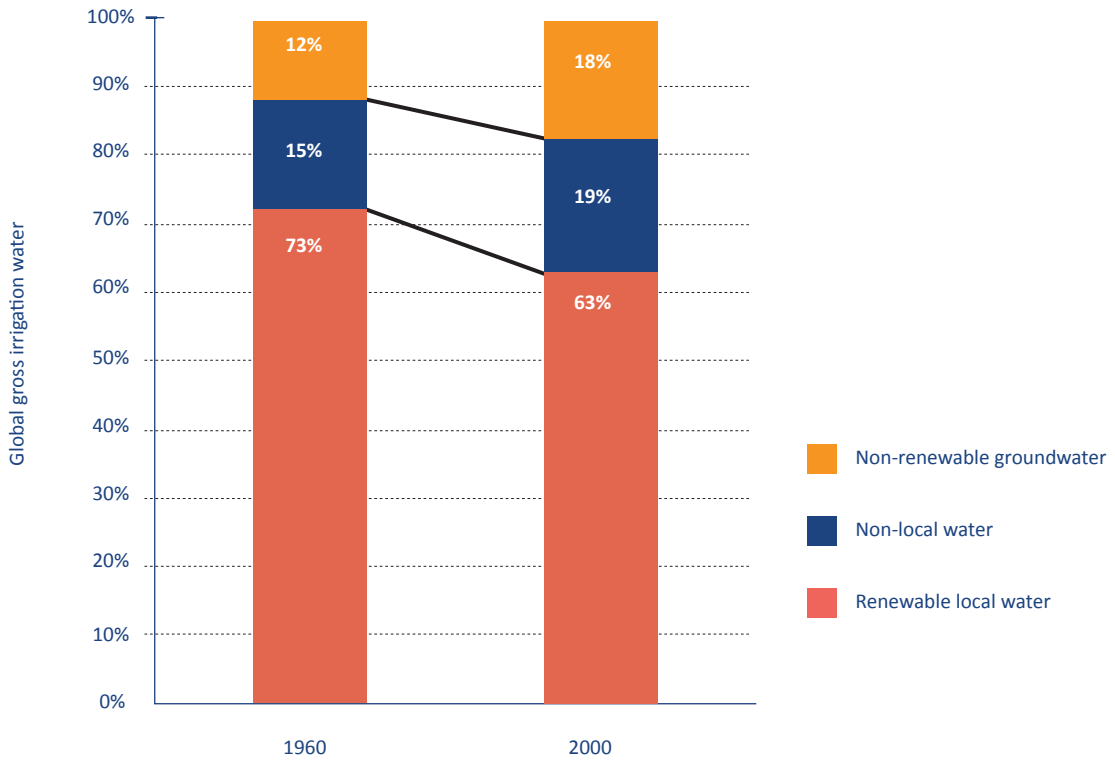

Exhibit 12: Between 1960 and 2000, the share of non-renewable groundwater increased from 12% to 18% of global gross irrigation water. The share of non-local water resources, transported to the regions via canals and pipelines for example, increased from 15% to 19% of global gross irrigation water. Renewable 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 1,340 km^3 per year), and non-renewable groundwater use increased three-fold (from 75 to 230 km^3 per year), between 1960 and 2000. Relatively few countries are responsible for most of the non-renewable groundwater use.

