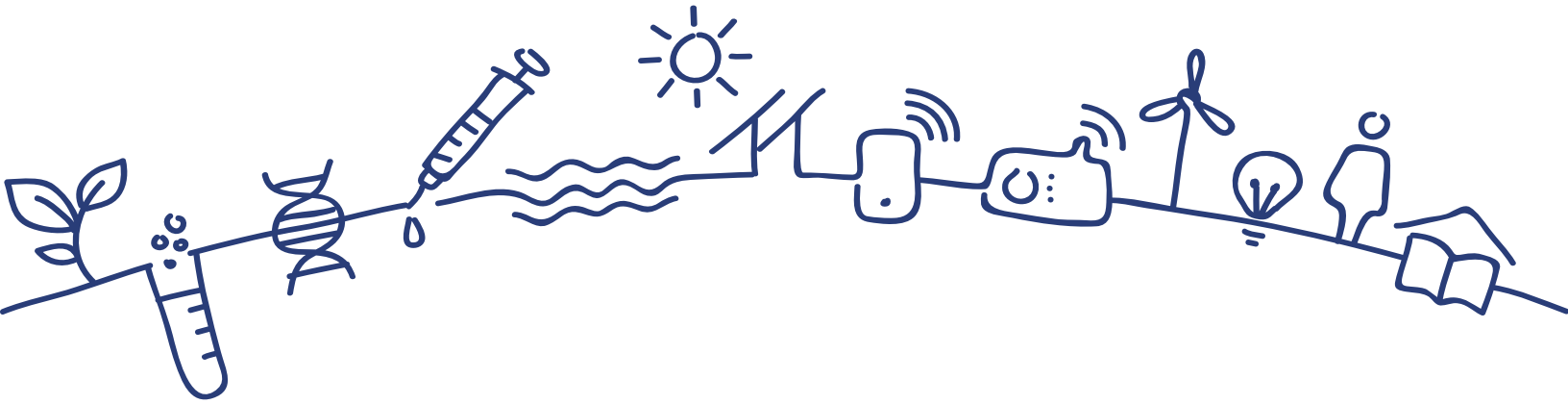
50 BREAKTHROUGHS

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.

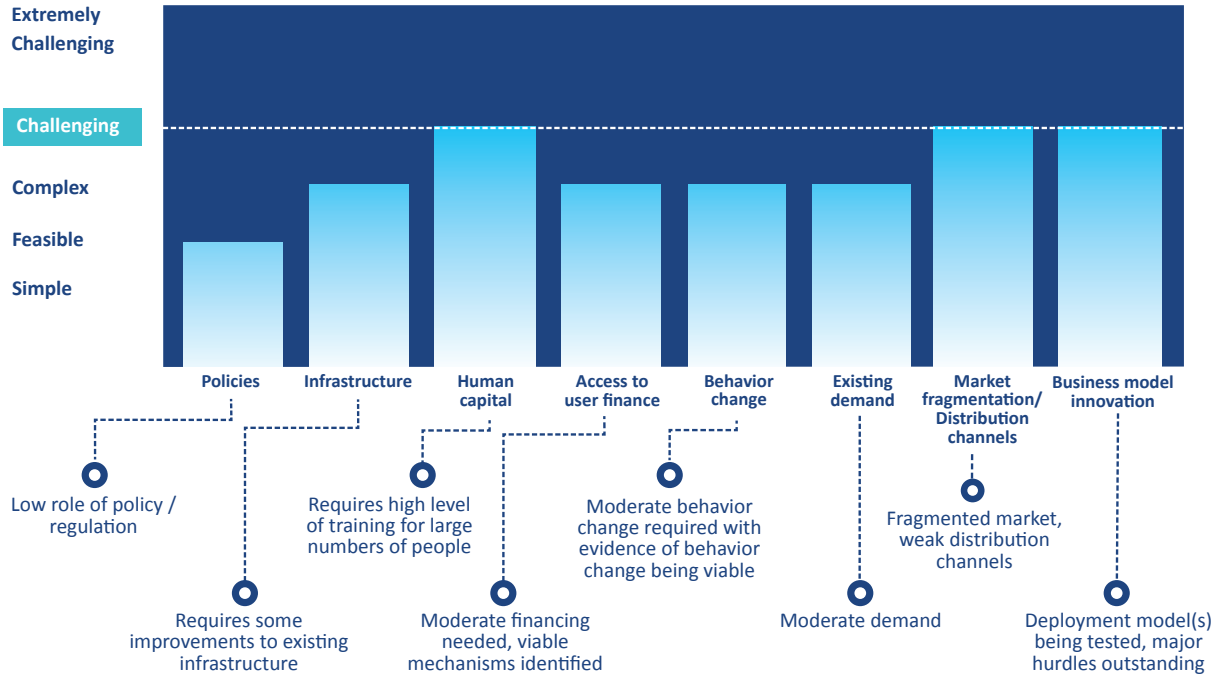
[1] A structured communication technique, originally developed as a systematic, interactive forecasting method which relies on a panel of experts who anonymously reply to questionnaires and subsequently receive feedback in the form of a statistical representation of the 'group response', after which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



RESILIENCE AGAINST CLIMATE CHANGE AND ENVIRONMENTAL DAMAGE

Throughout human history, changing the natural environment in the interest of human welfare and economic output has been an integral part of development efforts. These direct or first-order environmental changes have been hugely beneficial to humans, and were the basis of fundamental human advances—the Agricultural and Industrial Revolutions. However, as the scale of human enterprise increases relative to the scale of natural processes (i.e. those not managed by people), a growing number of indirect or second-order environmental consequences can be seen. Activities that previously were overwhelmingly beneficial now bring both positive and negative effects on human welfare. There are a number of pathways through which environmental changes may significantly impact human development, but direct cause-and-effect has not been clearly articulated, yet. Here we seek to understand the complex chain of events linking environmental change and human welfare.

We identify 7 broad categories that comprehensively describe the first-order environmental changes caused by human actions. Ranging in nature from biotic changes of living organisms to geochemical changes of the physical planet, these direct environmental changes are: altered species

and population distributions, lower ecosystem complexity, land cover change, carbon cycle alteration, water cycle alteration, nitrogen cycle alteration, and alteration of other geochemical cycles. We further establish the link between these first-order changes and their second-order consequences, including pollution, deforestation, rising sea levels, groundwater depletion, and soil erosion among others. These indirect consequences lead to human development challenges in terms of food security, health, human displacement, and conflict.

Second-order environmental consequences that pose major threats to food security include more frequent and severe droughts and floods, soil loss due to erosion, crop yield reductions due to warmer temperatures, irrigation constraints due to groundwater depletion (especially in South Asia), and long-term constraints on plant nutrient sources. Major threats to human health include water pollution that leads to diarrheal diseases, household air pollution due to indoor burning of solid fuels, altered disease vectors and extreme weather events due to climate change, and outdoor air pollution and environmental toxins. Threats of human displacement are expected for coastal populations affected by rising sea level, desertification leading to abandoned farmland due to untenably low agricultural yields, and agricultural yield limits due to irrigation constraints (especially in South Asia). Threats related to conflict involve questions of control of increasingly limited natural resources, including global markets for fossil fuels and mineral ores, as well as local needs such as water and grazing land.

Identifying solutions to human development challenges arising from environmental change is especially problematic, precisely because the changes have occurred due to human efforts towards development. Many non-technological hurdles exist that may constrain successful mitigation and/or adaptation to environmental change. These include a lack of effective regulatory and enforcement mechanisms, lack of adequate economic means to commit to solutions, and lack of economic incentives among key decision-makers and stakeholders.

Focusing on scientific and technological solutions, many of the breakthroughs identified in other chapters are equally relevant to issues of resilience to environmental change. For example, relevant breakthrough technologies include improved sanitation for human waste, precision irrigation systems, detection and sustainable utilization of groundwater resources, and soil nutrient analysis, as highlighted in our Global Health and Food Security and Agricultural Development sections. Beyond these, we identify 6 technological breakthroughs that could address some of the challenges of environmental change.

- A scalable, low cost method to desalinate water using renewable energy
- Low cost system for precision application of agricultural inputs, ideally combining fertilizers and water
- A scalable method for sustainable integrated aquaculture production
- Affordable homes that are resilient to extreme weather events, for the poor
- A retrofitted filter to reduce particulate matter exhaust from old heavy-duty vehicles
- Low cost, distributed monitoring sensors to identify environmental toxins and their concentrations

By now, there is ample evidence to demonstrate that climate change is already here. As the 2014 Intergovernmental Panel on Climate Change (IPCC) report points out, its effects are being felt; and they will continue to worsen, with vulnerable populations in low income countries bearing the brunt of phenomena like extreme weather events, higher temperatures, rising sea levels, and shifting rainfall patterns. As bad as the impact of climate change on these populations is, it is only a part of the larger problem. In much of the developing world, the combination of broad poverty, rapid economic growth in some populations segments, and the lack of political will and appropriate regulation, has led to significant damage to the environment: outdoor air is polluted because of automobile exhaust; indoor air is polluted due to poor ventilation and cooking methods; water systems are full of fecal pathogens; urban slums accumulate mountains of trash; and whatever factories there are, often feel unencumbered to pollute the air, water and land with toxins.

With the above context in mind, this section analyzes the needs of low income populations globally, through the following analytical lenses:

- We begin by examining which specific human actions lead to which specific direct or first-order environmental changes. We then try to connect these first-order environmental changes to detrimental indirect or second-order environmental consequences. This broad set of issues includes the various phenomena linked to climate change.

- We analyze the aggregate impact of first-order environmental changes and second-order consequences on low income human populations, within the 2050 time horizon. We fully recognize that there are a number of additional major threats that these populations will face beyond 2050, and that environmental change is taking a tremendous toll on other forms of life on the planet, but those aspects go beyond the scope of our study at present.

- Finally, we focus only on those actions that can be taken in developing countries. We recognize that in many cases (such as climate change), it is the actions of industrialized countries that are causing much of the damage. However, we believe that other studies (e.g., the IPCC report) are already addressing actions that must be taken by industrialized countries to mitigate such changes.

CORE FACTS AND ANALYSIS

To satisfy our human needs and desires, we modify our surrounding natural environment in many ways. We cause various direct, or what we term here as first-order, environmental changes—ranging in nature from biotic to geochemical—that enable provision of goods and services in the food, household and industrial sectors. While these first-order environmental changes bring huge benefits to humans, they also have indirect or second-order consequences that pose risks and challenges to human wellbeing in the longer term. Human-caused first-order environmental changes have increased rapidly during the past 100 years, and many second-order consequences are now becoming conspicuous. Some of these second-order effects may cause significant negative human development impacts related to food security, health, conflict, and human displacement.

1 We propose a new analytical framework to explain the links between environmental change and human development

There are numerous pathways through which environmental changes can seriously impact human development, but direct cause-and-effect has not yet been clearly articulated. We propose a new analytical framework (**Exhibit 1**), that links human actions to first-order environmental changes, to second-order environmental consequences, and ultimately to human development impacts. These linkages are mapped and further explained later in this section in **Exhibit 2**, **Exhibit 10** and **Exhibit 11**. Together, they seek to explain the complex chain of events linking environmental change and human welfare.

Linkage between human actions, environmental changes and human development

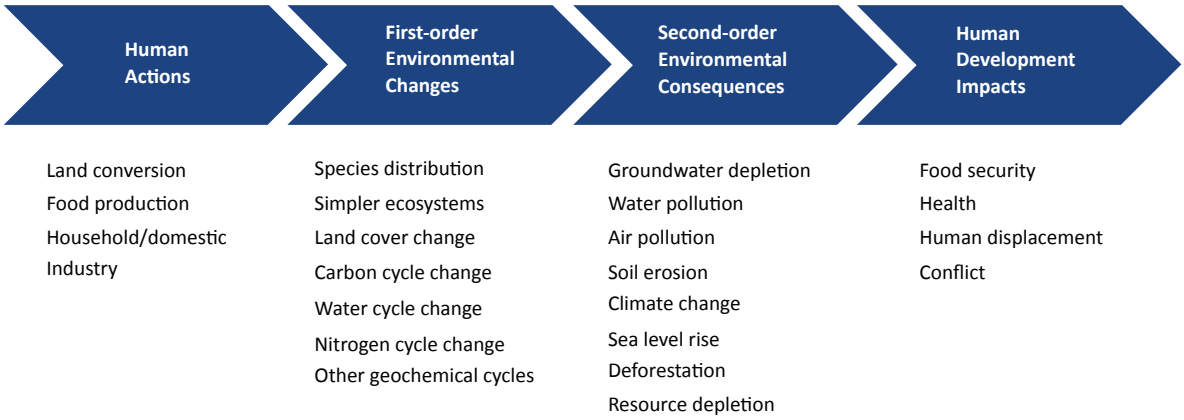


Exhibit 1: While human-caused environmental changes bring many intended benefits, these changes also lead to indirect consequences that pose long-term challenges. These linkages are mapped and detailed in Exhibits 2, 10 and 11.

As the focus of this report is global human development, this analysis is explicitly conducted from an anthropocentric perspective; we ask how environmental changes will affect human wellbeing. We acknowledge that an assessment of environmental change could be made from other perspectives, e.g. bio-centric or eco-centric, which may yield other conclusions based upon different priorities. Further acknowledging the long-term characteristics of environmental change and sustainability issues, our

main interests here are the implications for global development within the next human generation, i.e. until about 2050.

2 Seven first-order environmental changes caused by human actions

We humans carry out a range of actions in our quest for a better quality of life, stemming from our needs and choices regarding production and consumption in the food, household, and industrial sectors. To enable production of adequate *food* for the growing human population, we convert land that is 'wild' (i.e. not controlled by human influence), into managed cropland, pastures and orchards. We select certain animals to be domesticated, and care for these species while we actively exclude all other animal species. We favor a relatively small number of plant species such as wheat, rice and maize, and we cultivate these species across huge areas of cropland. All other plant species are considered 'weeds' and are eliminated by soil tillage or chemical poisons. We operate irrigation systems to provide water needed for the growth of our favored plants, and we apply chemical fertilizers to the land to provide for their nutrition.

To provide comfortable and healthy *household* conditions, we convert more wild land to create urban settlements. Within our houses we consume water, food and fuels, and we produce a range of waste products. Households with access to mechanized personal transport, such as automobiles and buses, consume additional fuels to gain mobility.

The food and household sectors are supported by an elaborate *industrial* system to process and use a wide variety of materials from the environment. This involves conversion of additional wild land for industrial purposes, such as mining and timber production. Raw materials are extracted, refined and processed to become consumer goods. Additional resources, such as water and energy, are also used in manufacturing processes. We generate electricity by various means, and distribute it for many uses. We create vast multi-modal cargo transportation networks, and shift natural resources globally to suit our needs. Our systems for managing wastes, however, are typically less elaborate, and for convenience waste materials are often discarded into our surroundings.

Exhibit 2 lists various examples of these human actions, and describes the first-order environmental changes caused by them. Adapting from Vitousek (1997), we identify 7 broad categories (listed below) that comprehensively describe the first-order environmental changes caused by human actions. There are significant interactions between these 7 categories.

- Humans now largely determine species and population distributions
- Humans are making ecosystems simpler and less diverse
- Humans significantly change the land cover when we use land
- Humans have significantly altered the natural carbon cycle
- Humans have significantly altered the natural water cycle
- Humans have significantly altered the natural nitrogen cycle
- Humans have significantly altered other geochemical cycles

First-order environmental changes caused by human actions

Legend:	Little effect	Moderate effect	Strong effect	Very strong effect

Human actions (examples)	First-order environmental changes: Biotic changes ←						→ Geochemical Changes
	Species Distribution	Lower ecosystem complexity	Land cover change	Carbon cycle alteration	Water cycle alteration	Nitrogen cycle alteration	Other geochemical cycles
Food production							
Land conversion (Wild land > agricultural land)	Conversion from wild to domesticated species	Relative simplicity of agro-ecosystems	Shift from natural to managed land	Biomass and soil carbon stocks	Change in infiltration and runoff		Increased soil erosion
Soil tillage	Tillage to favor crop species	Plant and soil community disturbance	Soil exposed to wind and rain	Altered soil carbon	Altered water runoff and quality		Increased soil erosion
Animal Husbandry (Intensive/extensive)	Several animal species are favored	Simple system of managed species	Land use for pasture	Biomass of animals and feed	Change in pasture land cover	Nitrogen in animal feed and manure	Nutrients for animals
Irrigation	Crop plant range is expanded		Expands range of agriculture		Watershed management for irrigation		Salinization of irrigated land
Fertilizer production and use				Increased biomass growth	Water quality from runoff, eutrophication	Nitrogen fixation via Haber-Bosch process	Mining and application of phosphorous
Pesticide/herbicide use	Target species are eliminated	Loss of target species	Plant cover by target species		Water quality from runoff		Creation of synthetic organic chemicals
Killing/consumption of wildlife	Target species are eliminated	Population reduction from overexploitation					
Household/domestic activities							
Land conversion (Wild land > urban land)	Conversion from wild to human habitat	Relative simplicity of urban ecology	Land cover by urban infrastructure	Biomass and soil carbon stocks	Change in permeability, transpiration		Mining of construction materials
Indoor solid fuel burning			Forest harvest for charcoal	Carbon stocks in fuel and forest			Contaminants in fuel
Mechanized public transport	Carriage of introduced species		Land cover by road infrastructure	Carbon in fossil fuels		NOx emission from vehicles	Lead added to gasoline
Household water consumption	Aquatic species affected by dams	Managed river ecosystems	Water supply infrastucture		Alteration of natural water flows		
Waste sewage disposal	Aquatic species biopathogens			Methane from decomposition	Water qualtity reduction from pollutants	Nitrogen content of sewage	Phosphorous content of sewage
Industrial activities							
Land conversion (Wild land > industrial land)	Conversion from wild to managed forest	Relative simplicity of managed forests	Land cover by managed forests	Biomass and soil carbon stocks	Changes in infiltration and runoff		
Extraction and processing of mineral raw materials			Land cover by mines and quaries	Carbon in fossil fuels, cement			Various elements, e.g. iron, copper
Mechanized cargo transport	Carriage of introduce species		Land cover by road infrastructure	Carbon in fossil fuels		NOx emission from vehicles	Lead added to gasoline
Material processing and fabrication				Carbon in fossil fuels, cement		NOx emission from vehicles	Industrial materials and byproducts
Electricity generation and distribution				Carbon in fossil fuels	hydroelectric and cooling water	NOx emission from power plants	Air emission of e.g. mercury
Industrial water consumption	Aquatic species affected by dams		Water supply infrastucture		Alteration of natural water flows		
Waste disposal	Aquatic species		Land cover by waste sites		Water quality reduction from pollutants	Nitrogen in fertilizer runoff	Toxic wastes, heavy metals POPs

Exhibit 2: Mapping of select human actions (food production, household activities, and industrial activities), to first-order environmental changes.