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

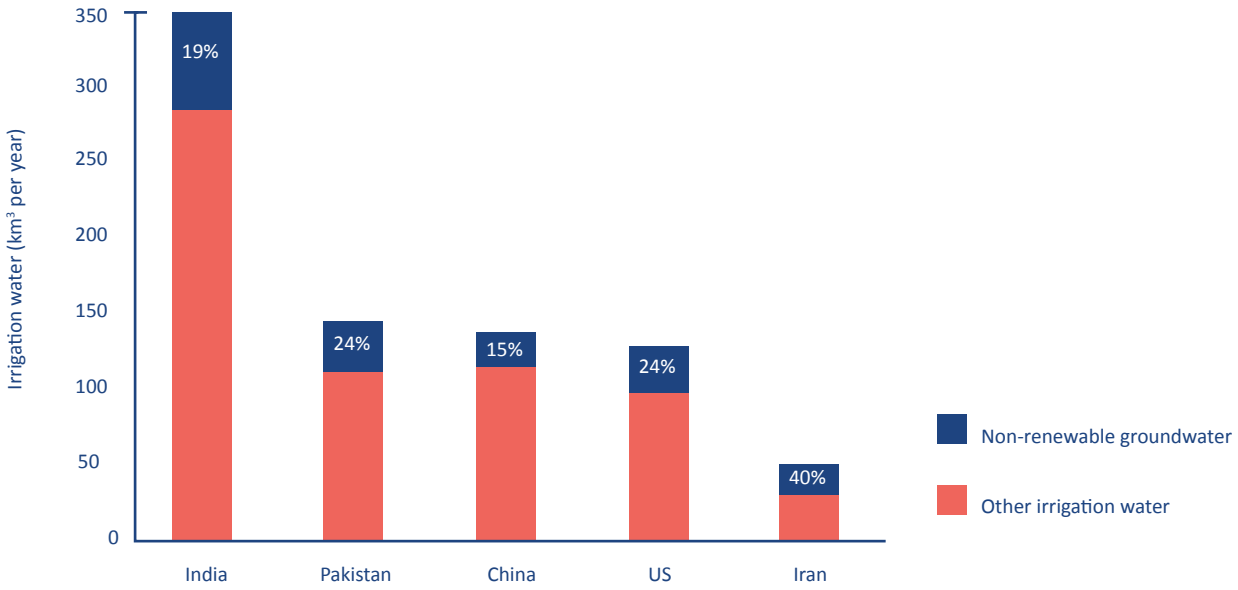

Exhibit 13: Non-renewable groundwater is a significant part of gross irrigation water used in several major countries. India uses more non-renewable groundwater for irrigation than any other country (68 km^3 per year, in year 2000). Iran uses less in absolute terms (20 km^3 per year) but more as a percent 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.

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 is typically tilled, or turned and mixed, during conventional farming practices to remove unwanted vegetation and give crops the best chance to thrive. These disturbances to the soil leave it more vulnerable to being swept away by water or 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

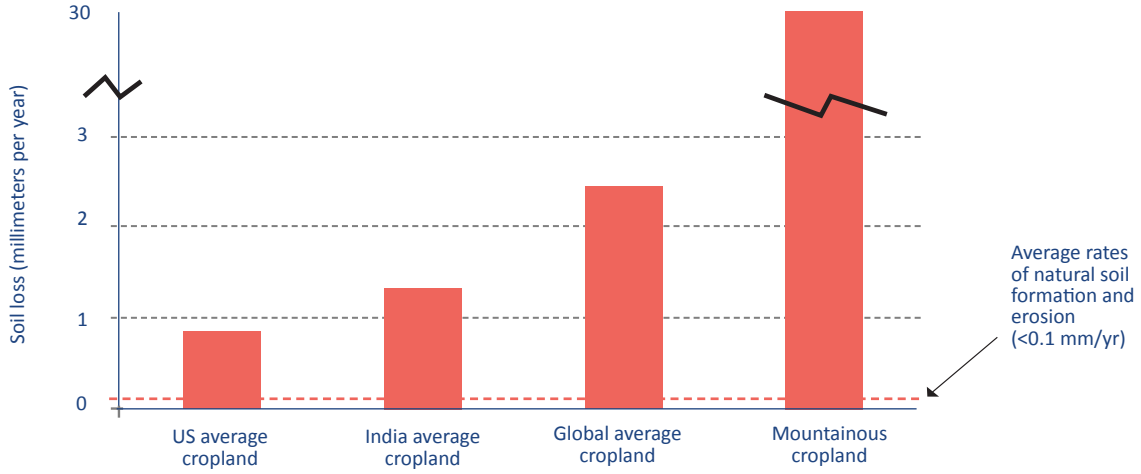

Exhibit 14: On average, about 1 to 3 millimeters of soil are lost each year from typical farmland. Soil erosion rates in mountainous regions can be 10 times greater. Under natural conditions, rates of natural soil formation and of soil erosion from land are at least 10 times lower.

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

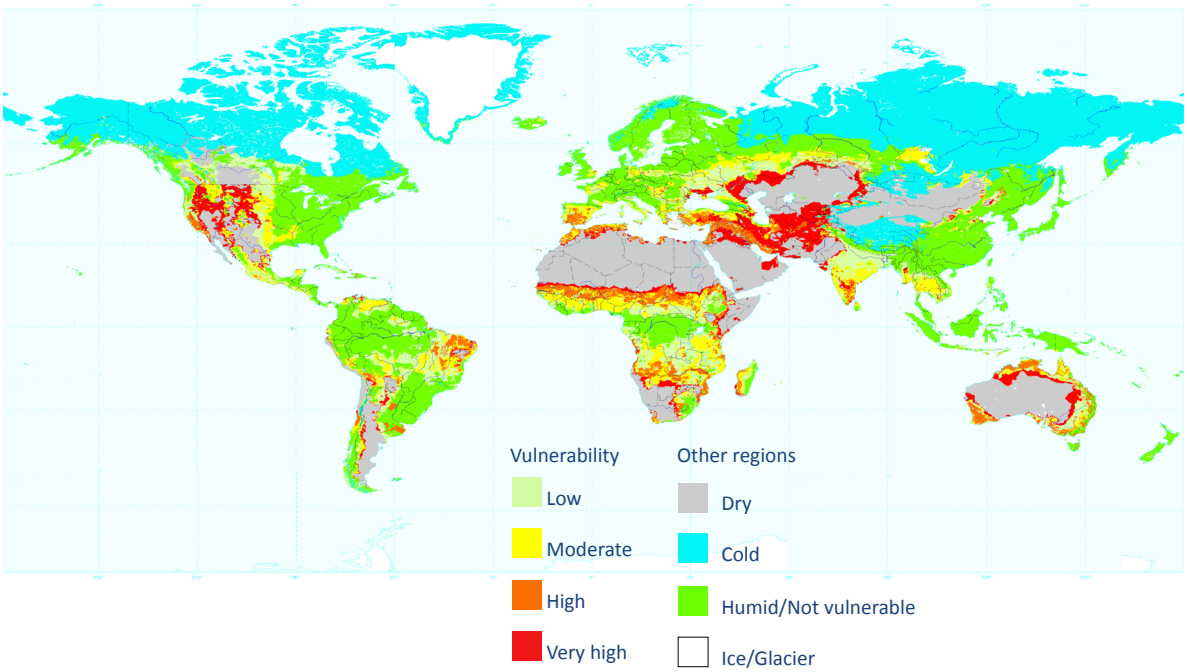

Exhibit 15: Dryland regions, which occupy 41% of Earth's land area and are home to more than 2 billion people, are at particular risk of land degradation and desertification (USDA 1998).

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

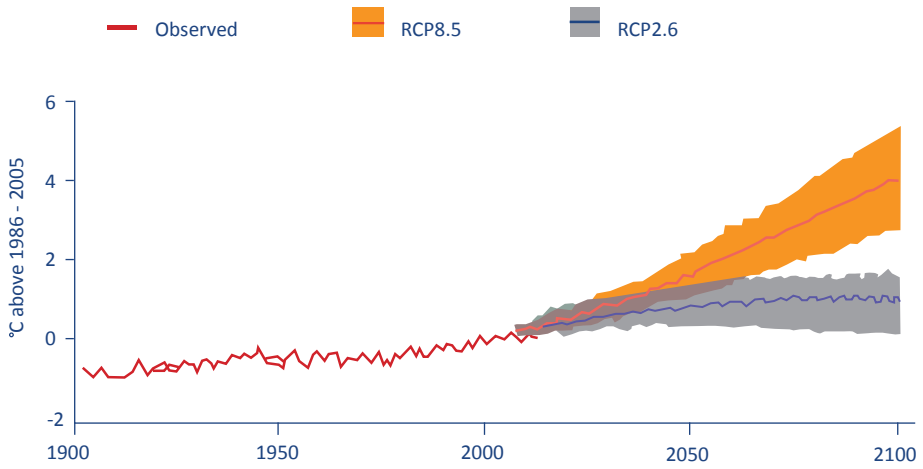

Exhibit 16: Global average surface temperature is projected to increase during this century. The temperature increase will be greater if greenhouse gas emissions continue at high levels, following the RCP8.5 emission scenario. A smaller temperature increase is projected to occur if emissions are limited 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

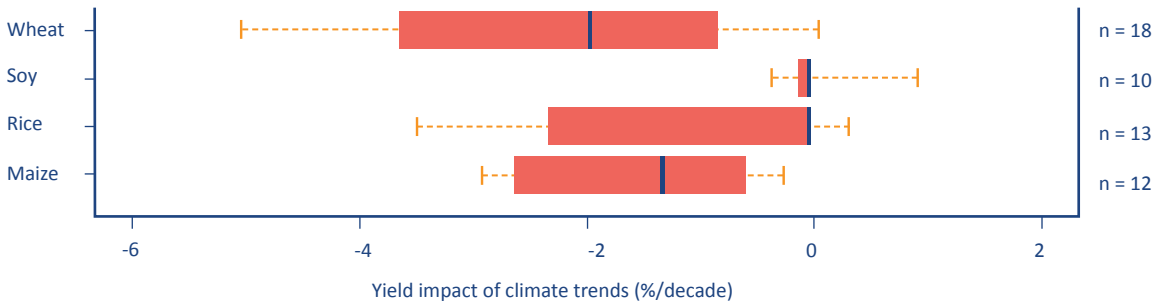

Exhibit 17: Yields of wheat, rice and maize are expected to decline due to climate trends including rising temperatures. This exhibit summarizes estimates from peer-reviewed literature of the impact of recent climate trends on yields for four major crops. The boxplots indicate the median (vertical line), 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

1 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.