Humans now largely determine species and population distributions

While humans were once a minor species struggling for existence in a landscape largely full of wild animals and plants, we have now dominated most land ecosystems. By favoring and domesticating certain plant and animal species, humans have developed extensive agricultural ecosystems and caused substantial changes in the number and range of many other organisms. Three types of wild grasses, wheat, rice and maize, have been domesticated and reproduced to such an extent that they now comprise the 3 most abundantly cultivated plants on earth. Domesticated animals are fed and protected by humans, while other animals that threaten them are killed or expelled. Our analysis demonstrates the current dominance of humans and domesticated animals over land by comparing the total mass of different animal species, in terms of carbon content in their collective biomass in living bodies (**Exhibit 3**). Living humans are estimated to contain about 45 million metric tons (Mt) of carbon; domesticated animals maintained by humans have about 130 Mt of carbon (Smil, 2003) (UN, 2013) (FAOSTAT, 2014) (Dirzo, et al., 2014). These quantities have more than doubled since 1950. In contrast, the biomass of all wild land vertebrates including mammals, birds and reptiles contains less than 5 Mt of carbon, and is steadily decreasing. Humans now largely control which animals live in most land areas of the world. However, human dominance does not extend to the smaller creatures, including the nearly 700 Mt of carbon in invertebrates (e.g. insects), approximately 4000 Mt in fungi, and about 20,000 Mt in soil bacteria (Smil, 2003).

Biomass of human and animal species since 1950

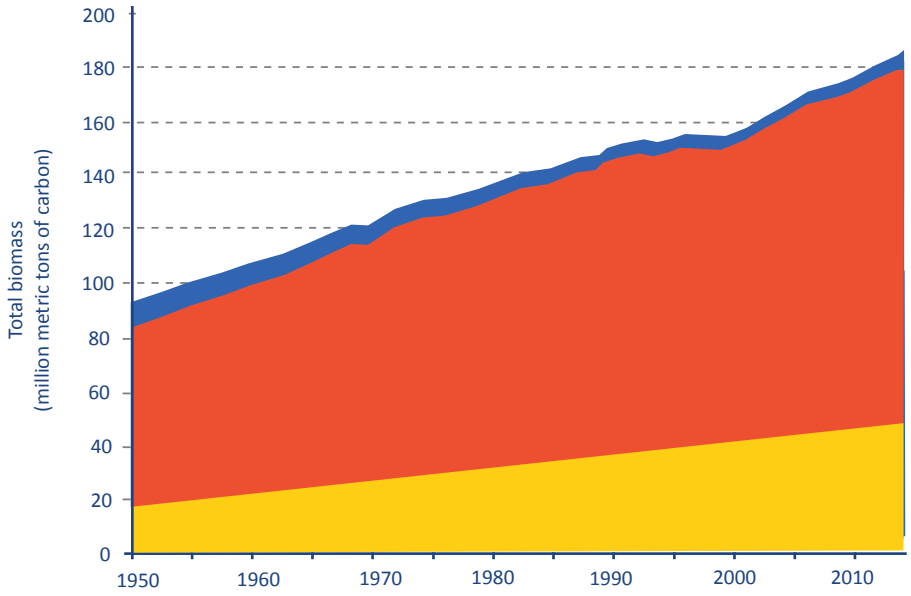


Exhibit 3: Humans and domesticated animals dominate over all other land animals. This figure shows the estimated amount of carbon contained in the living bodies of all humans, domesticated animals, and wild land vertebrates (mammals, birds, reptiles, etc.).

Humans are making ecosystems simpler and less diverse

The population shift from wild to domesticated animals and plants necessarily involves the simplification of the structure and functioning of ecosystems. Humans are causing ecosystems to lose complexity at several levels: species diversity (the number and variety of species), genetic diversity (the genetic possibilities a species contains), and ecosystem diversity (the variation between global ecosystem characteristics) (MEA, 2005). The distribution of species on earth is becoming more homogenous, meaning that the differences are, on average, diminishing between the group of species at one location on the planet and groups at other locations. Different types of species evolved in ecosystems in different regions, through the combination of natural barriers to migration and local adaptations. These regional differences in the biota of the earth are now diminishing. Genetic diversity, which serves as a way for populations to adapt to changing environments, is being lost.

Species tend to come and go, evolutionarily speaking, but human actions are now causing species extinction at a rate 1000 times greater than the natural background rate of extinction (Pimm, et al., 2014). This ongoing simplification is illustrated in Exhibit 4, based on the Living Planet Index that is calculated periodically by WWF International (WWF, 2014). This index estimates changes in the state of the planet's biodiversity, using trends in population size for vertebrate species from different biomes and regions to estimate average changes in abundance over time (Collen, et al., 2008). Trends in the Living Planet Index suggest that across the globe, wild populations of vertebrate animals were on average 52% smaller in 2010 than they were in 1970. The greatest reductions occurred in tropical regions, in particular the Neotropical biogeographical area that includes South and Central America, and the Indo-Pacific area that includes South Asia and Australasia. Temperate regions show smaller reductions, largely because those lands were cleared for agricultural use long before 1970, and now include abandoned farmlands that are reverting to natural growth. Acknowledging the imprecision of such simple proxy indicators, the global trends toward lower biodiversity and simpler ecosystems are robust.

Change in animal biodiversity since 1970

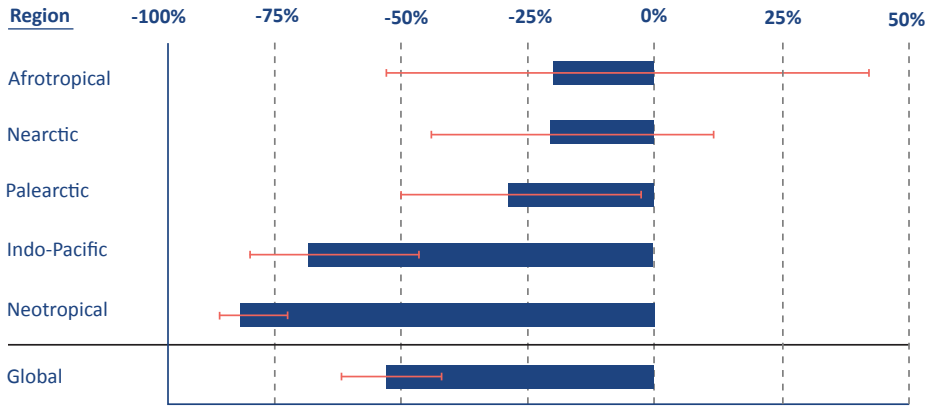


Exhibit 4: Regional and global biodiversity has generally decreased in recent decades, as estimated by WWF's Living Planet Index, based on wild populations of vertebrate animals between 1970 and 2010. Error bars represent 95% confidence limits. The 5 regions are biogeographic realms, where terrestrial species have evolved in relative isolation over long periods of time. Afrotropical includes sub-Saharan Africa. Nearctic includes North America. Palearctic includes Europe, North Africa, the Middle East, and most of Asia. Indo-Pacific includes South Asia and Australasia. Neotropical includes South and Central America (WWF, 2014).

Humans significantly change the land cover when we use land

Human use of land typically alters the interface between the atmosphere and the geosphere, affecting interactions between land, plants, air and water. For example, land cover largely determines the partitioning of precipitation into evapotranspiration, runoff, and groundwater flow. Humans have, over a span of centuries, converted land once covered by wild forests and grassland into cropland and pastures. **Exhibit 5** shows that about 10 million km^2 of forest land has been lost during the last three centuries (Ramankutty & Foley, 1999) (Pongratz, et al., 2008) (FAO, 2010) (World Bank, 2013). Cropland area (the extent of which may vary, depending on the definition used), increased by about 15 million km^2 during the same period. The rates of forest land decrease and cropland increase have remained fairly steady over the last 300 years, though have accelerated somewhat since about 1850. The current rate of deforestation is in line with this centuries-old trend, and direct human occupation of land continues to expand.

Global forest and cropland area since 1700

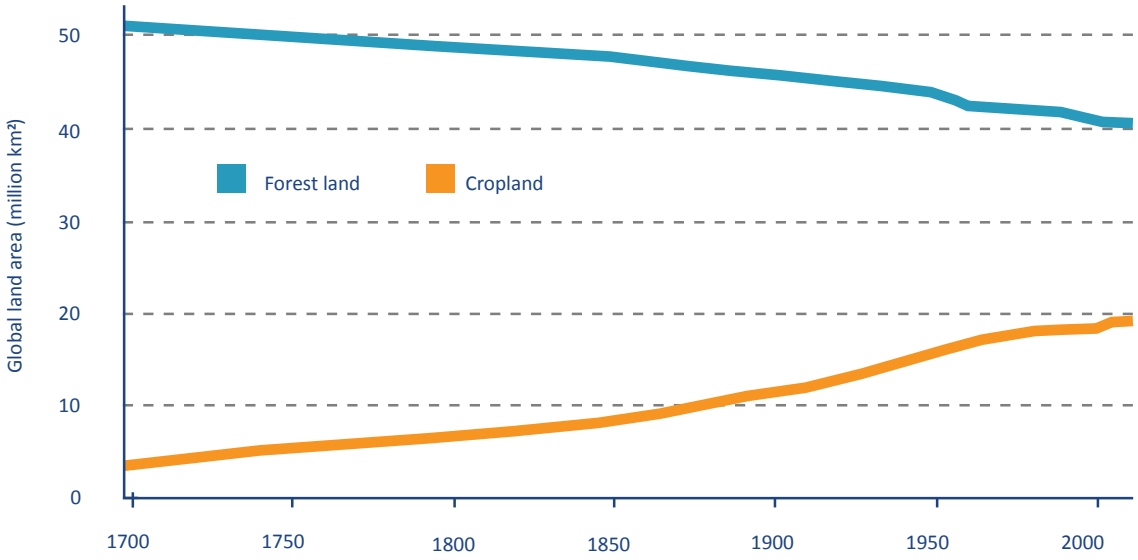


Exhibit 5: Over the last 3 centuries, humans have converted about 10 million km^2 of forest land to other uses, and have turned about 15 million km^2 of land into agricultural cropland. During the same period, natural grassland area has decreased, and pasture land area has increased (not shown in figure).

Humans have significantly altered the natural carbon cycle

Carbon is a chemical element, and natural forces cause it to cycle in various forms and rates. Carbon cycles on the earth between the atmosphere as carbon dioxide gas, in the biosphere as organic carbon compounds, in the oceans as dissolved carbon dioxide, and in the lithosphere as carbonate and hydrocarbon minerals. Humans have significantly changed natural carbon cycling by altering living biomass due to land use change, and by shifting carbon from geologic storage in the form of fossil fuels, into the atmosphere in the form of carbon dioxide. Humans have long influenced land cover, even before the introduction of agriculture. For example, fire has long been a relatively easy and effective way for

small-scale societies to reshape the vegetation communities in their regions, to increase the relative abundance of preferred plant and animal food resources (Smith, 2011). During the last century, however, the use of fossil fuels in the form of coal, oil, and gas has become the primary source of human-caused carbon emissions (**Exhibit 6**) (Le Quéré, et al., 2014) (Houghton, et al. 2012) (Boden, et al., 2013). Humans seek to extract and use the chemical energy stored in fossil hydrocarbon fuels. In doing so, carbon in the fuel changes into a more stable form, carbon dioxide. Currently, about 9 billion metric tons of carbon—over 200 times more than the amount of carbon in all living humans (**Exhibit 3**)—is emitted each year from fossil fuel use (IPCC, 2013). Another 0.5 billion ton of carbon is emitted each year during cement production, when a raw material (calcium carbonate) is heated in manufacturing kilns, creating carbon dioxide as a waste product. About 1 billion ton of carbon is currently emitted per year, due to land use. There are vast differences in the country-level emissions that comprise these global totals: lower income countries have relatively low emission levels that are dominated by land use, while higher income countries have much higher emission levels that are primarily due to fossil fuel use (IPCC WG3, 2014).

Carbon dioxide emissions caused by humans since 1850

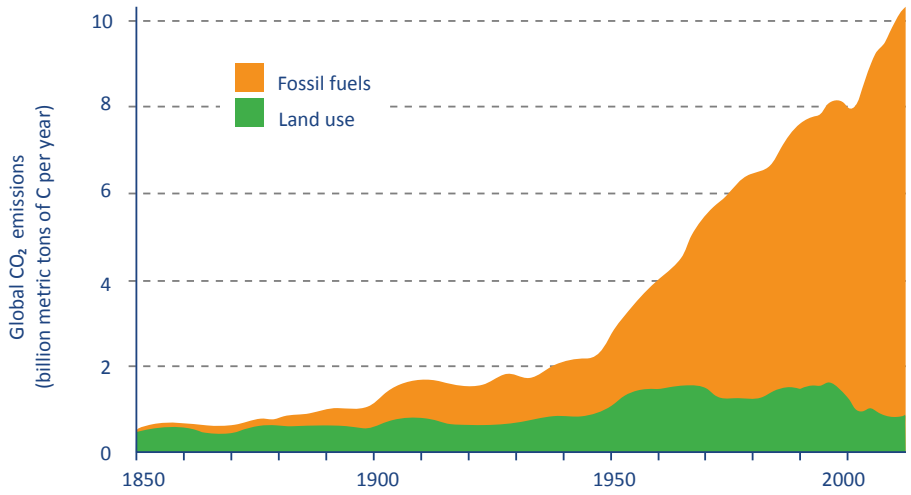


Exhibit 6: Land use change (such as deforestation) had long been the dominant human-caused source of carbon dioxide (CO_2) emissions. During the last 100 years, emissions from the combustion of fossil fuels (coal, oil, natural gas) have increased considerably and are now the largest source of emissions. Process emissions from cement manufacture are shown here as fossil fuel emissions, and comprise about 5% of those emissions.

Between 1750 and 2011, the combustion of fossil fuels and the production of cement have released a cumulative total of about 375 billion metric tons of carbon—over 8,000 times more than the amount of carbon in all living humans. Land use change since 1750, mainly deforestation, has released an additional 180 billion metric tons of carbon. Clearly, humans have a disproportionately large effect on the global carbon cycle. These large and sustained emissions of carbon dioxide have steadily increased the concentration of that gas in the atmosphere. For at least 2 million years prior to the industrial era (i.e. before 1750), the concentration of carbon dioxide in the atmosphere had fluctuated between

roughly 180 parts per million (ppm) and 290 ppm (IPCC, 2013). It has since increased from about 280 ppm in the year 1750 to 400 ppm in the year 2014.

Humans have significantly altered the natural water cycle

Water cycles naturally, from when it falls as rain or snow, flows downhill in soils and rivers, may be drawn up into living plants, and eventually returns to the atmosphere as water vapor, from which it falls again. Human actions have changed this cycle in several ways, some intended and others unintended (Meybeck, 2003). Management of the water cycle has improved human wellbeing by controlling floods, generating hydroelectricity, providing transportation, and irrigation. Humans have changed the patterns of surface water flow, e.g. by impounding river water behind dams, and by reducing rainwater infiltration through paved surfaces. **Exhibit 7** shows that artificial reservoirs now have the capacity to hold about as much water as contained in Lake Michigan, one of the great lakes of North America (Vörösmarty & Sahagian, 2000) (van der Leeden, et al., 1990). In densely populated areas of the world, actions such as river engineering, water withdrawals, and waste dumping have significantly changed the water and material transfers through river systems, such that these actions now likely exceed the influence of natural drivers (MEA, 2005). Surface runoff and river discharge generally increase when natural vegetation (especially forest) is cleared. Such actions to manage and control water flows have involved environmental trade-offs, including fragmentation and loss of habitat for other organisms, biodiversity loss, and changes in sediment transport.

Global water storage capacity in artificial reservoirs since 1900

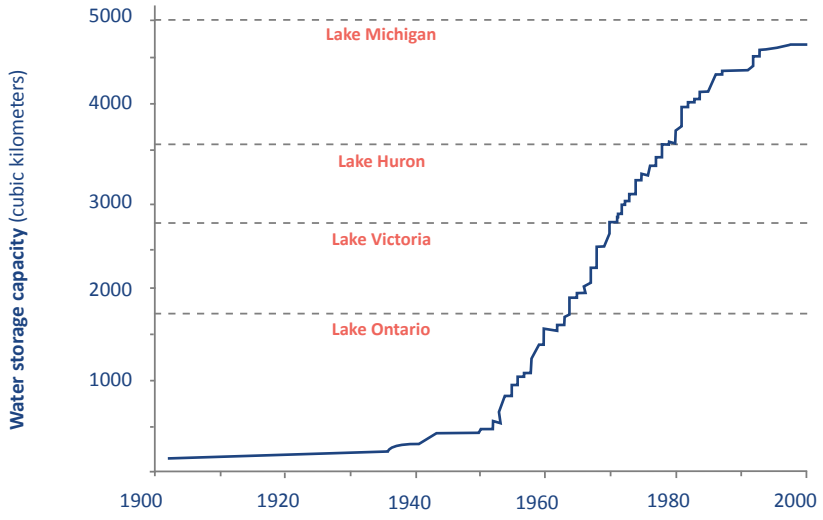


Exhibit 7: Human alterations to the water cycle, including intercepting and storing water flows, have increased substantially during the last century. Construction of dams and reservoirs increased significantly after 1950. By 1960 the total water storage capacity within artificial reservoirs globally was equivalent to that of Lake Ontario; by 1980 it was equal to Lake Huron. Currently, human-created reservoirs have the capacity to hold about as much water as there is in Lake Michigan.

In addition to changing the amount and timing of water flows, humans have also changed the quality of water by using water bodies like rivers, lakes and oceans as a dumping ground for biological wastes (e.g. sewage) and inorganic pollutants. Pollution is typically an unintended consequence of other

activities; people do not intend to cause pollution, but disposing of waste products into a nearby water body is often the most convenient, and inexpensive, form of disposal. Although 'the solution to pollution is dilution' approach was relatively effective when the amount of waste was small relative to the capacity of the environment to assimilate it, this approach is far less effective at larger scales.

Humans have significantly altered the natural nitrogen cycle

Nitrogen comprises about 78% of earth's atmosphere. However, it typically exists in the very stable N_2 form, with two nitrogen atoms bound tightly together, unwilling to form partnerships. Nitrogen is essential to life on earth, as it is needed to make amino acids, nucleotides and other basic building blocks of plants, animals and other life forms. A limited amount of nitrogen, known as reactive nitrogen, is 'fixed' from the atmosphere and then made available to living organisms in a more reactive form. There are several natural routes of nitrogen fixation, including by particular bacteria living in symbiosis with some types of plants. Humans have long managed croplands to incorporate these types of plants within crops rotation systems, to fix a modest amount of nitrogen within agroecosystems. During the last 50 years, the amount of nitrogen that is fixed through human actions has increased steadily, and now occurs at a scale similar to that of all natural land ecosystems (Robertson & Vitousek, 2009) (**Exhibit 8**). Most of this increase is due to fertilizer production using the Haber-Bosch process (described in the chapter on fertilizers and soil health, in the section on Food Security and Agricultural Development). The temporary reduction in nitrogen fertilizer production during the early 1990s was due to the collapse of the Soviet Union. Other human actions that fix atmospheric nitrogen include fuel combustion and managed biological fixation. This alteration of the nitrogen cycle has allowed us to grow significantly more food for consumption than otherwise would be possible. However, the increased overall availability of nitrogen fertilizer, coupled with the difficulty of precisely targeting application to ensure maximum absorption by plants, has led to nitrogen runoff well beyond the farmlands the fertilizer is applied to.