2 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

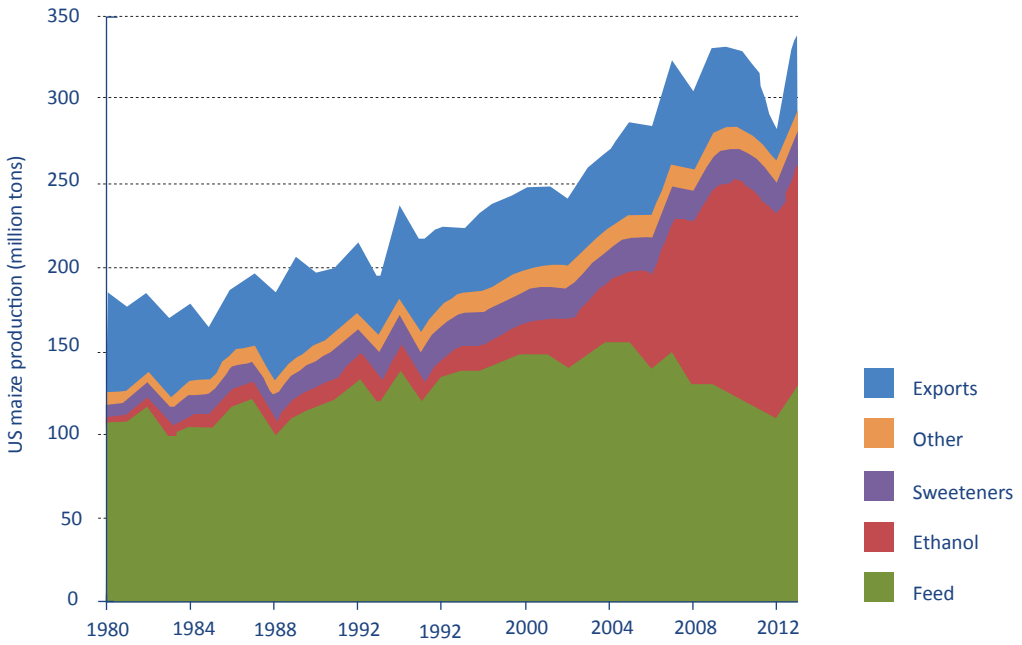

Exhibit 18: About 40% of current US maize production is used to produce ethanol, of which 97% is used as fuel. Another 40% is used to feed domesticated animals. 'Sweeteners' include high-fructose corn syrup, glucose and dextrose. 'Other' uses include cereals, starch and seeds.

3 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.

4 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.

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SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

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).

Breakthrough 1

Low cost, easy-to-construct rainwater storage repositories where harvested rainwater can be stored for several months without contamination

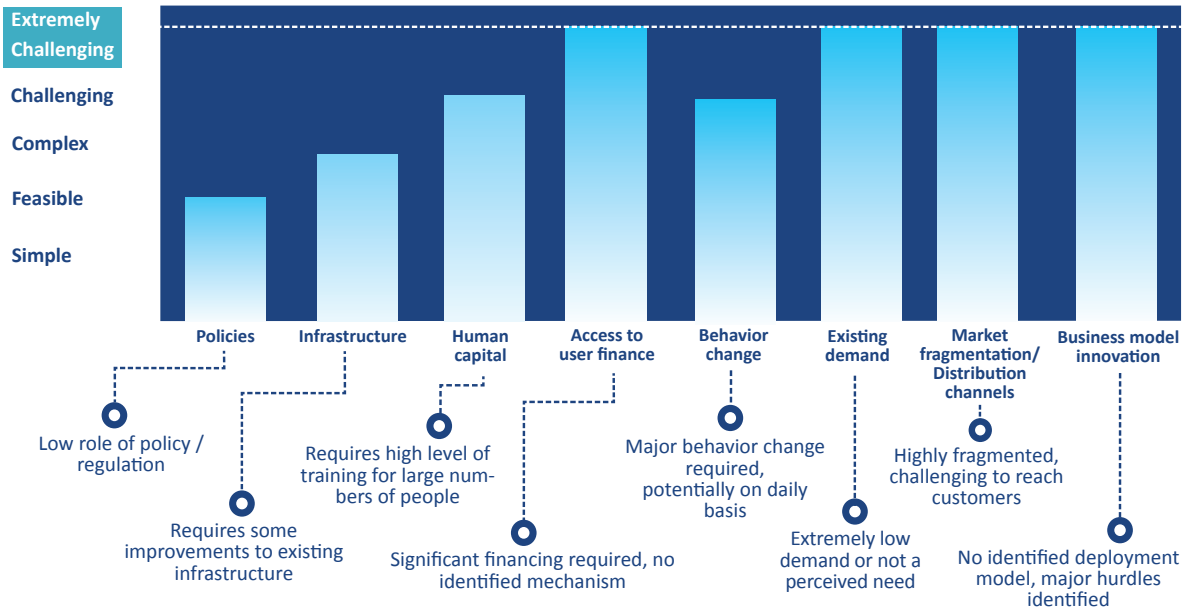
A feasible mechanism to capture and store rainwater for several months at a time, can prevent runoff-related losses, and create shallow groundwater reserves. There is considerable research on the artificial recharging of groundwater (Government of India, 2007), but most techniques (e.g., percolation 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 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.

Breakthrough 1 – Difficulty of deployment



Breakthrough 2

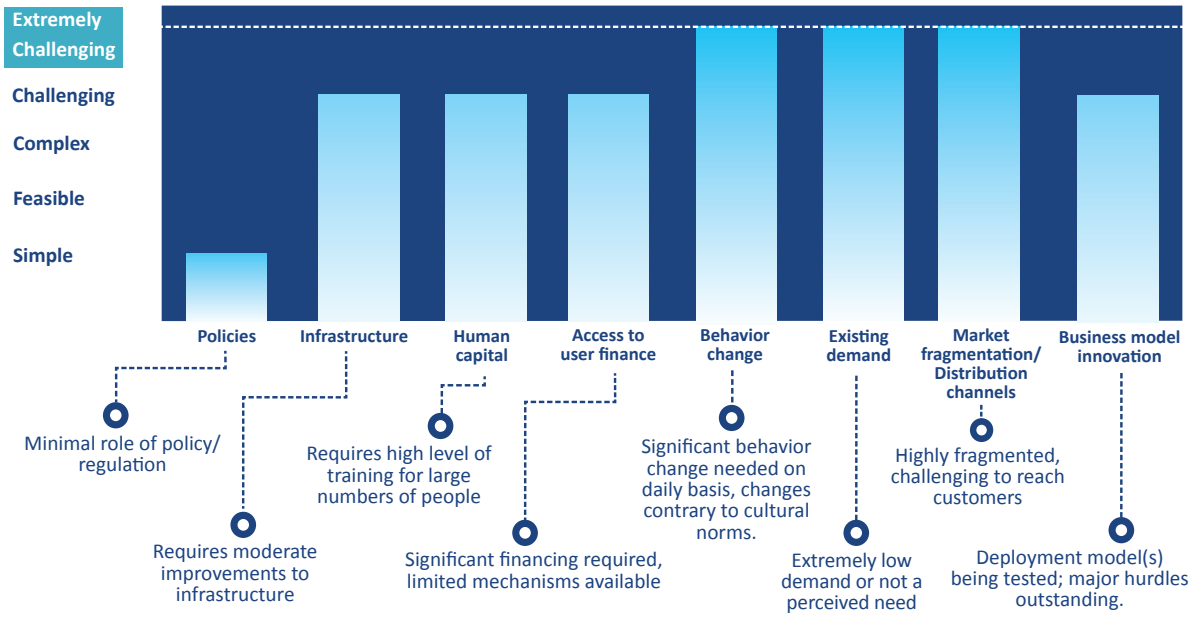
New methods for nitrogen fixation and producing other fertilizer components, instead of the energy-intensive and capital-intensive methods used currently

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 2 – Difficulty of deployment



Breakthrough 3

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.

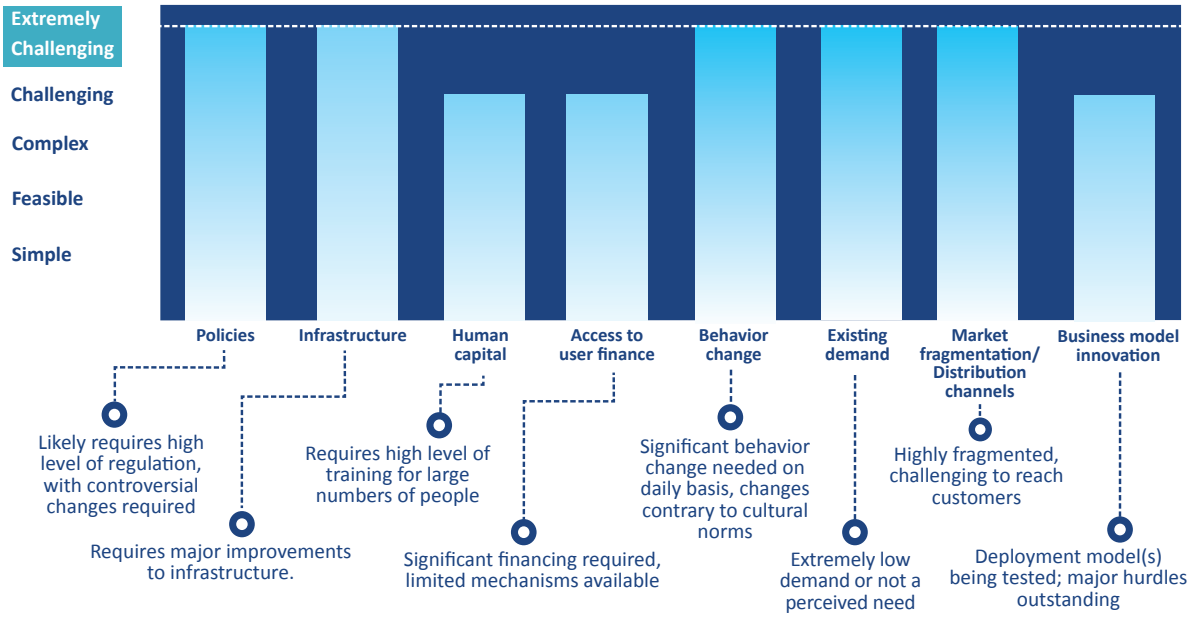
Using human waste to make fertilizer presents its own set of challenges. Collecting human waste safely for converting it to fertilizer can help tackle the spread of diarrheal diseases—mostly caused by the spread of fecal pathogens—that are one of the biggest drivers of childhood mortality. The process 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