Reactive nitrogen fixed by human actions

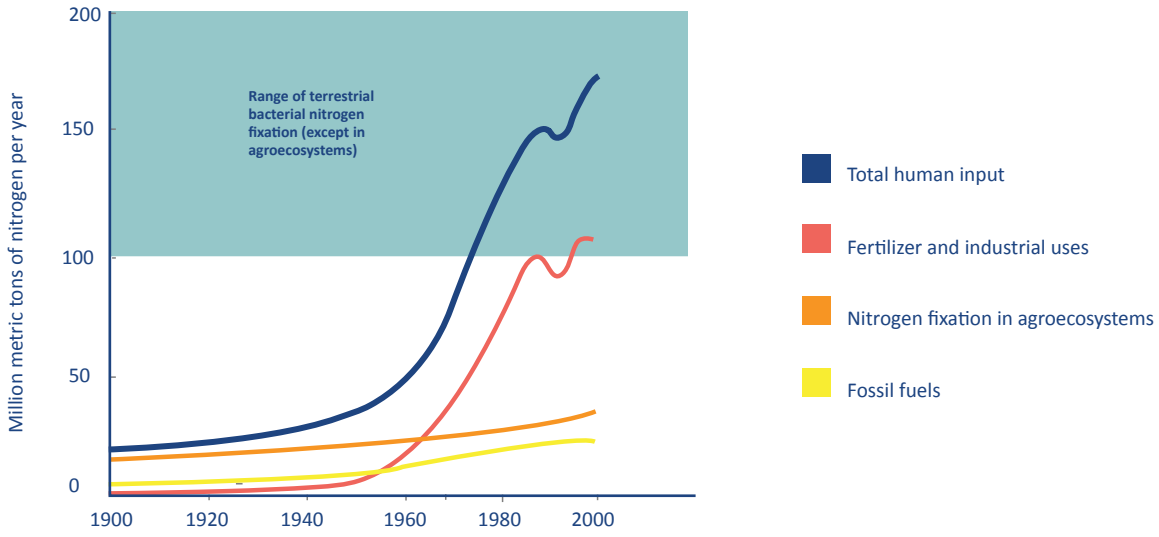


Exhibit 8: Human production of reactive nitrogen has increased substantially during the last 50 years, and now occurs at the same rate as it does in all natural land ecosystems put together. Most of this increase is due to fertilizer production using the Haber-Bosch process, using natural gas as feedstock (MEA, 2005).

Humans have significantly altered other geochemical cycles

In terms of shaping the surface of the earth, humans now cause about 10 times more erosion and sedimentation than that caused by glaciers, rivers, and other natural processes combined (Wilkinson, 2005). From intentional transport of construction materials and mineral ores, to unintentional facilitation of natural erosion processes through soil tillage, humans have become the dominant geologic force on the planet. In addition to soil erosion and alterations to the carbon, nitrogen and water cycles, humans are affecting changes to other global geochemical cycles at various scales of time and place. An important example is the chemical element phosphorous, which is an essential nutrient for plant growth. Phosphorus fertilizers are important because of the slow natural cycling of phosphorus, the low solubility of natural phosphorus-containing compounds, and the essential nature of phosphorus to living organisms. Traditional sources of agricultural phosphorous are animal manure and guano (bird droppings). **Exhibit 9** shows that phosphate rock mining expanded considerably after 1950, and is now the dominant source of phosphorous fertilizer, an essential input to intensive agriculture (Cordell, et al., 2009). The countries currently mining the most phosphate rock include China, US and Morocco (USGS, 2014). Global reserves of phosphate are concentrated in the Western Sahara region of Africa, a disputed region controlled by Morocco. Sustained disruption of supply, whether due to geological or geopolitical forces, would significantly affect food security (Dawson & Hilton, 2011).

Sources of phosphorous fertilizer since 1800

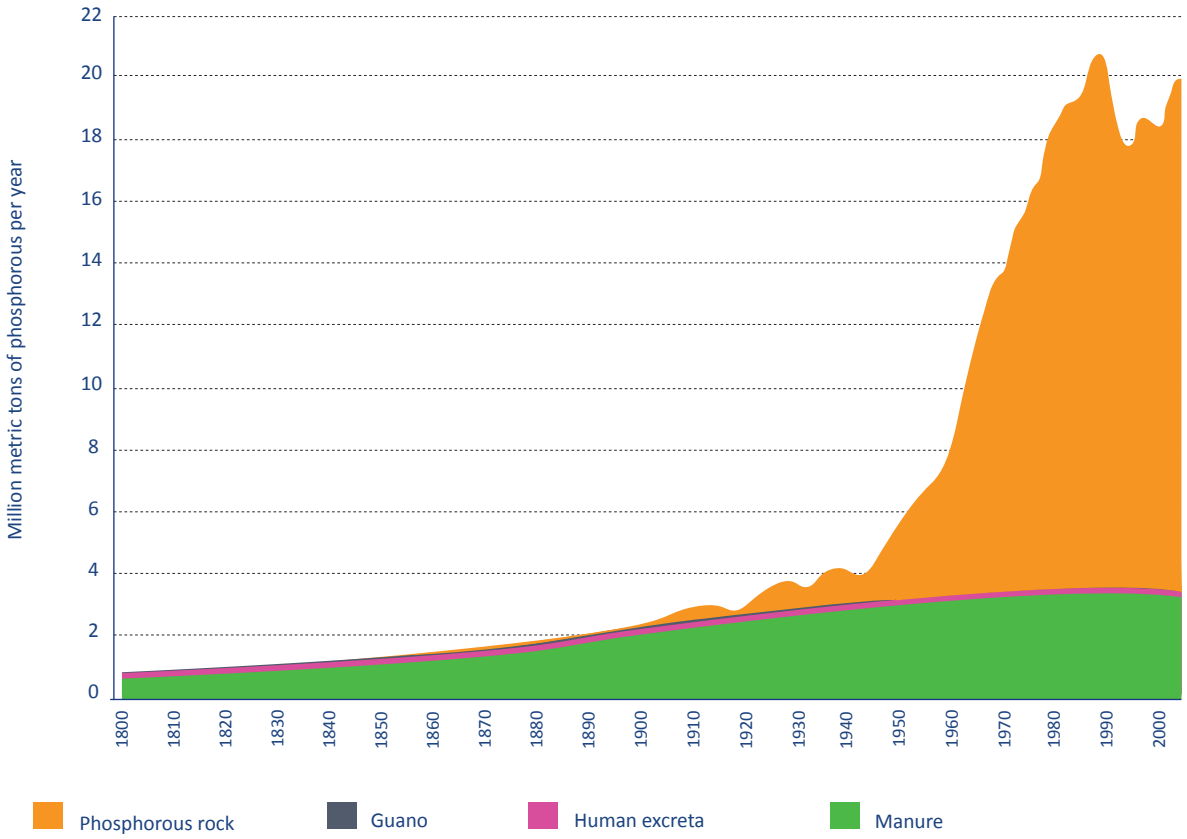
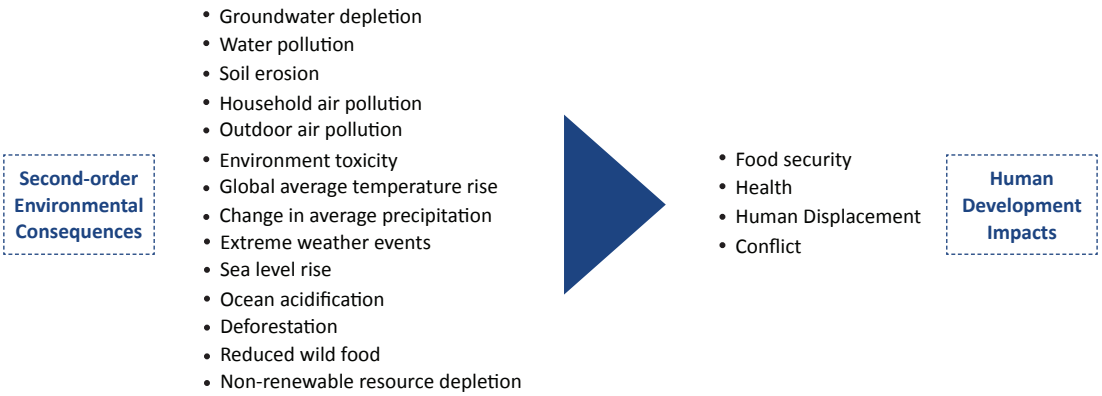


Exhibit 9: Mining of phosphate rock expanded considerably after 1950, and is now the dominant source of phosphorous fertilizer used in agriculture (Cordell, et al., 2009).

3 First-order environmental changes cause a variety of second-order environmental consequences

The first-order environmental changes described so far have mainly brought positive benefits for human populations, including provision of basic needs like food and shelter. Indeed, these changes were made primarily to improve the quality of our lives. However, as the scale of human enterprise increases relative to the scale of natural (i.e. not managed by people) processes, a number of indirect or second-order consequences can be identified. Activities that were previously overwhelmingly beneficial now bring both positive and negative effects on human welfare.

Exhibit 10 shows how first-order environmental changes lead to second-order environmental consequences for human populations. These are unintended consequences that result from the first-order changes brought about by human activities as described in **Exhibit 2**. As illustrated in **Exhibit 1** earlier, and now in a sectional view reproduced below, second-order environmental consequences have significant human development impacts.



Some of these second-order environmental consequences manifest locally, close to the human actions that provoked them, and others are seen globally. For example, household air pollution occurs immediately within a building where solid fuels are burned for cooking. Climate change, on the other end of the spectrum, is a global phenomenon regardless of where greenhouse gases are emitted.

Second-order environmental consequences of first-order environmental changes

Little effect	Moderate effect	Strong effect	Very strong effect	Legend

First-order environmental changes							Second-order environmental consequences (examples)
Biotic changes ←					→ Geochemical changes		
Species distribution	Lower ecosystem complexity	Land cover change	Carbon cycle alteration	Water cycle alteration	Nitrogen cycle alteration	Other geochemical cycles	
		Reduced infiltration of precipitation		Over-extraction of groundwater resources			Groundwater depletion
		Sediment flow due to soil erosion	Organic matter in sewage	Waste dumping into water bodies	Sewage and fertilizer runoff	Other pollutants	Water pollution
Loss of soil cover plants	Simpler plant communities	Soil exposed to wind and rain		Altered water flows and landform			Soil erosion
			Combustion of solid fuels			Contaminants in fuels	Household air pollution
		Burning of land cover	Combustion of fossil fuels		NOx from vehicles and industry	Contaminants in fuels	Outdoor air pollution
			Creation of synthetic organic chemicals			Industrial use of heavy metals,POPs, etc.	Environmental toxicity
Emission of CH_4 from livestock		Net emission of CO_2	Emission of CO_2 and CH_4		Emission of N_2O	Emission of other GHGs	Global avg. temperature rise
Emission of CH_4 from livestock		Net emission of CO_2	Emission of CO_2 and CH_4		Emission of N_2O	Emission of other GHGs	Change avg. precipitation
Emission of CH_4 from livestock		Net emission of CO_2	Emission of CO_2 and CH_4		Emission of N_2O	Emission of other GHGs	Extreme weather events
Emission of CH_4 from livestock		Net emission of CO_2	Emission of CO_2 and CH_4		Emission of N_2O	Emission of other GHGs	Sea level rise
		Net emission of CO_2	Emission of CO_2				Ocean acidification
Growth of crops instead of trees	Simpler managed ecosystems	Growth of crops instead of trees					Deforestation
Over-exploitation of desired species	Lower trophic level of marine ecosystems	Destruction of natural habitats		Water pollution and flow levels	Water body eutrophication		Reduced wild food
			Extraction and burning of fossil fuels	Exploitation of fossil water aquifers	Inputs to Haber-Bosch process	Exploitation of phosphorus and other minerals	Non-renewable resource depletion

Exhibit 10: Mapping of first-order environmental changes to second-order environmental consequences. (GHGs are greenhouse gases, CO_2 is carbon dioxide, CH_4 is methane, and POPs are persistent organic pollutants)

4 Second-order environmental consequences lead to significant impacts for low income human populations

Exhibit 11 indicates how second-order environmental consequences lead to challenges for human development, including issues of food security, health, human displacement, and conflict. Major threats to food security include more frequent and severe droughts and floods, soil loss due to erosion, crop yield reductions due to warmer temperatures and/or untimely precipitation, irrigation constraints due to groundwater depletion (especially in South Asia), and long-term limitations on nutrient supplies. Major threats to human health include diarrheal diseases due to water pollution, chronic respiratory and lung diseases caused by household air pollution due to indoor burning of solid fuels, altered disease vectors and extreme weather events due to climate change, and outdoor air pollution and environmental

toxins. Threats of human displacement are expected for coastal populations affected by sea level rise, abandoned farmland due to untenably low agricultural yields caused by desertification, and agricultural yield limits due to irrigation constraints because of groundwater depletion (especially in South Asia), among others. Threats related to conflict include questions of control of increasingly limited natural resources, including global markets for fossil fuels and metal ores for instance, as well as local needs for water and grazing land.

The impact of second-order environment consequences on human development by 2050

Legend	Little impact	Moderate impact	Strong impact	Very strong impact
Second-order environmental consequences (examples)	**Impacts on human development by 2050**			
	Food Security	Health	Human displacement	Conflict
Groundwater depletion	Limited supply of irrigation water (SA)		Constraints on irrigated farming (SA)	Conflict over water supply
Water pollution		Diarrheal diseases and other health issues		
Soil erosion	Loss of fertile soil and crop yields		Desertification, abandoned farmland	Conflict for farm/pasture land
Household air pollution		Burning of solid fuels indoors		
Outdoor air pollution		Exhaust emissions from vehicles and industry		
Environmental toxicity	Contamination of food products	Chronic and acute effects of toxins		
Global avg. temperature rise	Reduced crop yields, expanded pest ranges	Expansion of disease vectors		
Change avg. precipitation	Long-term reduction in water supply (SSA)		Constraints on rain-fed farming (SSA)	
Extreme weather events	Food production impacts by droughts and floods	Health impacts from storms and floods		Conflict over local food supplies
Sea level rise	Land inundation and groundwater salinization		Displacement of coastal populations	Conflict due to displacement
Ocean acidification	Change in supply of ocean foods			
Deforestation			Displacement of forest populations	
Reduced wild food	Reduction in wild fish stock			
Non-renewable resource depletion	Energy for Haber-Bosch process, phosphorous			Conflict over increasingly scarce resources

Exhibit 11: Mapping of second-order environmental consequences to likely impacts on human development by 2050 (SA is South Asia and SSA is sub-Saharan Africa).

Groundwater depletion will constrain irrigated agricultural production, especially in South Asia

As described in detail in the section on Food Security and Agricultural Development, irrigation plays a key role in global food security. While only an estimated 18% of global cropland is irrigated, that land accounts for 40% of global food production (Schultz, 2001). There are two types of groundwater sources used for irrigation. The first are renewable groundwater sources, in which the groundwater is periodically replenished when sufficient precipitation infiltrates the soils or when floodplains become inundated. The second type are non-renewable or fossil groundwater sources, which are typically locked in deep aquifers that have little or no long-term source of replenishment. When this water is extracted, it is effectively

'mined' and the aquifer will eventually be depleted. Globally, about 18% of gross irrigation water demand for the year 2000 was met with non-renewable groundwater extraction (Wada, et al., 2012). **Exhibit 12** shows the sources of water used globally for irrigation in 1960 and 2000, during which time the share of non-renewable groundwater increased from 12% to 18%. In absolute terms, the use of non-renewable groundwater more than tripled, from 75 to 230 cubic kilometers per year.

Sources of water used globally for irrigation, 1960 to 2000

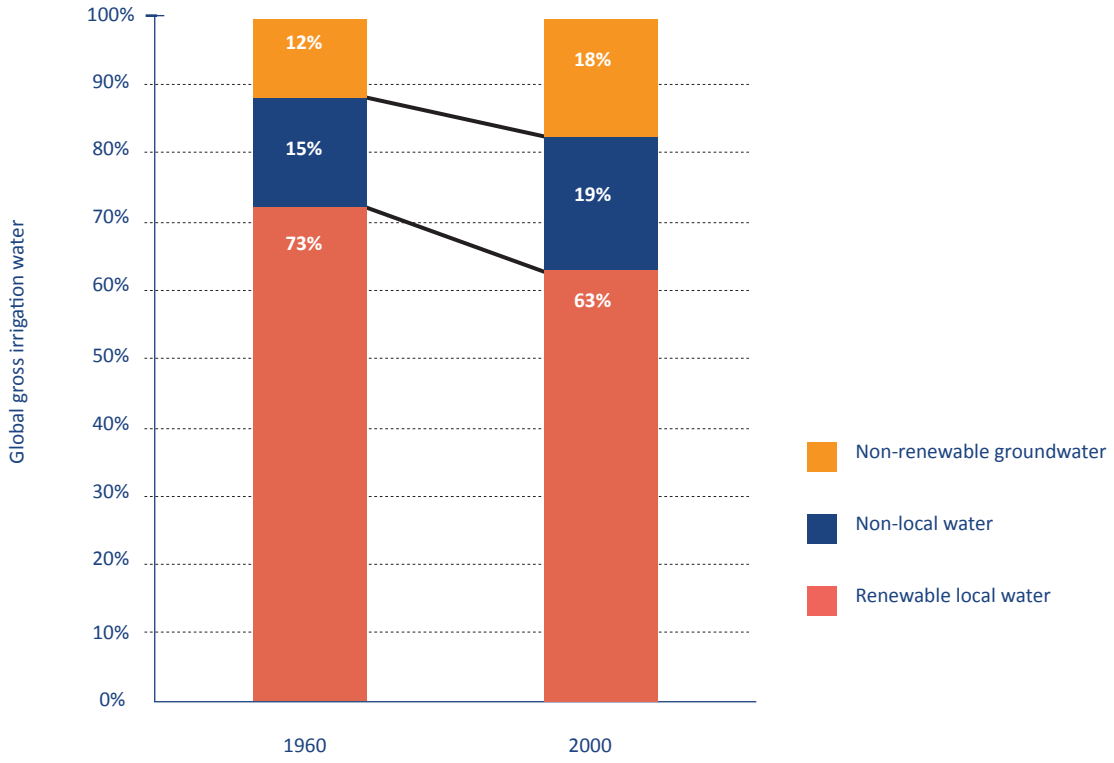


Exhibit 12: Between 1960 and 2000, the share of non-renewable groundwater increased from 12% to 18% of global gross irrigation water. The share of non-local water resources, transported to the regions via canals and pipelines for example, increased from 15% to 19% of global gross irrigation water. Renewable 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 1340 cubic kilometers per year), and non-renewable groundwater use increased three-fold (from 75 to 230 cubic kilometers per year), between 1960 and 2000. Relatively few countries (described in Exhibit 13) are responsible for most of the non-renewable groundwater use (Wada, et al., 2012).