Breakthrough 4

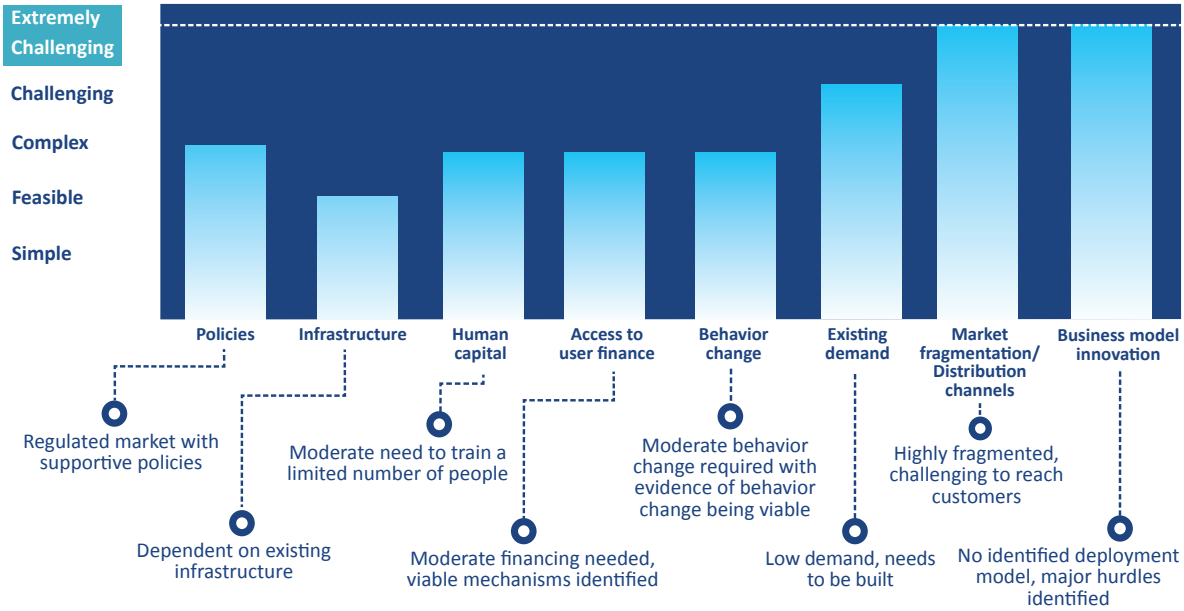
Herbicides or other affordable mechanisms to control weeds, ideally ones that are more environmentally friendly than herbicides currently on the market

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



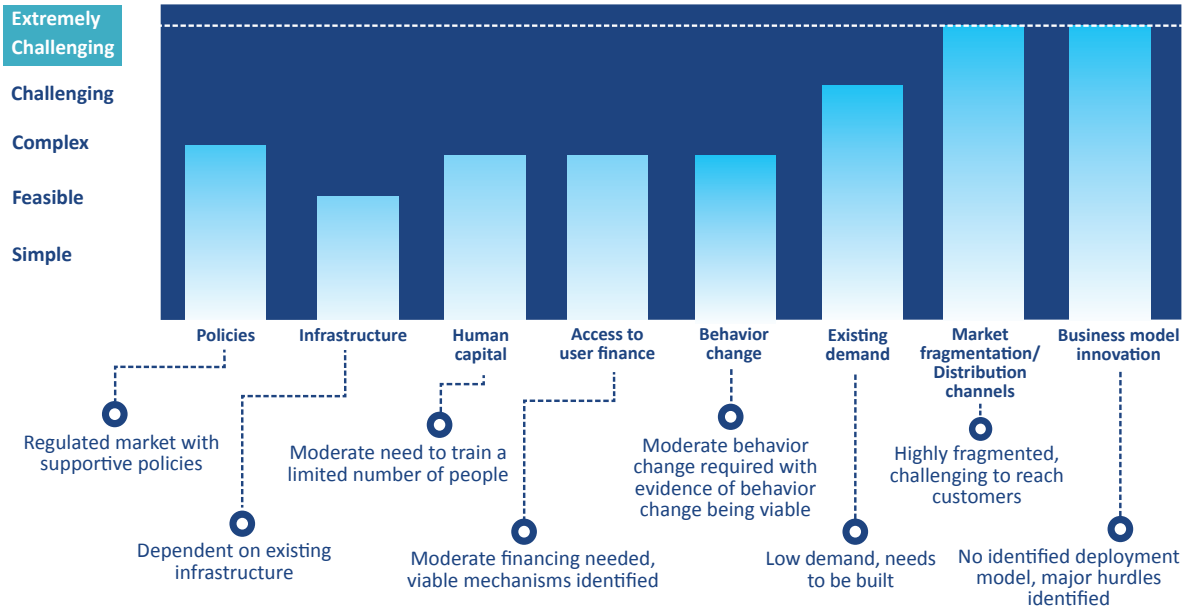
Breakthrough 5

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.

Breakthrough 5 – Difficulty of deployment



Breakthrough 6

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**).

Cost of current desalination processes

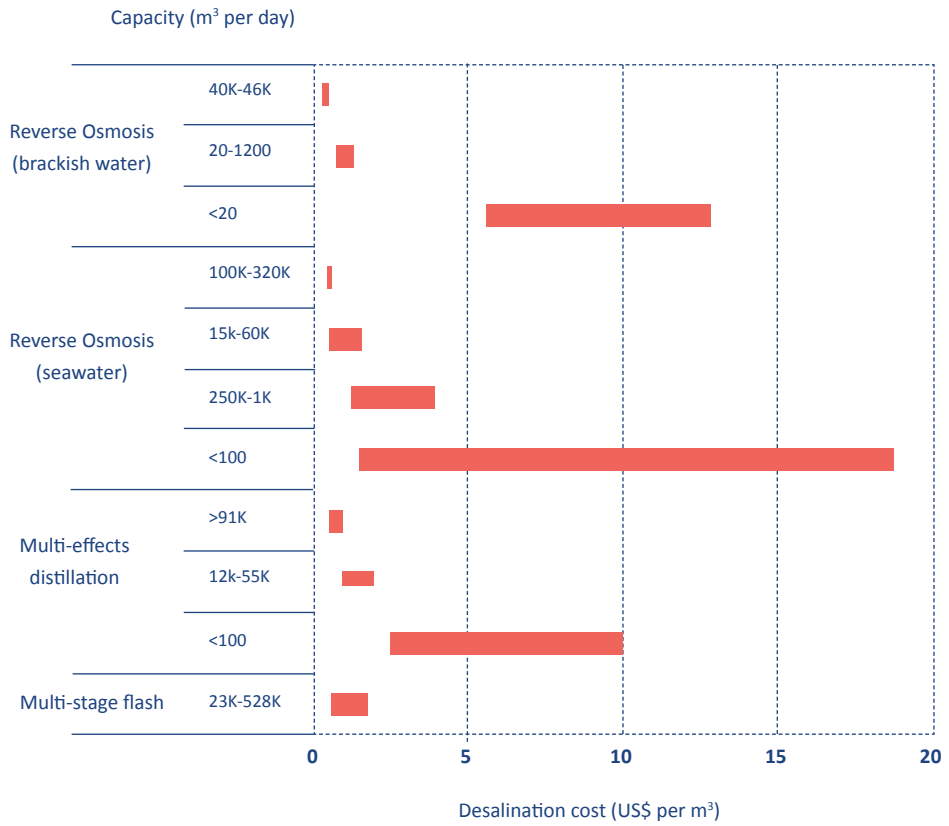
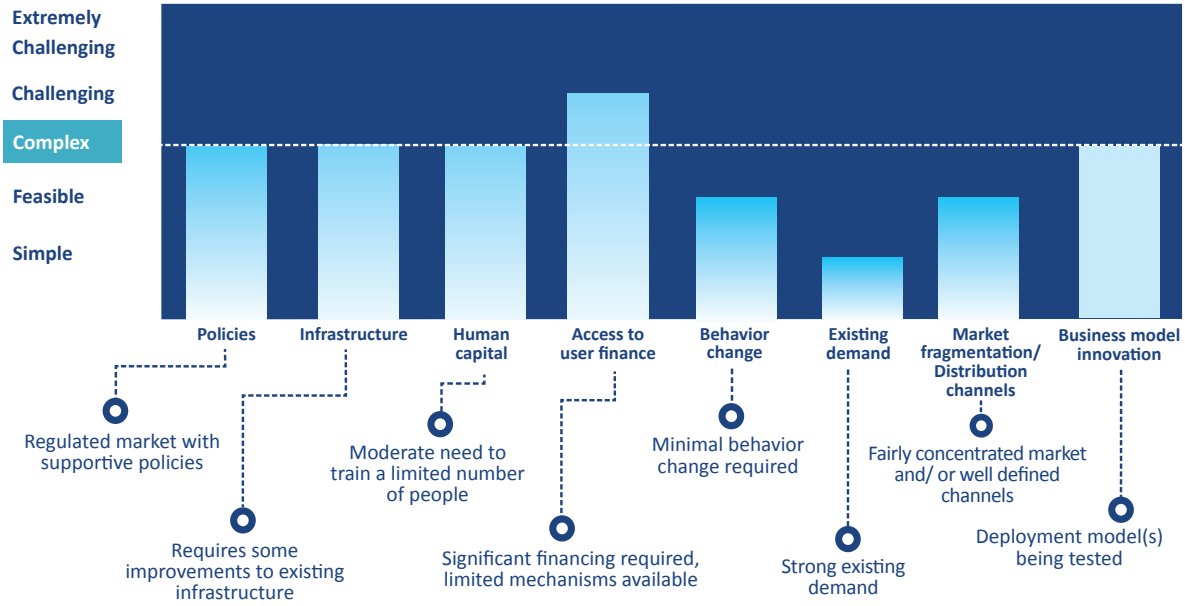


Exhibit 19: The cost of current desalination processes ($ per m^3 of fresh water) varies depending on the technology used and the scale of the process. The cost of energy inputs is also a significant variable. Conventional desalination technologies are too expensive and energy intensive to scale sufficiently to provide fresh water for significant global human development (Shatat & Riffat 2012).