Relatively few countries, including India, Pakistan and USA, are responsible for most of the non-renewable groundwater use (Gleason, et al., 2012). **Exhibit 13** shows that India used more non-renewable groundwater for irrigation than any other country, in year 2000. About 19% of India's irrigation water came from non-renewable sources. Other countries used smaller amounts of non-renewable water, but it comprised larger proportion of their total irrigation water use. In both Pakistan and USA, the share of non-renewable groundwater was 24%; in Iran it was 40%. In Libya and Saudi Arabia, over 70% of irrigation water was sourced from non-renewable groundwater (Wada, et al., 2012).

Sources of irrigation water used by select countries, in 2000

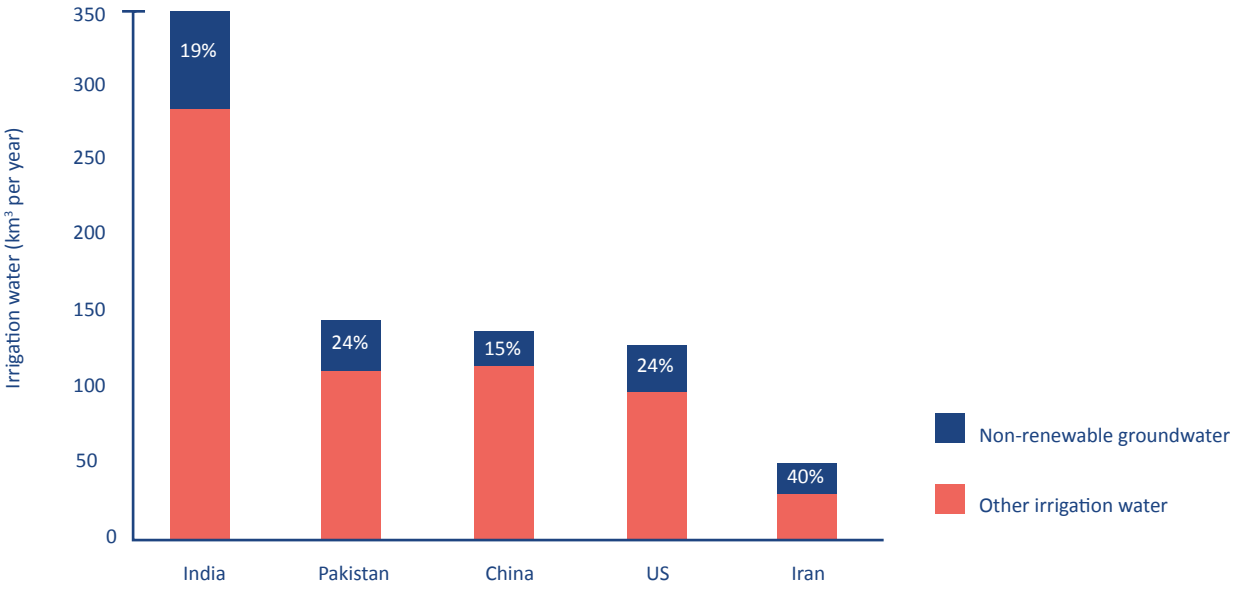


Exhibit 13: Non-renewable groundwater is a significant part of gross irrigation water use in several major countries. India uses more non-renewable groundwater for irrigation than any other country (68 km^3 per year, in year 2000). Iran uses less in absolute terms (20 km^3 per year) but more as a percent of total irrigation water: 40% of Iran's irrigation water is sourced from non-renewable groundwater. 'Other irrigation water' includes non-local water and renewable local water (Wada, et al., 2012).

Groundwater depletion affects global development primarily due to its impact on food security. It limits the amount of water available for agriculture and other human uses, and makes the available water more difficult to obtain. As groundwater supply becomes more limited, wells may go dry intermittently or constantly. Wells may need to be extended deeper to reach water, and more energy is needed to pump water from greater depths. Water quality of depleting freshwater aquifers may deteriorate due to intrusion of brackish water from surrounding aquifers. Land surfaces may subside, or gradually lower in elevation, as aquifers below become depleted. As a development challenge, South Asia is particularly affected, where strategies for future food security must account for constrained groundwater extraction. Sub-Saharan Africa appears to have relatively abundant renewable groundwater resources (MacDonald, et al., 2012). Unsustainability of groundwater use for irrigation is a concern not only for countries that are using groundwater intensively, but also the world at large since international trade directly links food production in one country to consumption in another.

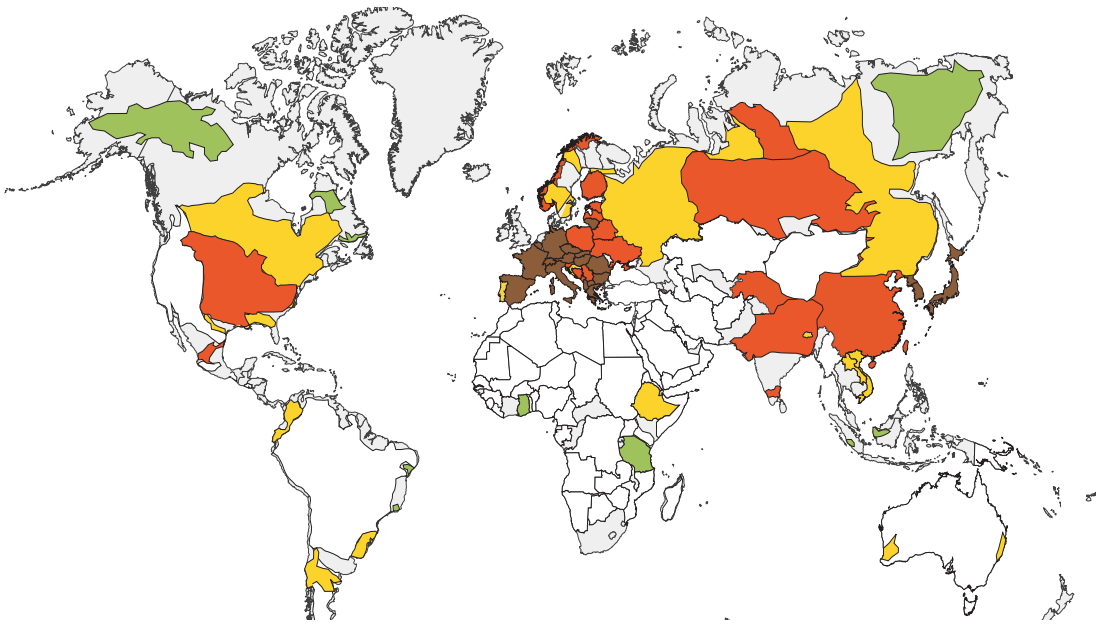
Water contamination by organic and inorganic pollutants adversely affects health

Two important types of pollutants that degrade water quality are biological pollutants like human sewage, and inorganic pollutants like fertilizer runoff. Biological water pollution by human sewage is considered in detail in the chapter on diarrheal diseases in the section on Global Health. Another important type of water pollution includes runoff of nitrogen and phosphorus fertilizer from agricultural land. Just as fertilizing agricultural fields can stimulate crop growth, increasing nutrient levels in rivers, lakes and estuaries can cause eutrophication or excessive growth of algae and other aquatic plants. Huge blooms of cyanobacteria (also known as blue-green algae), and other organisms can come to

dominate aquatic ecosystems, seriously degrading water quality (Smith, 2003). Negative effects include hypoxia, or depletion of oxygen in the water, which causes the death of fish and other animals in the water. Over 400 marine 'dead zones' resulting from nutrient runoff are reported worldwide, having approximately doubled each decade since the 1960s (Diaz & Rosenberg, 2008). Many cyanobacteria also produce toxic compounds that are hazardous to humans and domesticated animals. Mass blooms of toxic cyanobacteria occur regularly in water subject to nutrient runoff, with the timing and duration of the bloom season varying by location. For example, the water supply for the city of Toledo, Ohio, USA was interrupted for several days in August 2014 due to an algae bloom caused largely by phosphorous fertilizer runoff.

In recent decades, the amount of reactive nitrogen in rivers has increased dramatically (Green, et al., 2004) (MEA, 2005), with river basins in North America, continental Europe, and South and East Asia showing the greatest change (**Exhibit 14**). Africa suffers little from nutrient pollution, mainly because fertilizer use in Africa is still very low.

Increase in nitrogen runoff leading to aquatic dead zones



Percent increase in nitrogen transport to river mouth

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

Exhibit 14: Reactive nitrogen flows in many river systems have increased dramatically in recent decades—primarily due to fertilizer runoff from agricultural lands—especially evident in Europe, Asia and North America. This has led to 'dead zones' in waterways.

Other sources of inorganic water pollution include silt and sediment from soil erosion, waste discharge from small or large scale industrial activities, heavy metals such as mercury or lead, and synthetic and persistent engineered chemicals like plastics and agricultural pesticides (Meybeck, 2003).

Loss of fertile agricultural soil due to erosion causes significant impacts on farm yields and food security

Soil erosion is the removal of soil from the land surface, typically carried away by rain or wind. Some level of soil erosion is natural, and over geologic time spans it has shaped the river valleys and deltas of our landscape. Soil erosion under native vegetation occurs at roughly the same rate at which new soil is produced through natural geomorphologic processes (**Exhibit 15**). However, agricultural practices such as tillage and heavy grazing remove vegetative cover and expose the soil surface to rain and wind. Soil erosion from agricultural fields occurs at rates 10 to 100 times greater than erosion from natural land surfaces (Pimentel, 2006) (Montgomery, 2007). Soil erosion is widespread: about 80% of global agricultural land suffers moderate to severe erosion (Pimentel & Burgess, 2013). Erosion is much greater on sloping land, where soil particles are carried away downhill by flowing water. Wind can also carry soil particles for long distances.

Soil erosion affects global development by reducing food security. Loss of fertile, nutrient-rich cropland soil reduces the productive capacity of the land and causes lower harvest yields. This is a major problem for poor rural populations living on marginal land with low soil quality and steep topography. As productivity of agricultural fields is reduced, farmers are compelled to apply fertilizers to maintain yields (Lal, 2009). Eventually, when enough productive soil is lost, the land is not worth using, and is abandoned. It is reported that about 3 million hectares of cropland worldwide are abandoned annually because of productivity declines due to severe land degradation (FAO, 2012).

A related issue is desertification, which is the gradual degradation of drylands to become unfertile. While traditionally ascribed to overgrazing, it is now known that many factors affect desertification, including soil erosion, climate change, soil nutrient management and water cycle changes (D'Odorico, et al., 2013). Underlying driving forces include demographic, economic, technological, institutional, socio-cultural, and meteorological factors. Land degradation and desertification is caused by interactions between natural processes such as weather variability including droughts and floods, and human actions of unsustainable land use practices on fragile resources. External forces are also key drivers, including inadequate governance mechanisms, ineffective land tenure, and global economic forces. Locally, this leads to decreased land productivity, overexploitation, and a worsening spiral of land degradation, poverty, and food insecurity.

Loss of fertile soil due to erosion from cropland

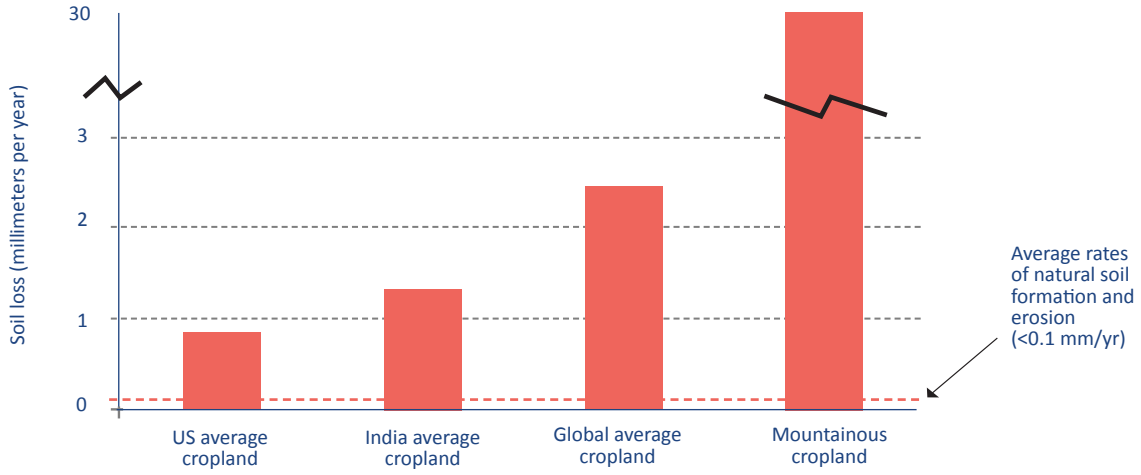


Exhibit 15: On average, about 1 to 3 millimeters of soil are lost each year from typical farmland. Soil erosion rates in mountainous regions can be 10 times greater. Under natural conditions, rates of natural soil formation and of soil erosion from land are at least 10 times lower.

Household air pollution from burning solid fuels is a significant, yet largely preventable, health risk

Household air pollution (HAP) in developing countries is primarily caused by burning solid fuels indoors for domestic purposes like cooking or heating. Around 3 billion people cook and heat their homes using open fires and simple stoves that burn biomass—wood, animal dung, crop residues—and coal. Household air pollution from solid fuel combustion affects global development because of chronic health impacts on affected populations. About 4.3 million people die prematurely every year from illness attributable to household air pollution from cooking with solid fuels (WHO, 2014). This is detailed by location and type of disease in **Exhibit 16.** In total, about 34% of deaths are from strokes, 26% from ischemic heart disease or heart attacks, 22% from chronic obstructive pulmonary disease (COPD), 12% are due to pneumonia and 6% are from lung cancer. While overall more deaths are caused by household pollution in Asia, more children are affected by it in Africa. Over half of all deaths among children under 5 from acute lower respiratory infections (ALRI) are due to particulate matter inhaled from indoor air pollution from household solid fuels (WHO, 2014). The combustion smoke that causes household air pollution contains particulate matter (PM), carbon monoxide, benzene and other harmful agents. PM consists of a complex mixture of solid and liquid particles of organic and inorganic substances suspended in the air. They contain sulfates, nitrates, ammonia, sodium chloride, black carbon, mineral dust and water. Most health damage is caused by particles with a diameter of 10 microns or less, (≤ PM10), which can enter deep inside the lungs.

Numerous types of improved cookstoves exist that could substantially reduce household air pollution, if they were more widely adopted. The damages from household air pollution have been increasingly recognized, and considerable effort has been applied toward solutions. Strategies to reduce indoor air pollution have focused on enhancing demand for clean cookstoves and fuels, strengthening the supply of such stoves and fuels, and fostering an enabling environment for their widespread use (GACC, 2011). While a number of improved stove technologies exist, widespread diffusion and use remains elusive (Subramanian, 2014). Long-term solutions to satisfying household heating needs must also consider the sustainability and security of primary energy supplies (e.g. biomass for charcoal production, and supply chains of fossil natural gas).

Estimated deaths due to household air pollution

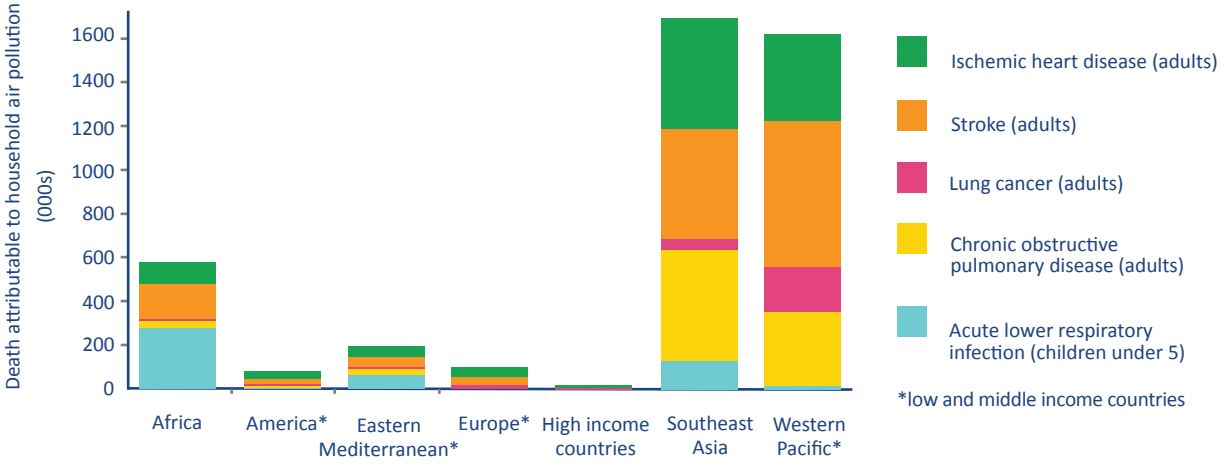


Exhibit 16: 4.3 million people died in 2012 from illness attributable to household air pollution, which is primarily caused by burning solid fuels indoors for cooking or heating. Of these deaths, about 34% were from stroke, 26% from ischemic heart disease, 22% from chronic obstructive pulmonary disease (COPD), 12% were due to pneumonia and 6% were from lung cancer. More total deaths were caused in Asia, though more children were affected in Africa. The regions indicated are standard WHO regions; the Southeast Asia WHO Region includes South Asia (WHO, 2014).

Outdoor air pollution, largely caused by vehicles, is a significant health risk in many urban areas

Outdoor (ambient) air pollution in both cities and rural areas is estimated to have caused 3.7 million premature deaths globally in 2012 (WHO, 2014). About 80% of premature deaths related to outdoor air pollution were due to strokes and ischemic heart disease, while 14% of deaths were due to chronic obstructive pulmonary disease or acute lower respiratory infections, and 6% were due to lung cancer. About 88% of those premature deaths occurred in low and middle income countries, and the greatest number in the WHO Western Pacific and Southeast Asia regions. As shown in **Exhibit 17**, concentrations of air pollutants are typically higher in the urban areas of low and middle income countries.

These air pollution related deaths are largely because of exposure to small particulate matter (PM) with diameter of 10 micrometers or less (PM10 and PM2.5). Chronic exposure to PM contributes to the risk of developing cardiovascular and respiratory diseases, as well as lung cancer. Other serious risks to health from outdoor air pollution are due to excessive exposure to ozone (O_3), nitrogen dioxide (NO_2) and sulfur dioxide (SO_2). Ozone plays a major role in asthma morbidity and mortality, while nitrogen dioxide and sulfur dioxide contribute to asthma, bronchial symptoms and reduced lung function. Outdoor air pollution primarily comes from fuel combustion, mainly from mobile sources such as vehicles and also from stationary sources such as power plants. Most air pollution in cities in developing countries is attributed to vehicle emissions (UNEP, 2014). In rural areas, outdoor air pollution is typically much less of a problem, and may result from burning of agricultural waste, forest fires and activities like charcoal production.

Exposure to outdoor air pollution in urban areas

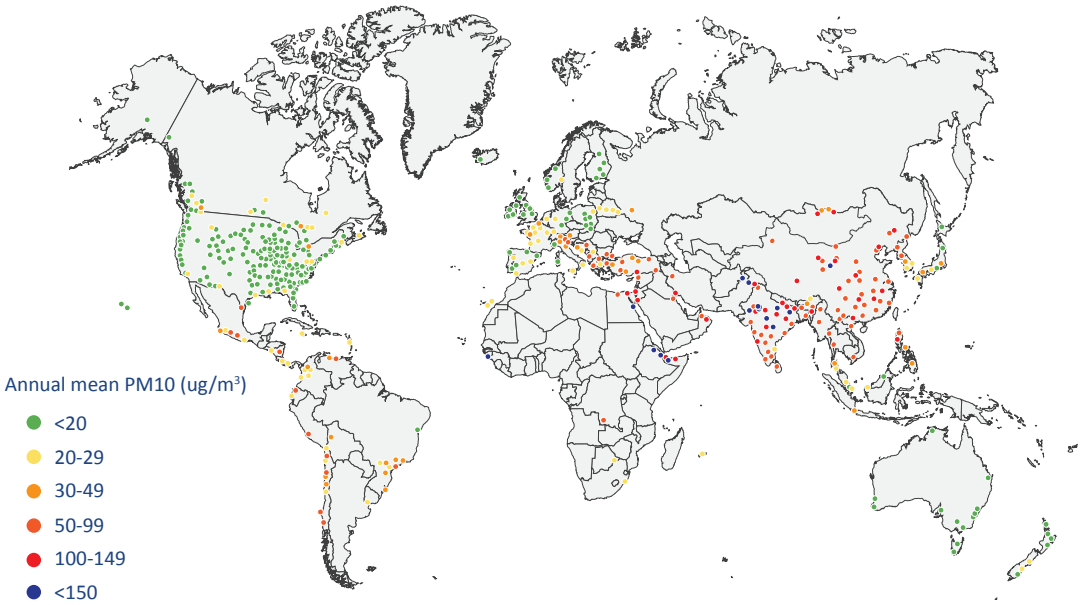


Exhibit 17: Health conditions due to outdoor (ambient) air pollution are primarily caused by exposure to particulate matter (PM10). Concentrations of PM10 were measured in 1600 urban areas from 2008 to 2013; mean annual concentrations are shown here. Particulate matter levels are highest in urban areas in Asia. Most cities in North America and Europe have low levels. Few data points are available for African cities (WHO, 2014).

Exposure to a broad range of environmental toxins causes chronic health conditions

People are exposed to environmental toxins—a diverse range of chemicals with potentially serious health effects— through air, water, food, or other means. Important examples of environmental toxins include heavy metals and persistent organic pollutants (POPs). Environmental toxins play a role in global development primarily due to their observed or projected chronic health impacts. Acute health impacts can also occur. Toxic materials from industry, mining and agriculture, including substances such as heavy metals and pesticides, affect populations in many countries throughout the world (GAHP, 2013). Although environmental toxins may be less prevalent overall in developing countries because of lower industrial activity compared to industrialized countries, the less stringent industrial regulations typically found in developing countries is a serious concern. Sources of toxic pollution include small- to large-scale mining and processing (e.g. battery recycling) activities, agricultural run-off containing fertilizer and pesticide residues, and toxic wastes that have been illegally disposed of in developing countries. Locations in developing countries that process e-waste (post-use electronic devices) have become 'hot-spots' of toxic exposure. The Agbogbloshie area in Accra, Ghana is a prime example (Blacksmith Institute, 2013). Industrial accidents such as the tragic 1984 gas leak at a pesticide factory in Bhopal, India are another source of exposure and lingering, adverse health effects.

An important type of environmental toxin is persistent organic pollutants (POPs), which are organic compounds that do not degrade readily and persist in the environment. They tend to bioaccumulate in organisms, meaning that it remains and accumulates within bodies. Many POPs are pesticides (such as DDT), either currently in use or formerly used but still present in the environment. This chemical

group also includes dioxins, furans and polychlorinated biphenyls. Dioxins are formed during incomplete combustion and when materials containing chlorine (e.g. some plastics) are burned. Another important type of environmental toxin are heavy metals, which are basic metal elements such as lead, mercury, cadmium and chromium. As elemental materials, they cannot be degraded or destroyed and also bioaccumulate in the body over time. Exposure to lead affects multiple body systems. Young children are particularly vulnerable to the toxic effects of lead and can suffer profound and permanent brain and nervous system damage. An emerging threat from some environmental toxins is their potential impact to the endocrine system. Some chemicals, including POPs and heavy metals, act as endocrine disruptors, interfering with the body's natural hormones. This leads to reproductive and other health problems in humans and animals, including infertility and early puberty (Frye, et al., 2011).

There have been few quantitative analyses of human risks due to environmental toxins in developing regions (Prüss-Ustün, et al., 2011). Impact estimates will likely increase as the problems are more clearly understood. WHO (2013) estimates that childhood lead exposure contributes to about 600,000 new cases of children developing intellectual disabilities every year. They estimate that lead exposure accounts for 143,000 deaths per year, with the highest burden in developing regions. About half of the burden of disease from lead occurs in the WHO Southeast Asia Region (which includes India), with about one-fifth each in the WHO Western Pacific Region (including China) and Eastern Mediterranean Region (including Egypt and Pakistan). Studies carried out at 373 toxic waste sites in India, Indonesia, and the Philippines found that 8.6 million people were at risk of exposure, resulting in 0.83 million DALYs (range of 0.81 to 1.56 million) (Chatham-Stephens, et al., 2013). This disease burden is comparable to the estimated disease burdens for outdoor air pollution (1.45 million DALYs) and malaria (0.73 million DALYs) in these countries. Exposure to lead and hexavalent chromium accounted for 99% of the total DALYs from exposure to environmental toxins. A study on human exposure to POPs in India found high levels of the pesticides DDT and HCH, often exceeding limits established by international regulatory agencies (Sharma, et al., 2014). Results from human biomonitoring showed levels of these pesticides in human milk and blood exceeding safety limits. This is due to the elevated use of pesticidal POPs in agriculture until recent years, and the ongoing application of DDT for malaria control.

In addition to direct impacts on human health, environmental toxins may also significantly impact global development through their deleterious effects on other species. For example, honey bees provide an invaluable environmental service by pollinating many human crop plants. For almost a decade, bee populations have suffered from the symptomatic disease of colony collapse disorder (CCD), apparently due to exposure to neonicotinoids (Lu, et al., 2014). Neonicotinoids are a class of neuro-active, nicotine-based systemic insecticide that was brought into commercial use in the mid-1990s. Neonicotinoids have a high persistence in soil and water, resulting in sustained and chronic exposure of non-target organisms, such as honeybees and other invertebrates. Because they are relatively water-soluble, they run off into aquatic habitats easily, and are still toxic even at very low doses. Use of neonicotinoids is expected to result in substantial impacts on biodiversity and ecosystem functioning, including the distribution, abundance, and effectiveness of pollinators (van der Sluijs, et al., 2014). This could significantly impact food security due to reduced crop production.

Global average temperatures will become warmer in the future, affecting agricultural yields and human health

Climate change is a long-term alteration of global weather patterns, due to increased heat energy accumulated in the earth system, largely as a result of greenhouse gases emitted into the atmosphere. Some level of future climate change is unavoidable due to previous emissions, which remain in the atmosphere for long time spans. The extent of future climate change impacts will depend on levels of current mitigation efforts and future adaptation efforts. Current greenhouse gas emissions trajectories

correspond closely to high emission scenarios (RCP8.5) modeled by climate scientists. Continuation of such trends can be expected to result in a global mean temperature increase of about 4°C by 2100 (IPCC WG2, 2014) (**Exhibit 18**). Global cooperation towards greatly reduced emissions (RCP2.6 scenario) could result in a smaller temperature rise. Such cooperation has not been forthcoming, to date.

Historical and projected global average surface temperature, 1900 to 2100

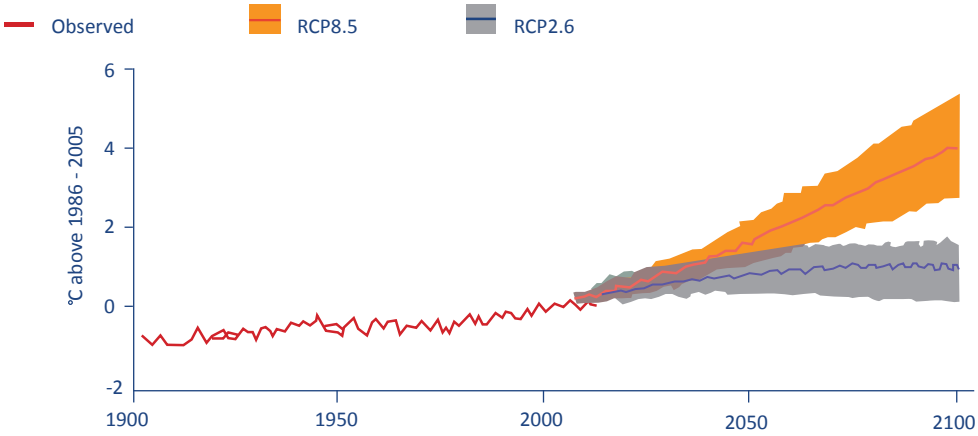


Exhibit 18: Global average surface temperature is projected to increase during this century. The temperature increase will be greater if greenhouse gas emissions continue at high levels, following the RCP8.5 emission scenario. A much smaller temperature increase is projected to occur if emissions are limited to the lower RCP2.6 scenario. Temperature changes are shown relative to average 1986-2005 temperature (IPCC WG2, 2014).

Rising temperatures due to climate change are expected to affect global development due to potentially significant effects on food security, water supply, and health. Over most land areas, the coldest days and nights will be warmer and fewer, and the hottest days and nights will be warmer and more frequent. At lower latitudes, especially in seasonally dry and tropical regions, crop productivity is projected to decrease with even a small rise in average temperature (IPCC WG2, 2014). At mid to high latitudes, crop productivity is projected to increase slightly with a small rise in temperature, and eventually decrease as temperatures rise further due to limited heat tolerance by crop plants. **Exhibit 19** summarizes numerous estimates from the peer-reviewed literature of the impact of climate trends on yield of several major crops. Yields of wheat, rice and maize are projected to decrease by several percent per decade. Soy is more heat tolerant, and should be less affected. Water pollution issues are also expected to increase due to higher water temperature and altered water flow patterns. Incidence of some vector-borne diseases, such as malaria, is expected to increase in highland regions as temperatures rise (Siraj, et al., 2014).

Projected impact of climate change on yields of 4 food crops

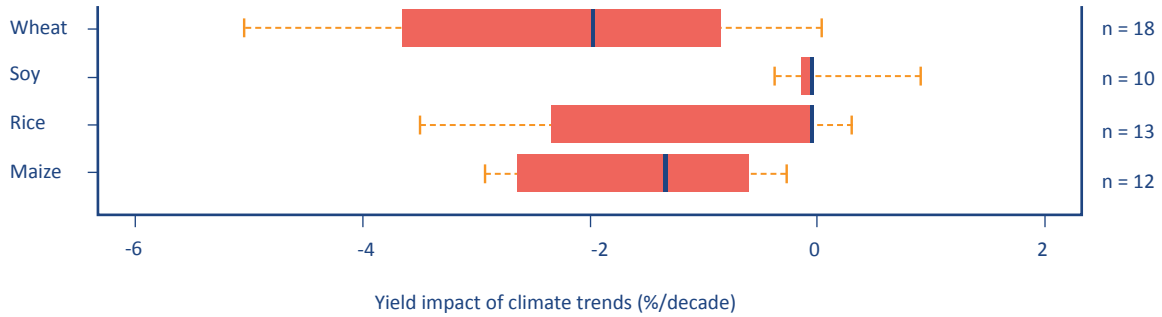


Exhibit 19: Yields of wheat, rice and maize are expected to decline due to climate trends including rising temperatures. This exhibit summarizes estimates from peer-reviewed literature of the impact of recent climate trends on yields for four major crops. The boxplots indicate the median (vertical line), 25th - 75th percentiles (box), and 10th - 90th percentiles (whiskers) for estimated impacts, and n indicates the number of estimates. The studies were taken from the peer-reviewed literature and used different methods (i.e., physiological process-based crop models or statistical models), spatial scales (stations, provinces, countries, or global), and time periods (median length of 29 years). Some included positive effects of 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 (IPCC WG2, 2014).

Average long-term precipitation patterns will shift, and some areas will become dryer

Changes in the global water cycle are projected to occur as the climate warms (IPCC, 2013). Average global precipitation is projected to gradually increase in the 21st century. The global hydrological cycle will intensify generally due to global warming, and mean water vapor, evaporation and precipitation are projected to increase on global average. Changes of average precipitation in a much warmer world will not be uniform, with some regions experiencing increases, and others with decreases or little change. Precipitation is expected to increase in many wet tropical areas and at high latitudes. Many mid latitude and subtropical arid and semi-arid regions will likely experience less precipitation. The Asian monsoon will likely increase in average total precipitation, but with greater variation from year to year. The melting of snowpack and glaciers will affect the amount and timing of water flows in downstream areas.

Despite variability and uncertainty in climate change projections, there is now agreement from a number of different climate models that Africa is at the highest risk from climate change, given the magnitude of existing stresses in the continent (UNDP, 2009). It is highly likely that significant areas of African drylands will see changing rainfall patterns in the coming decades. **Exhibit 20** shows model projections of future changes in annual precipitation in Africa, under high and low emission scenarios. Average precipitation is expected to decrease in northern and southern Africa, and increase in central and eastern Africa.

Projected future changes in annual precipitation in Africa

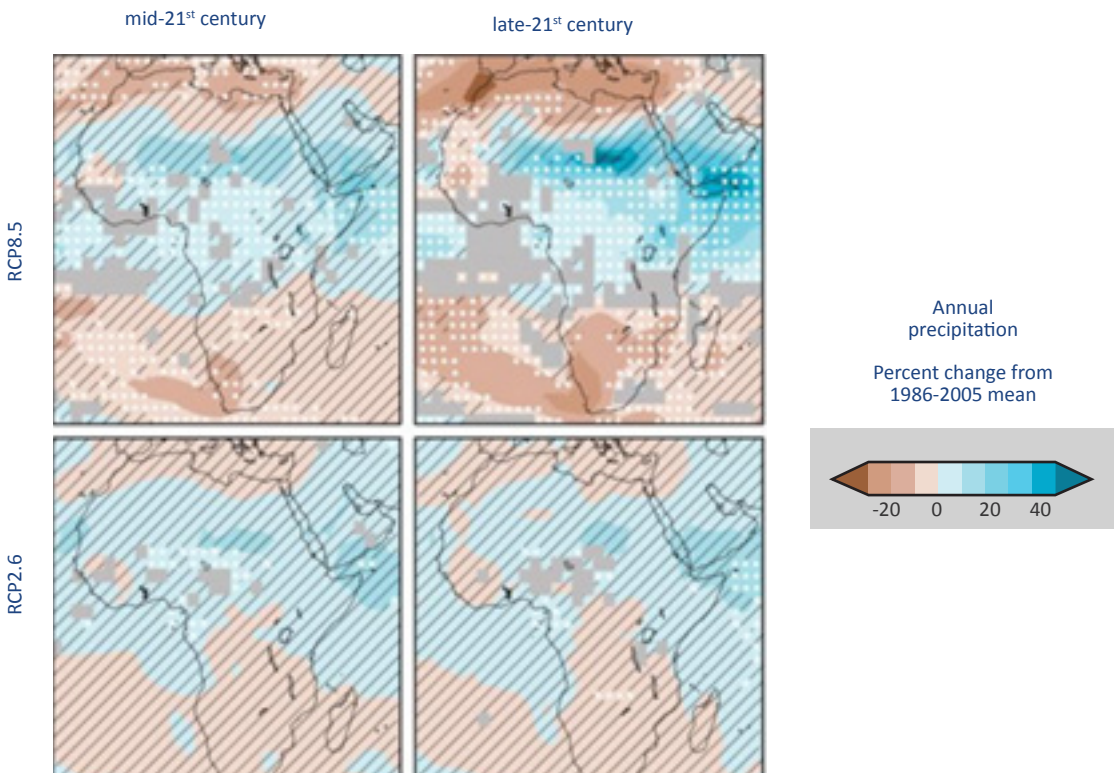


Exhibit 20: Results from climate models suggest that annual precipitation patterns in Africa will change, by the mid-21st century (left) and late-21st century (right), under high emission scenario (RCP8.5; top) and low emission scenario (RPC2.5; bottom). Average precipitation is expected to decrease in northern and southern Africa, and increase in central and eastern Africa (IPCC WG2, 2014).

Extreme weather events such as drought, storms and floods will become more frequent and more intense

Global climate change is expected to result in more frequent and intense extreme weather events. Warm spells and heat waves will very likely occur more frequently (IPCC WG2, 2014). Storms such as tropical cyclones are expected to become more severe, including storm surges in coastal areas. Precipitation is more likely to come as heavy rainfall (even in regions that receive less total precipitation), leading to increased erosion, landslides and flooding. Precipitation extremes are projected to negatively affect water quality, due to increased sediment, nutrient and pollutant loadings caused by heavy rainfall, reduced dilution of pollutants during droughts, and disruption of treatment facilities during floods.

The most significant impact of extreme weather events on human development will likely be due to frequent and prolonged droughts in some regions. Many climate models project an increased likelihood of agricultural droughts in regions that are presently dry, with extended decreases in soil moisture (IPCC WG2, 2014). Farmers and pastoralists in drylands with insufficient access to drinking and irrigation water risk the loss of agricultural productivity. This will affect the livelihoods of rural people, particularly those depending on water-intensive agriculture. There is a corresponding risk of food insecurity and conflict over available water and food resources (UNDP, 2009). Droughts also affect

urban populations with inadequate water services, who risk an insufficient water supply for domestic and industrial use, causing health and economic impacts. Droughts can also significantly affect energy security, because they reduce the energy supply from hydropower stations and can force water-cooled thermal power stations to shut down. A major drought in 2001 in Brazil, where 80% of electricity is from hydropower, caused a 20% reduction in electricity supplies in the country and led the government to introduce rationing (Lee, at al., 2012). Ethiopia is particularly vulnerable to droughts, because of its high dependence on agriculture as well as hydropower for electricity.