As an illustration of desalination costs, let's consider the 68 million km^3 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



Breakthrough 7

A low cost system for precision application of agricultural inputs, ideally combining water and fertilizers

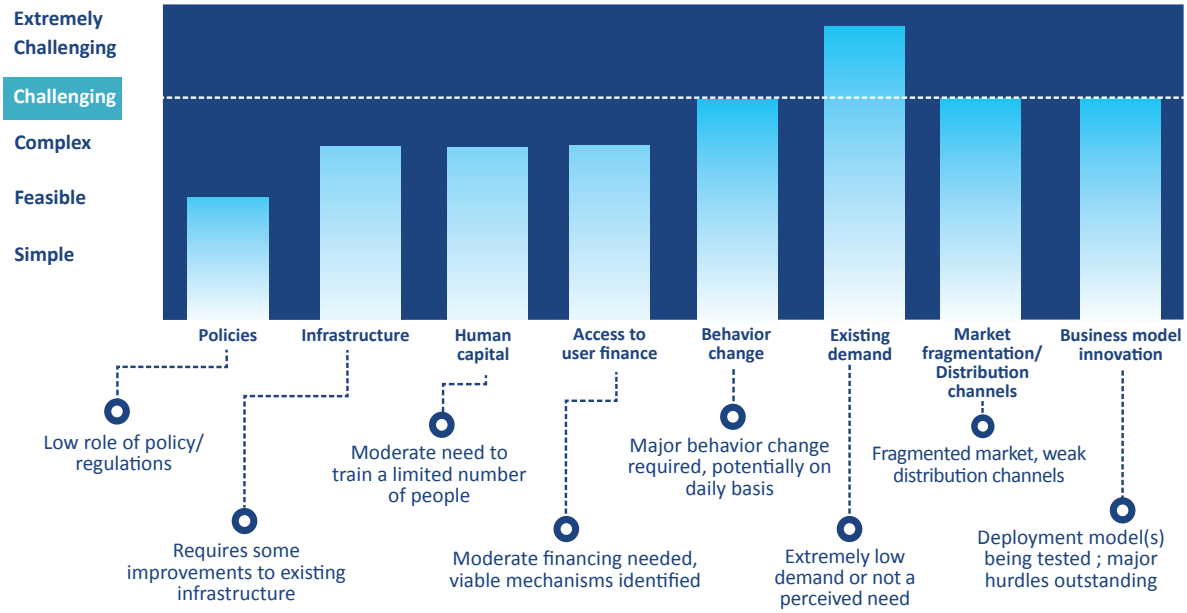
The lessons from the Green Revolution in Asia, also discussed in other sections of this study, show that a few decades of overuse can devastate groundwater reserves for the long term. The additional stress of climate change and the consequent change in rainfall patterns increases the need for efficient 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 7 – Difficulty of deployment

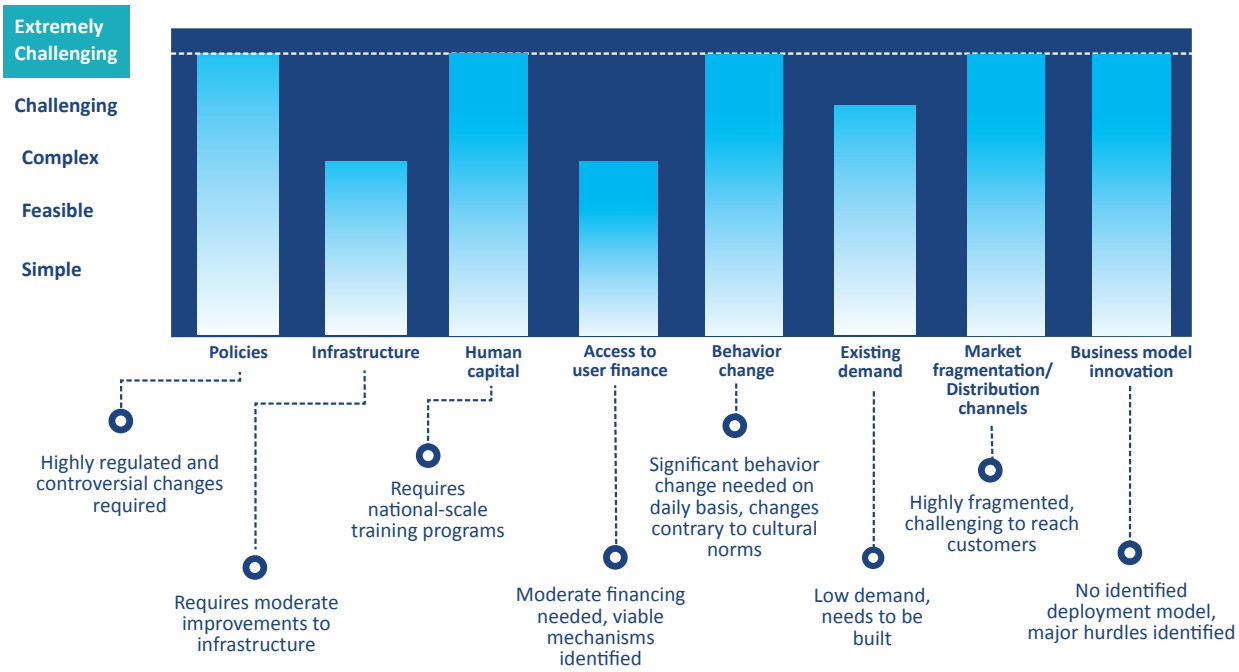


Breakthrough 8

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



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 four 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, & Pinstrup-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 cisgenesis 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.

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