Sea level will slowly but inevitably rise in the future, affecting coastal populations

Global mean sea level has risen about 0.2 meters since 1900, at a rate of about 1.7 millimeters per year (IPCC WG2, 2014). Sea level is expected to continue rising at an accelerating pace, depending on future greenhouse gas emission scenarios. Forecasting future sea level rise is challenging, but modeling capabilities have improved in recent years and current projections are fairly robust (Horton, et al., 2014). For the low emission climate scenario (RCP2.6), sea level is expected to rise by another half meter by 2100. For the high emission climate scenario (RCP8.5) it is expected to rise a full meter by 2100 (**Exhibit 21**). Much of this sea level rise is due to thermal expansion of the slowly warming ocean water. Another, more uncertain, contribution to rising sea levels will be melting glaciers and ice caps. Sea level rise will affect global development due to permanent or episodic displacement of coastal populations, inundated agricultural land, and reduced freshwater supply due to saltwater intrusion into aquifers.

Historical and projected mean sea level, 1700 to 2100

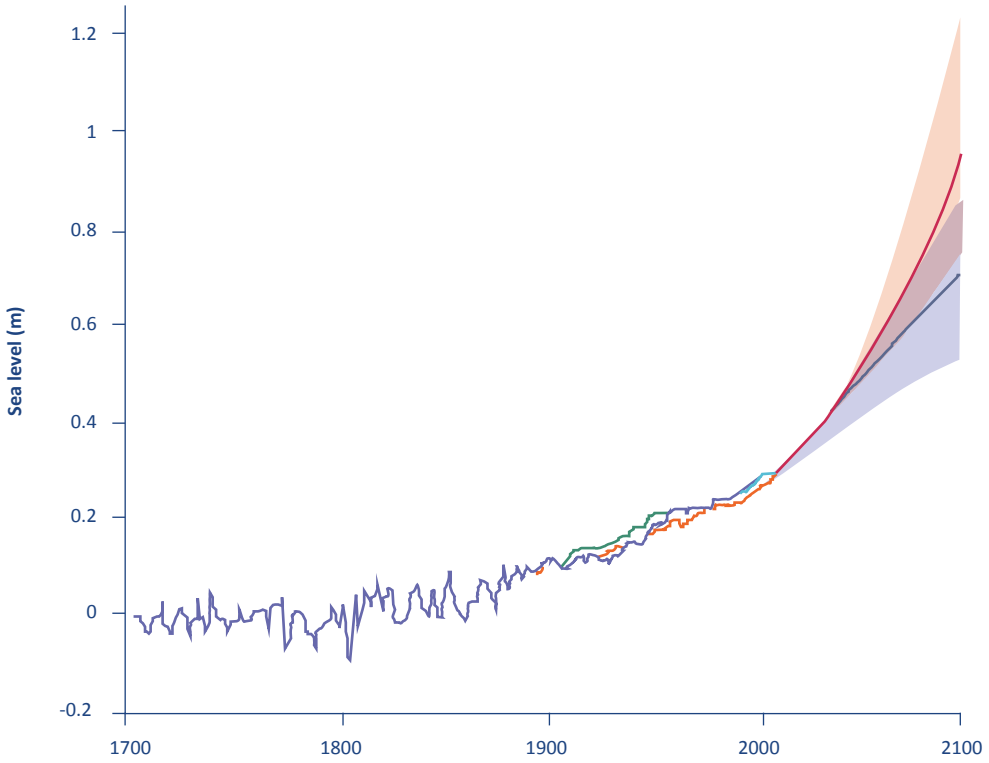


Exhibit 21: Global mean sea level has risen at a rate of about 1.7 millimeters per year since 1900, rising a total of about 0.2 meters since pre-industrial times. The mean sea level is projected to continue to rise at an accelerating pace through 2100 and beyond. Future sea level rise is projected for the low emission RCP2.6 scenario (blue) and the high emission RCP8.5 scenario (red) (IPCC WG2, 2014).

Coastal areas are highly vulnerable to extreme events, such as storms and their associated surge, which will be exacerbated with higher average sea levels. River delta regions are highly vulnerable to the impacts of climate change, particularly sea level rise and changes in runoff. Many delta plains, especially those in Asia, are very densely populated. Some studies estimate (Ericson, et al., 2006) that over a million people will be directly affected by 2050 in three megadeltas: the Ganges-Brahmaputra delta in Bangladesh, the Mekong delta in Vietnam, and the Nile delta in Egypt. Their modeling suggests that 75% of the population affected by sea level rise live on deltas in Asia, and many of the remainder live on African deltas. About 8.7 million people could be affected by coastal inundation by 2050. GIS based models (Dasgupta, et al., 2009) estimate that a 1 meter rise in sea level will directly affect over 56 million people in developing countries. Several countries are expected to be particularly impacted, including Vietnam and Egypt; both countries may see 10% of their population being displaced by a 1 meter rise in sea level. Some freshwater aquifers in coastal areas are expected to become brackish, due to the intrusion of rising salt water levels (Werner, et al., 2013).

Coastal adaptation practices can seek to protect, accommodate or retreat in response to rising sea levels. Protection efforts can involve 'hard' or 'soft' measures, but will face increasing pressure over time and may ultimately be untenable. Efforts at accommodation focus on reducing damage from

high waters through flood-resilient infrastructure or floating agricultural systems, for instance. Retreat options may ultimately be inevitable, but if opted for in populated areas will result in large numbers of 'climate refugees' who will need permanent resettlement elsewhere.

Ocean water is absorbing atmospheric CO_2 and becoming more acidic, affecting sea plants and animals

As described earlier, the concentration of carbon dioxide (CO_2) gas in the atmosphere has risen from about 280 parts per million (ppm) during pre-industrial times to about 400 ppm now. Some of the CO_2 that is emitted into the atmosphere is absorbed by the oceans, and this has a significant impact on the chemistry of seawater. CO_2 reacts with water to form carbonic acid (H_2CO_3), which increases the acidity of the ocean. Acidity is measured in pH units using a logarithmic scale: a 1 unit decrease in pH corresponds to a 10-fold increase in hydrogen ion concentration, or acidity. Since the beginning of the industrial era, the pH of ocean surface water has changed by about 0.1 unit (from about 8.2 to 8.1, on the full pH scale). This corresponds to a 26% increase in hydrogen ion concentration (IPCC, 2013). While not directly related to the changing climate, ocean acidification is caused by the same global drivers, and is typically considered as an impact of global climate change.

Ocean acidification is expected to increase in the future, as the oceans absorb additional CO_2 from the atmosphere. Climate models project a global increase in ocean acidification for all greenhouse gas emissions scenarios (IPCC, 2013). The high emission scenario (RCP8.5) is projected to lead to a decrease in the pH of surface ocean water by about 0.3 units by the end of 21st century. The low emission scenario (RCP2.6) would decrease the ocean water pH by only about 0.07 units by 2100.

The consequences of changes in ocean acidity for marine organisms and ecosystems are just beginning to be understood, but are expected to affect fundamental biological and chemical processes of the sea. Geological records, as well as results from laboratory, field, and modeling studies, suggest that marine ecosystems are highly sensitive to changes in ocean acidity. For example, the acidity of seawater largely determines the saturation state of calcium carbonate minerals, which affects the formation of shells for marine animals such as corals, plankton, and shellfish. Some marine species like reef fishes and shelled mollusks are expected to be negatively affected by ocean acidification, while other species like crustaceans may fare better (Branch, et al., 2013). Overall effects on primary productivity and food webs will be complex, and hard to predict.

Forest land continues to be converted to agricultural land, especially in Latin America

Deforestation is the removal of trees from a forested area, where the land is then converted to non-forest use. Globally, about 31% of total land area is covered by forests, corresponding to a forest area of just over 4 billion hectares (FAO, 2010). Global forest area has decreased by about 1 billion hectares during the last three centuries, corresponding to an average deforestation rate of 3.2 million hectares per year (see Exhibit 5). More recently, forest area decreased at a rate of about 5.2 million hectares per year during the period 2000 to 2010, down from an estimated 8.3 million hectares per year during the period 1990 to 2000. Net global decrease in forest area is the result of two opposing processes. First, deforestation occurred at a rate of about 13 million hectares per year during the period 2000 to 2010, down from about 16 million hectares per year in the 1990s. Second, afforestation and natural expansion of forests occurred in other areas. Globally, much of the increase in forest area occurs in China, where large-scale afforestation efforts increased the forest area by an average of 3 million hectares per year during the period 2000 to 2010. Most of the loss of forest currently occurs in South America (4 million hectares per year) and Africa (3.4 million hectares per year). **Table 1** lists the countries with the largest annual net loss of forest area between 2000 and 2010.

Countries with the highest annual loss of forest area, 2000-2010

Country	Annual loss of forest area (2000-2010)	
	1000 hectares per year	Percentage change per year
Brazil	-2640	-0.5
Australia	-560	-0.4
Indonesia	-500	-0.5
Nigeria	-410	-3.7
Tanzania	-400	-1.1
Zimbabwe	-330	-1.9
DR Congo	-310	-0.2
Myanmar	-310	-0.9
Bolivia	-290	-0.5
Venezuela	-290	-0.6
Total	**-6040**	**-0.5**

Table 1: These 10 countries experienced the largest net loss of forest area between 2000 and 2010. The decrease in Australia's forest area is due to extended drought (FAO, 2010).

Around 80% of deforestation worldwide is driven by agriculture (Kissinger, et al., 2012). In Latin America, where most deforestation occurs, about 95% is caused by agriculture (including livestock), primarily commercial agriculture (**Exhibit 22**). In Africa and subtropical Asia, about 70-75% of deforestation is due to agriculture, of which about half is commercial and half is subsistence agriculture. In terms of impact on human development, deforestation occurs largely due to conversion of forest area to agricultural land, with corresponding positive implications for food security. However, deforestation has negative short-term to medium-term ramifications like landslides, flooding and loss of access to forest products, as well as potential long-term consequences on biodiversity, habitat for wild species, and global climate. The net effect of deforestation on global development is a balance of these forces.

Primary drivers of deforestation, 2000-2010

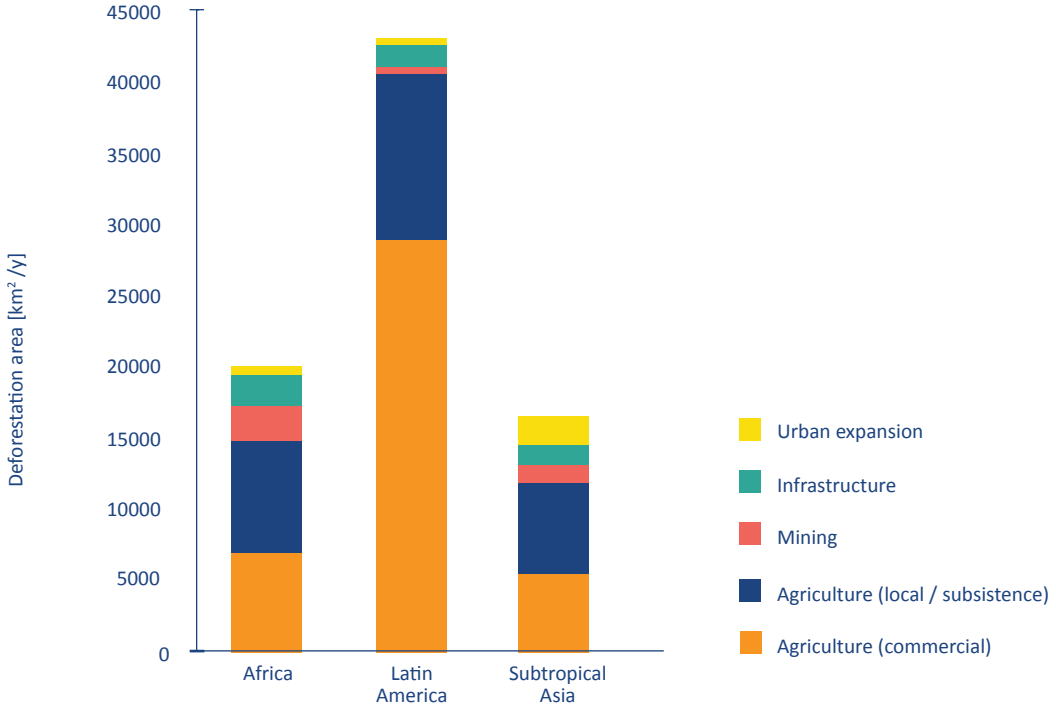


Exhibit 22: Deforestation is driven largely by agriculture. Most deforestation occurs in Latin America, and is largely due to commercial agriculture. Less deforestation occurs in Africa and Asia, where it is driven by both subsistence and commercial agriculture (Kissinger, et al., 2012).

Supplying food by catching wild fish is becoming increasingly difficult and constrained

Sources of wild food have become less important for humans since the adoption of agriculture and animal husbandry as food security strategies. Meat from wild land animals, or bushmeat, continues to form only a minor part of the human diet in select countries. Bushmeat was reported in 1997 to contribute about 8% of total protein consumption in several African countries including DR Congo, Liberia, and Ghana (FAO, 1997). More recent figures are unavailable, but overall consumption is expected to have decreased since 1997. Most animal protein for humans now comes from domesticated land animals such as cattle and poultry.

Although the ocean environment is more challenging than land for humans, a similar transition from wild fish catch to cultivated fish production is underway. Protein from wild fish continues to be an important component in some regions; fish constitute at least half of total animal protein intake in Bangladesh, Cambodia, Ghana, The Gambia, Indonesia, Sierra Leone and Sri Lanka (FAO, 2012). In 2009, fish accounted for 16.6% of the global population's intake of animal protein and 6.5% of all protein consumed. However, global stocks of wild marine fish are increasingly overexploited to provide this supply of food (**Exhibit 23**). The global catch of wild fish has remained roughly level since the late 1980s, despite a greater capture effort (Watson, et al., 2013). The gap has been made up by aquaculture production, allowing expanded human consumption of fish (**Exhibit 24**).

Exploitation of global marine fish stock since 1974

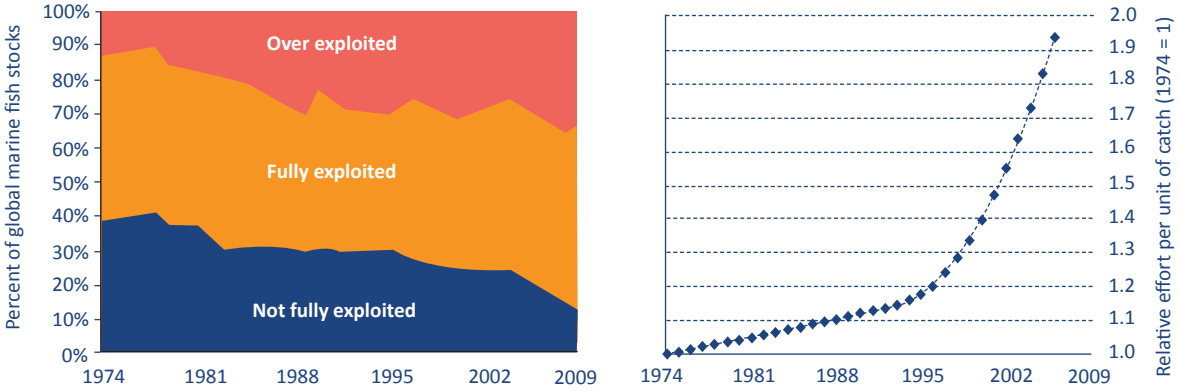


Exhibit 23: Human exploitation of global marine fish stocks is becoming less sustainable, and catching wild fish today requires more effort than before (FAO, 2012) (Watson, et al., 2013).

Global fish production since 1950

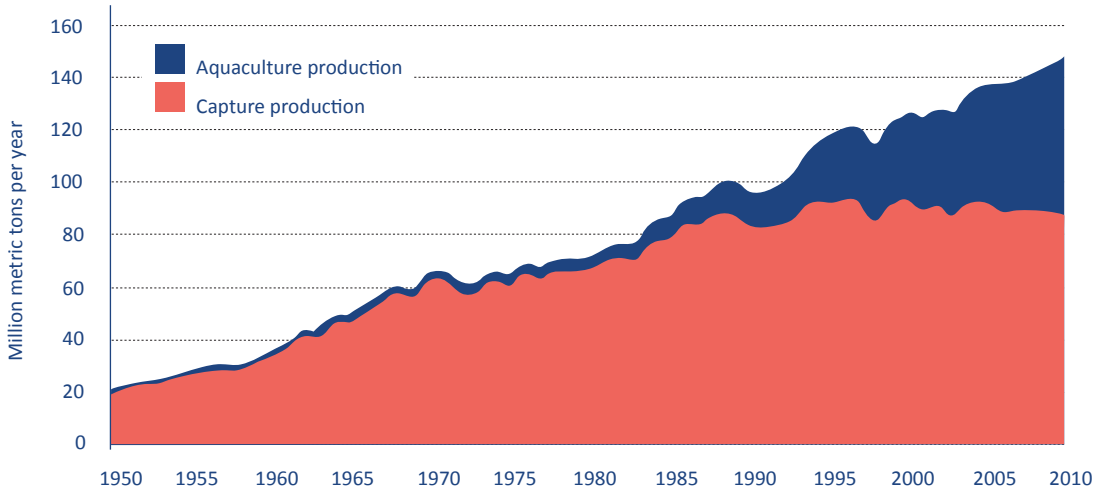


Exhibit 24: Global catch of wild fish has remained roughly level since the 1990s, while aquaculture fish production has increased significantly since then (FAO, 2012).

Gradual depletion of non-renewable natural resources will increase their real cost

Non-renewable resource depletion results from human use and dissipation of one-time stocks of natural resources that were created over geologic time periods, such as fossil fuels, metal ores and other minerals. Public discourse regarding resource depletion is typically polarized in two camps. Cornucopians maintain that technological innovation and market forces will overcome resource scarcity, by developing substitutes or by improving efficiencies of extracting and using the resources. Doomers believe that our historical success at improving human welfare has resulted precisely from our one-time exploitation of the most concentrated and accessible of these resources, and fundamental limits to human activities will then be seen. A broader analysis suggests that elements of both arguments can be

seen currently in effect, and can be expected to continue into the future.

Geologic resources such as mineral ores and fossil fuels, which have played essential roles in human development to date (e.g. the Iron Age), were created in fixed amounts in the earth's crust over geologic time spans of millions of years. An ore is a rock with a relatively high concentration of some desired element, and results from geological and meteorological forces such as plate tectonics, volcanoes, folding, faulting, weathering, erosion and sediment deposition. For example, the earth's crust as a whole contains an average of only about 0.004 grams of gold per ton, but at particular locations and depths it contains several grams per ton. These locations are prospected and selected to become gold mines. Sites with the highest ore grade are typically exploited first, because the cost and effort of mining and processing metal increase strongly as the concentration of metal in the ore decreases. In particular, the energy needed to refine the ore increases exponentially as ore grade decreases (Norgate, et al., 2007). **Exhibit 25** shows historical trends in gold ore grade from 1840 to 2010 in major gold-producing countries (UNEP, 2011). Although gold is not essentially related to global human development, it is a well documented natural resource for which long-term data are available, and serves as a proxy for more functional metals such as copper. The ore grade fluctuates from year to year as individual deposits of gold are exploited, but the long-term trend is of declining ore grade in all regions. Clearly discerning the effect of this trend on gold prices and production levels is difficult due to concurrent changes in economic and technologic factors, though it has necessarily made the physical exploitation of gold resource more challenging. Similar trends toward lower ore grades are seen for most other industrially-important metals, like copper (Harmsen, et al., 2013).

Quality of gold ore in major producing countries since 1840

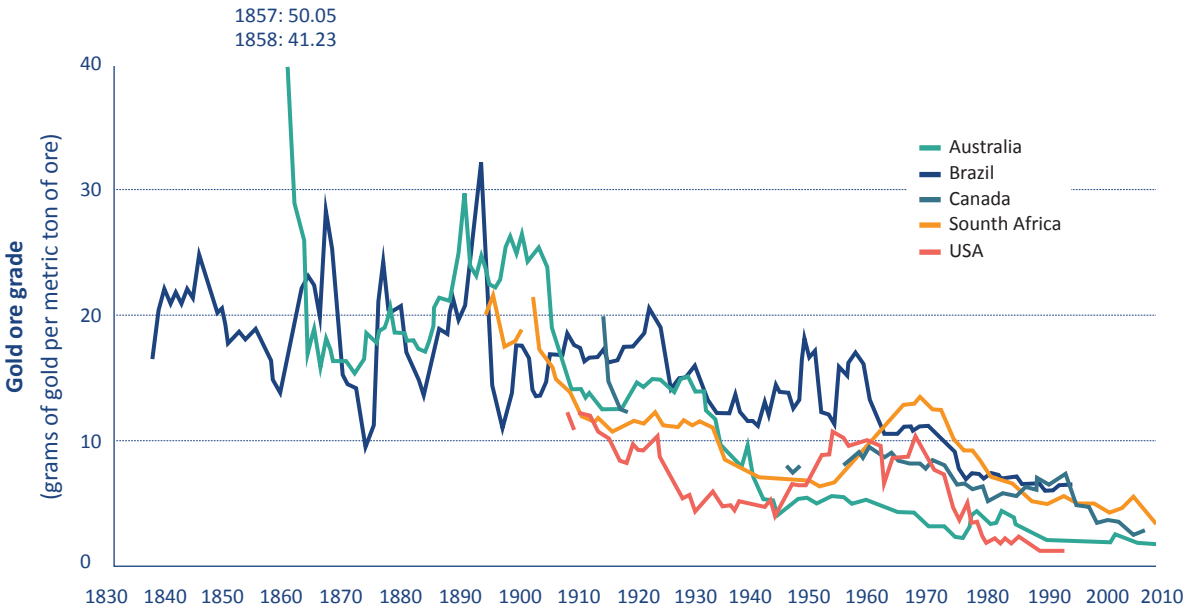


Exhibit 25: The quality of gold ore has decreased considerably since 1840, and high-grade deposits are no longer encountered (UNEP, 2011).

Another important example is fossil fuel use and sourcing. The three types of fossil fuels—coal, oil and natural gas—supply about 82% of all global primary energy use (IEA, 2014). Globally, we are heavily dependent on fossil fuels for transportation, electricity, heat and other energy services such as nitrogen fertilizer production. Fossil fuels were formed from decayed organic matter that was exposed to heat and pressure in the earth's crust over long periods of time. Most fossil fuels are made from plants and animals that were alive during the Carboniferous Period, about 350 million years ago. As such, fossil fuels are clearly non-renewable over time scales of interest, and long-term human development will require a transition to renewable energy sources. Notwithstanding, the global use of fossil fuels has more than doubled in the last 40 years, and overwhelmingly remains the dominant source of energy for human society (**Exhibit 26**). Geologic deposits of fossil fuels have shown declines in resource quality over time, similar in nature to that shown for gold in **Exhibit 25** (Hall, et al., 2014). However, continued expansion of fossil fuel production has been made possible by a range of advanced technologies such as deepwater drilling, horizontal drilling, hydraulic fracturing and oil sand recovery. These techniques to exploit unconventional fossil fuel resources come at an economic and energetic cost, and have become necessary only because the preferred conventional reserves have become increasingly depleted.

Global total annual primary energy use since 1971

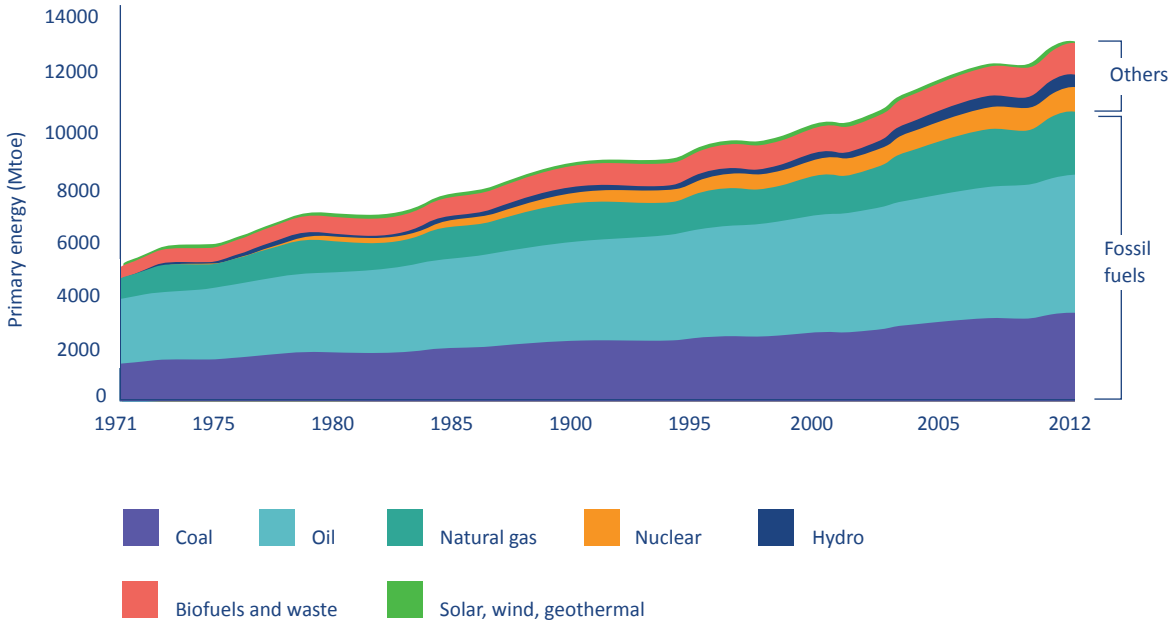


Exhibit 26: The total annual primary energy used globally has more than doubled since 1971; fossil fuels remain the dominant source of energy. Global energy use is shown here by the source of the primary energy, in units of million tons of oil equivalent (Mtoe) per year (IEA, 2014).

As available deposits of natural resources become less concentrated and less accessible, increasing effort must be dedicated by society to obtain the still available natural resources. Other things equal, this will result in less surplus resource wealth that can be applied to improving human welfare (Murphy, 2013). As increasingly complex unconventional techniques are needed to access and exploit remaining fossil fuel resources, the real cost, including externalities, is likely to increase. This may affect human

development by constraining potential solutions that are too energy or resource intensive to scale effectively (Lee, et al., 2012). The concern is less about running out of a resource, but of bearing the increasing costs and risks involved with obtaining it. In this light, our increasing use of unconventional fossil fuel extraction techniques (such as hydraulic fracturing and oil sand recovery) is less of an energy revolution and more of an evolution toward the use of lower grade resources.

Prudent planning of human development efforts should not pre-suppose the existence of indefinitely plentiful natural resources, but should anticipate long-term supply shifts. As a vital example, virtually all nitrogen fertilizer, which is necessary to maintain agricultural yields, is made with fossil natural gas. Dynamic resolution will occur at the intersection of increasing human demand, decreasing geologic abundance, and improving efficiency of extraction and utilization technologies. Early transition to renewable energy sources and production systems will offer increasing benefits over time, as the quality of accessible non-renewable resources further declines. Deployment of renewable energy has strong synergies with sustainable development goals (Sathaye, et al., 2010).

5 The various environmental changes and consequences are driven by global and local actions, but not all of them have significant impact on human development by 2050

The level of impact of the numerous second-order environmental consequences on human development will vary, and only some of these problems can be fully resolved through actions within developing countries. **Exhibit 27** shows the estimated severity of impacts on human development goals, and whether the primary drivers of environmental change are global or local actions. Some of the primary drivers like indoor air pollution and soil erosion are clearly local, meaning that these problems could, in principle, be fully solved through local efforts. Other environmental consequences like ambient air pollution and groundwater depletion have regional drivers, and require some level of regional administration to overcome. Some consequences, including climate change and natural resource depletion, have clearly global drivers, and will cause local damages regardless of the location of the drivers. These problems require global cooperation for effective mitigation, while local adaptation measures are needed to accommodate inevitable changes. The drivers of other environmental consequences like deforestation and reduced wild ocean food are more challenging to localize, in part because local actions such as logging and fishing may be stimulated by global market forces.
The four quadrants of **Exhibit 27** represent issues with varying severity of impacts and potentials of solution.

- Quadrant A contains high impact problems with local focus of mitigation and/or adaptation.
- Quadrant B contains medium impact problems with local focus of mitigation and/or adaptation.
- Quadrant C contains high impact problems with local adaptation focus. Mitigation, where possible, will require global cooperation.
- Quadrant D contains medium impact problems with local adaptation focus. Mitigation will require global cooperation.

Anticipated human development impacts of environmental change consequences

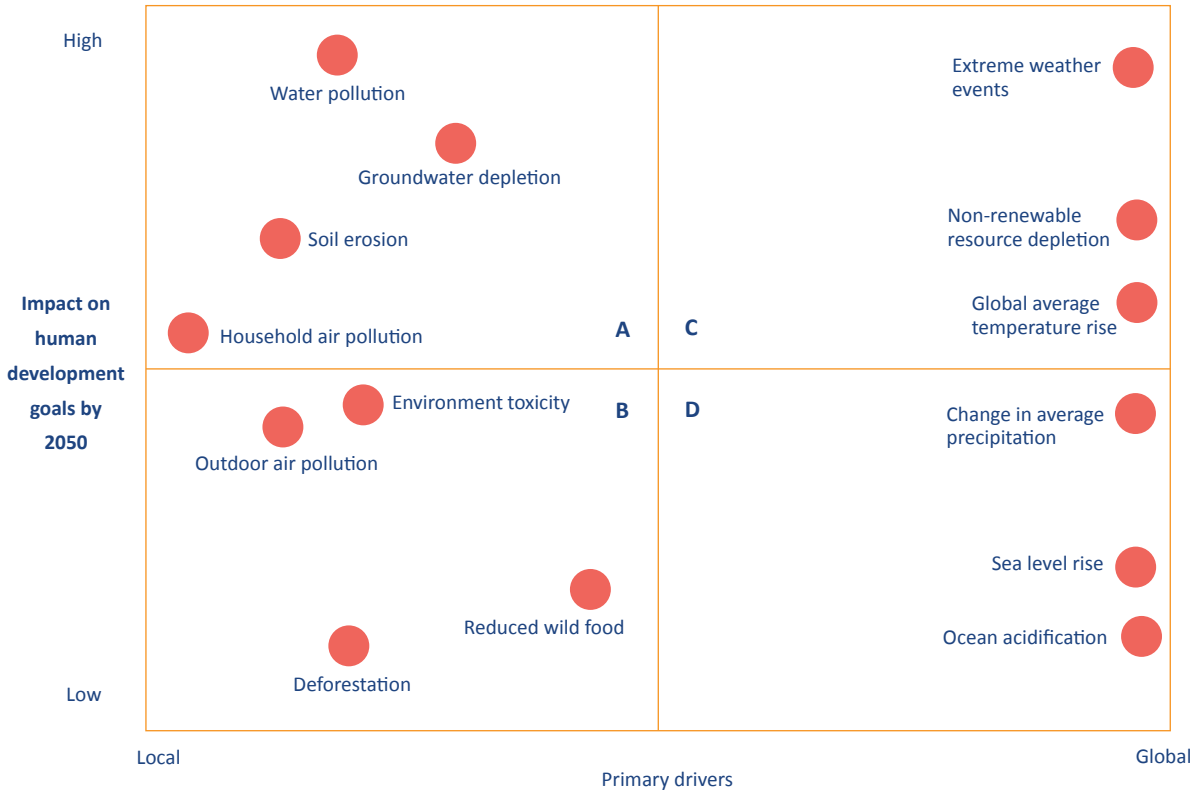


Exhibit 27: Matrix of environmental change consequences, showing anticipated impacts on human development by 2050 on the vertical axis, and source of primary drivers on the horizontal axis (left = local drivers, right = global drivers).

KEY CHALLENGES

Identifying major barriers will help define the constraints and requirements of potential breakthroughs. Beyond scientific and technological challenges, many hurdles exist that may constrain successful resilience to environmental changes.

1. Many environmental processes are interlinked, and problems often have multiple causes that cannot be addressed independently. Advances in one field of human development may cause setbacks in other fields.

2. There is often a time lag between beneficial first-order environmental changes and detrimental second-order consequences. Current political and economic systems, with their focus on short-term rewards, are ill-suited to confront these long-term challenges.

3. Many current environmental problems result from externalities of economic activities, meaning the costs are borne by people not involved in the original activities. Externalities are poorly incorporated into current economic metrics of success.

4. Definitive solutions to environmental change issues may also require breakthroughs in human behavior. Many aspects of the lifestyle in industrialized countries remain as aspirational goals for developing country populations, yet are clearly unsustainable at scale.

5. Depending on context, other important barriers may include the lack of effective regulatory and enforcement mechanisms, lack of adequate economic means to commit to solutions, and lack of economic incentives among key decision-makers and stakeholders.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

Prescribing solutions to human development problems arising from environmental changes is especially challenging, because the changes have occurred precisely due to human efforts towards development. The approaches used successfully in the past to enable human development, e.g. the coal-powered Industrial Revolution in Europe and North America in the 18th and 19th centuries, and the resource intensive Green Revolution in Asia and Latin America in the 20th century, have allowed great advances in human development. However, the compromises and consequences of these approaches, and their potential threats to long-term human wellbeing, are growing more evident. Future-oriented human development efforts should learn from both the successes and failures of past approaches.

Numerous high-potential technological breakthroughs are being pursued for use in industrialized countries, and if successful could also apply to developing countries. For example, scalable means of harnessing and storing solar energy could resolve primary energy supply constraints. While beneficial to industrialized countries due to enhanced energy security, such a technology, if successful, could fundamentally benefit human development goals that promote universal energy availability. In this section, however, we focus on potential breakthroughs with primary applications within developing regions.

Please note that a number of the breakthroughs identified in other sections of this study are equally relevant to the issues discussed in this section. For example, breakthrough technologies relevant to resilience against environmental change include:

- Sanitation for human waste
- Precision irrigation systems
- Detection and utilization of groundwater resources
- Soil nutrient analysis

Additional critical breakthroughs are described below.

A scalable low cost method to desalinate water using renewable energy

Desalination is the process of making potable water from saline water sources (sea water or brackish water). The mineral/salt content of water is typically measured in milligrams of total dissolved solids (TDS) per liter of water. The salinity of ocean water averages 35,000 mg/L globally, varying from about 32,000 to 38,000 mg/L. Water is considered potable when it contains TDS less than 500 to 1000 mg/L. The vast majority, about 97.5%, of the earth's water is seawater. Of the remaining 2.5% fresh water, 70% is frozen in polar ice and snow, and the rest is mostly groundwater (MEA, 2005). A breakthrough technology for scalable desalination using renewable energy would allow greater access to the huge resource of ocean water.

Desalination is currently used in select regions of the world. There are more than 7500 desalination facilities worldwide, over half of which are located in the Middle East (Shatat & Riffat, 2012). Virtually all are powered by fossil fuels, and are often integrated with, and use waste heat from, electricity generating stations.

There are currently two main types of desalination processes: thermal and membrane. Thermal desalination involves evaporating and condensing water, as in distillation. Various thermal processes operate at different temperatures and pressures, including the dominant multi-stage flash process, and the multi-effects distillation process (Shatat & Riffat, 2012). In recent decades, membrane technologies

have matured and most new desalination installations use membranes. Of these, the reverse osmosis (RO) process is the most common, and uses a semi-permeable membrane through which pressurized saline water is forced. Other membrane processes include electrodialysis and membrane distillation. A major difference between the various processes is the source of energy that drives desalination; heat, pressure, and electricity are used in different processes. The cost of the energy supply strongly affects the cost of desalination. The cost of the various processes also varies, and is heavily dependent on scale. Larger facilities are far less expensive per cubic meter of fresh water (**Exhibit 28**).

Cost of current desalination processes

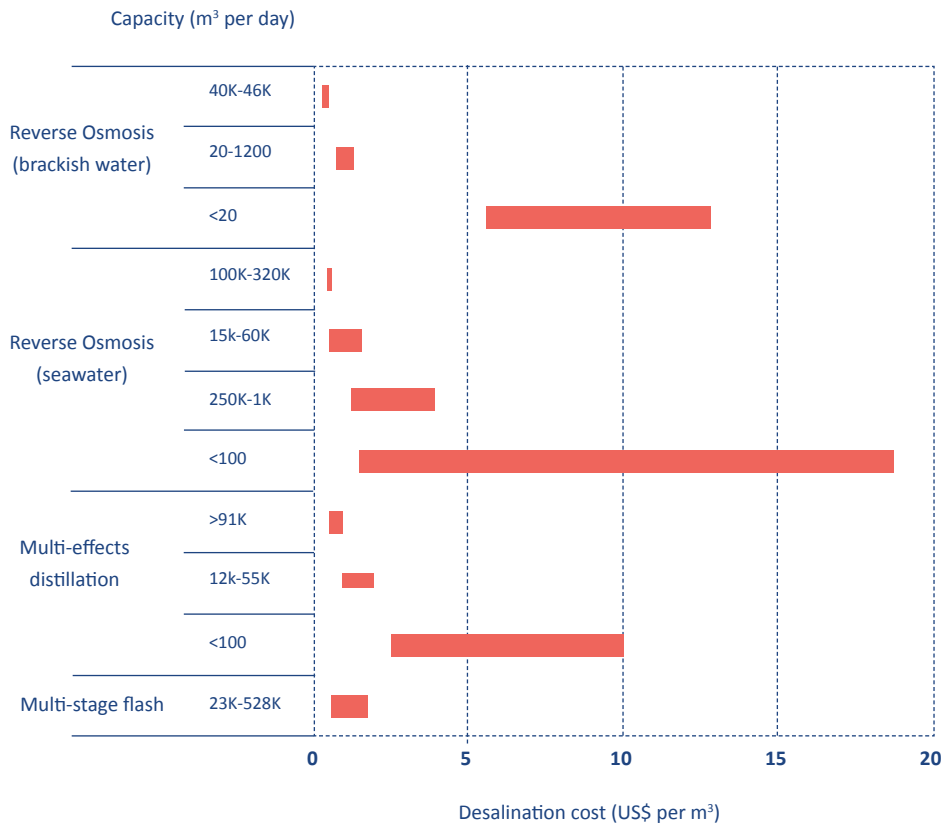


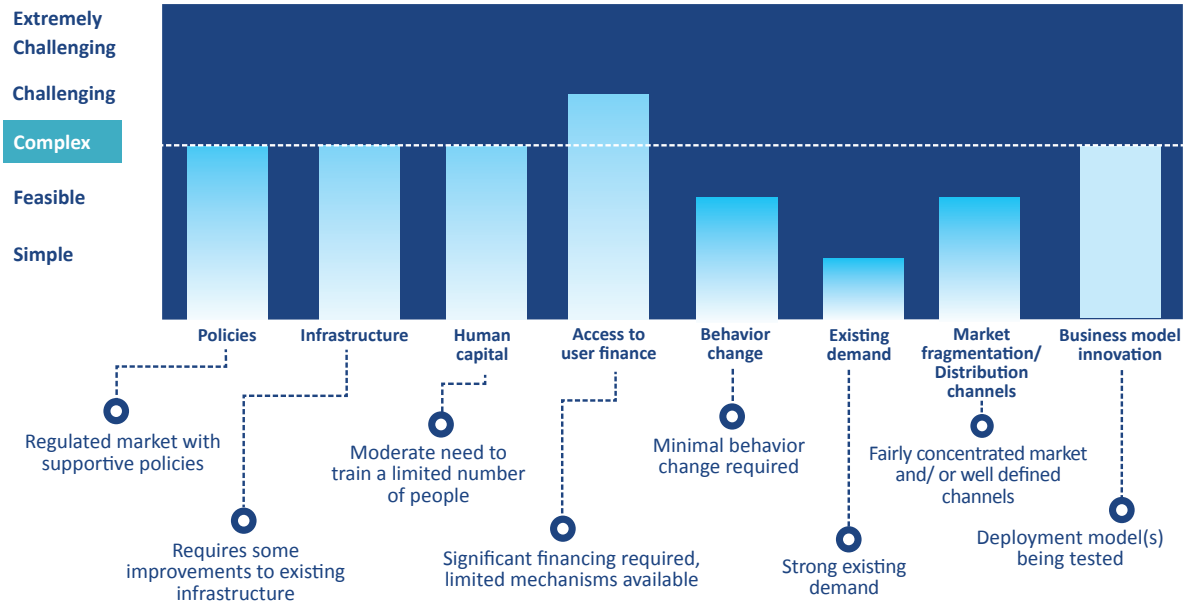
Exhibit 28: The cost of current desalination processes ($ per m^3 of fresh water) varies depending on the technology used and the scale of the process. The cost of energy inputs is also a significant variable. Conventional desalination technologies are too expensive and energy intensive to scale sufficiently 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 1 – Difficulty of deployment



Breakthrough 2

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

As described in detail elsewhere in this report, nutrient management is critical for optimal agricultural yields. Some areas, such as much of Africa, would benefit greatly from additional plant nutrients in the form of fertilizer. In areas where fertilizer is available, overuse can be significantly reduced. Crop yields respond very well with initial inputs of fertilizer, but as additional nutrients are supplied the marginal yield increase becomes smaller. Optimal results occur somewhere along that gradient, depending on the cost of fertilizer, land, and harvested crops. Furthermore, it is necessary to apply not just the right quantity of fertilizer, but also at the right time and right place, for optimal nutrient use (Roberts, 2007). The efficiency of using agricultural inputs such as fertilizer is low in conventional farming. It is estimated that overall efficiency of applied fertilizers is about 50% for nitrogen, less than 10% for phosphorous, and about 40% for potassium (Baligar, et al., 2001). The rest of the applied resource is unavailable to the plants and is wasted as runoff. The mismatched timing between availability of nitrogen and crop need for nitrogen is likely the single greatest contributor to excess nitrogen loss in annual cropping systems (Robertson & Vitousek, 2009). Ideally, nutrients should be applied in multiple small doses when plant demand for them is greatest.

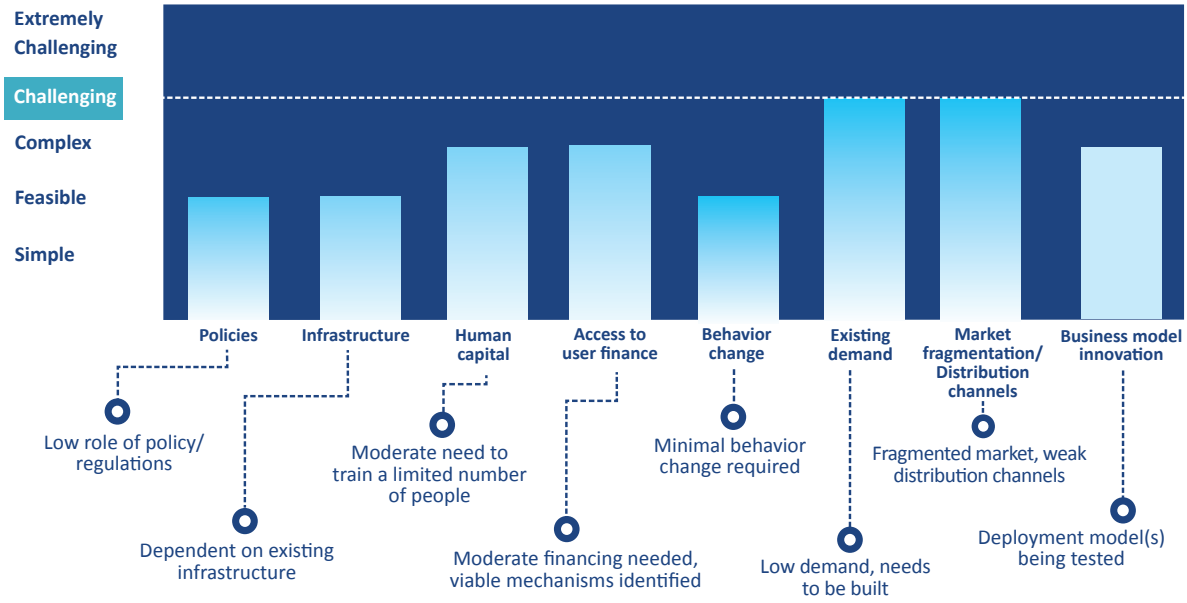
A low cost, robust, scalable technology is needed to precisely meter and distribute plant nutrients and/or other inputs. This would allow farmers to apply the right amounts of fertilizer, at the right time, to maximize economic returns and reduce nutrient loss.

Another major type of environmental damage caused by agriculture is overuse of water from non-renewable sources, as seen in South Asia. Different crops need different amounts of water, at different stages in the lifecycle. Application techniques also vary by crop; some crops need longer, infrequent deep watering, while others need more frequent watering with lower volumes per session).

The proposed breakthrough can be strongly leveraged by low cost soil nutrient analysis and low cost and efficient irrigation methods (identified as breakthroughs in other chapters). This would provide farmers with decision support tools that allow them to better predict crop nutrient requirements over time, avoid over-fertilization, and better schedule irrigation. This could be complemented with adjusted crop rotation patterns and additional biotic complexity to improve the plant community's ability to take up more of the available nutrients. By allowing better management of the timing, placement, and formulation of fertilizer in cropping systems, this would ensure that nutrients are available where and when needed by the plant. Economic outcomes for farmers would improve, because less fertilizer would be needed to achieve optimal yields. This would also protect watersheds and populations downstream from farm fields, by greatly reducing runoff.

If resources are devoted to accomplish this breakthrough, we expect that it will take less than 5 years to be market ready. Once ready, it will face a number of deployment challenges including a fragmented market (of farmers), access to finance for potential users, and training of farmers to install, use and maintain the technology. In addition, a significant amount of behavior change will be required, given the low demand for such inputs (in sub-Saharan Africa), and the limited incentives for sustainable use (in South Asia). Therefore, deployment will likely be CHALLENGING.

Breakthrough 2 – Difficulty of deployment



Breakthrough 3

A scalable method for sustainable integrated aquaculture

As shown earlier in **Exhibits 23** and **24**, the global catch of wild fish has remained roughly constant since the late 1980s, and yet the effort necessary to catch the same amount of fish has increased. The gap in fish supply has been made up by aquaculture, which has allowed increasing human consumption of fish. Aquaculture, the farming of aquatic organisms such as fish, crustaceans and aquatic plants, is currently the fastest growing animal food-producing sector. Within 30 years, between 1980 and 2010, global aquaculture production of fish has expanded by almost 12 times, at an average annual rate of 8.8% (FAO, 2012). In 2010, about 60 million metric tons of farmed food fish was produced globally. Asia accounted for almost 90% of world aquaculture production by volume in 2010; this was dominated by China, which produced more than 60% of global aquaculture volume. Other major producers are India, Vietnam, Indonesia and Bangladesh. Freshwater fish account for 56% of global aquaculture production, followed by mollusks (24%), crustaceans (10%), diadromous fish such as salmon (6%), and marine fish (3%).

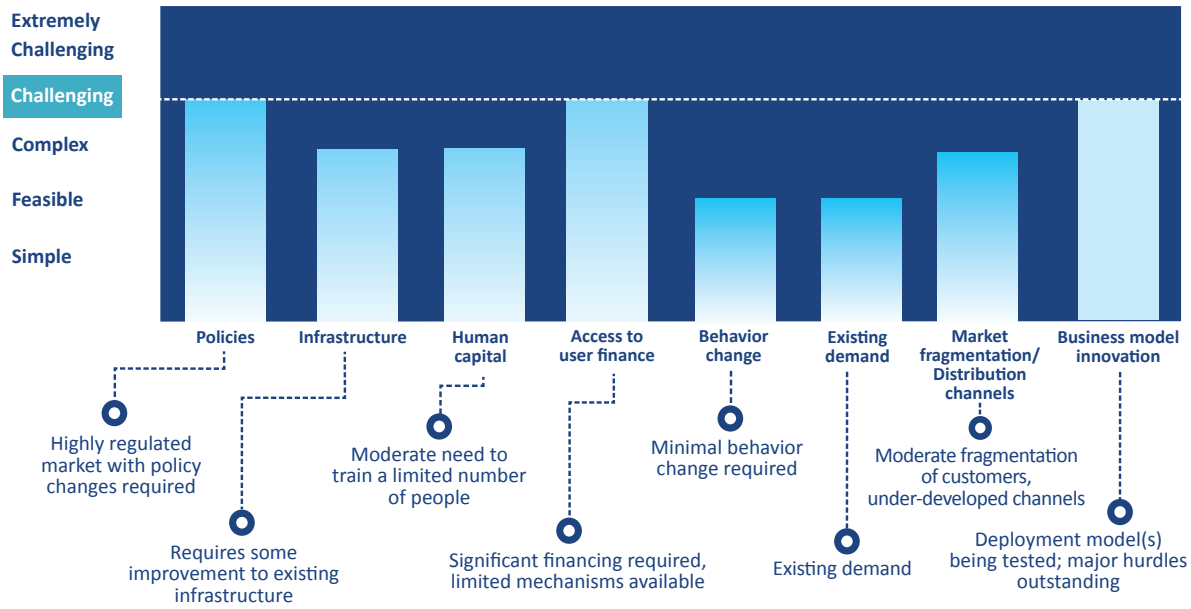
Despite the increasing importance of aquaculture to human food supply, current models of aquaculture production are largely unsustainable, and their ability to substantially scale up is questionable. Two-thirds of all farmed food fish production currently relies on artificial feeding. This share has increased from less than half in 1980. Artificial feeding requires prepared fish feed, and results in relatively faster growth rates compared to non-fed species. Fishmeal has been the preferred feed for aquaculture production, and is made by cooking, pressing, drying, and grinding fish or fish byproducts. Small pelagic species of fish, such as anchoveta, are typically caught and used for fishmeal production. A substantial portion, roughly one-third, of all wild-caught fish is used for non-food uses including fishmeal production. Fishmeal production peaked in 1994 at about 30 million tons (live weight equivalent) and has fluctuated since then, dropping to 15 million tons in 2010 due to reduced anchoveta catches (FAO, 2012). While fishmeal was once a cheap commodity used widely as animal feed, demand has increased strongly while supply has fluctuated (Olsen & Hasan, 2012). The current

reliance of aquaculture on fishmeal feeding is unscalable and untenable in the long term. Current aquaculture production is also vulnerable to disease and changing environmental conditions. Disease outbreaks in recent years have affected aquaculture in numerous countries around the globe, resulting in significant loss of production (FAO, 2012). In 2010 in China, aquaculture production suffered losses of 1.7 million metric tons caused by natural disasters, diseases, and pollution. Disease outbreaks almost eliminated marine shrimp farming production in Mozambique in 2011.

A breakthrough is needed to develop a scalable method of sustainable integrated aquaculture. About 71% of the earth's surface is covered by water, and a large share of sunlight received by the planet falls on water. A successful aquacultural technique that directly captures this sunlight through managed photosynthesis processes and converts the accumulated biomass into various food products, could greatly enhance global food security. An ecologically appropriate system would focus on integrating flows of energy, nutrients and biomass through the system. This may include integrating aquatic and terrestrial food production, for example, by using waste material from land as food and nutrients. Important issues with current generation aquaculture systems will need to be overcome. Advances are needed in hatchery systems, feeds and feed-delivery systems, and disease management (Godfray, et al., 2010). Other potential improvements may come from better stock selection, optimizing scale of production technologies, and the culture of a wider and synergistic range of species. Other important issues are disease resistance and tolerance to temperature and salinity variation, to enable a broader range of production options. To avoid unintended consequences, a scalable system would avoid discharge of organic effluents or disease treatment chemicals, and avoid being a source of diseases or genetic contamination among wild species.

Substantial research and development work is required for this breakthrough. We expect that it will take 5-10 years for this to be market ready, given adequate resources. Concurrent with technology development, appropriate business models must be developed to allow wide scale-up in developing regions. Deployment challenges include access to finance, and policies regarding land and water use. The difficulty of deployment is CHALLENGING.

Breakthrough 3 – Difficulty of deployment



Breakthrough 4

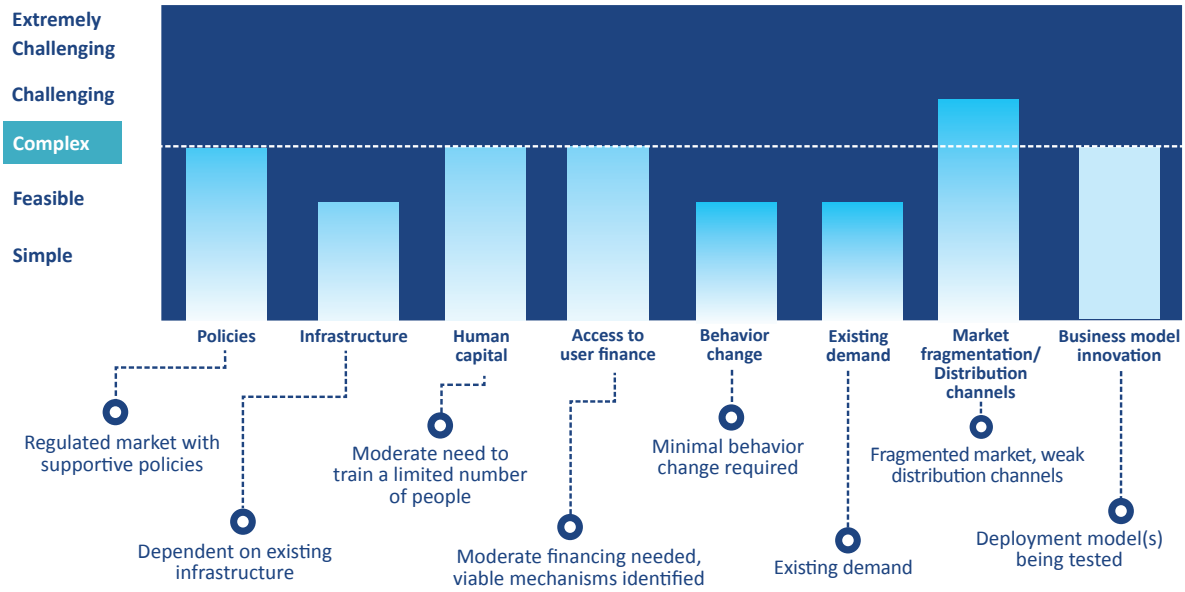
Affordable homes that are resilient to extreme weather events

Shelter is a fundamental human need, but a large segment of the world's population is either homeless or lives in very poor housing. More than 43 million people are refugees or displaced persons who have been forced to flee their homes and find shelter elsewhere (UNHCR, 2013). Over 800 million people reside in urban slums, often living in improvised dwellings with insecure land tenure (UN HABITAT, 2011). Long-term trends towards urbanization suggest that the urban population in less developed regions, currently less than 3 billion, will exceed 5 billion people by 2050 (UN, 2012). Creating adequate housing for these people will be challenging. Constructing housing with traditional building materials used in rural areas, such as grass and earth, cannot scale up sufficiently in urban areas with much higher population densities. The only option for poorer segments of the population is to create provisional shelter from found materials such as cardboard and plastic sheets. Life is precarious for these people due to their exposure to physical insecurity and unsanitary living conditions. A further challenge is changing temperature and precipitation patterns, which are expected to alter the habitability and safety of homes. The increased frequency and intensity of extreme weather events is expected to place homes and communities at greater risk (World Bank, 2012). A comprehensive and lasting solution to the problem of inadequate shelter requires concerted action in the political, economic, and technological spheres. In particular, technology-related advances are needed to develop robust, affordable, environmentally compatible housing materials and designs that can scale-up to meet global demand.

A breakthrough is needed to develop a functional, resilient, and very low cost housing system accessible to the global poor. Applied research is needed to identify appropriate types of building materials, and the scale and location of manufacturing facilities, in different social, geographical and cultural contexts. Trade-offs may exist between large-scale centralized production versus smaller-scale decentralized production closer to end users. Trade-offs may also exist between production automation and local employment opportunities. The potential use of locally-available raw materials suggests that various geographically specific solutions may exist. Beyond material properties, sensitive design work is required to produce robust, efficient, comfortable, and culturally-appropriate housing solutions that can scale to the extent needed. Potential integration of renewable energy technologies, e.g., photovoltaic or solar-thermal collectors, could allow synergies between human development goals.

While broad in scope, if resources were allocated to allow adequate research and development efforts, we expect that it will take 5 years for this breakthrough to be deployment ready. Significant deployment challenges include a fragmented building industry with multiple actors and components, access to finance for both producers and end users, and municipal and national policies supporting urban poor. The difficulty of deployment would be COMPLEX.

Breakthrough 4 – Difficulty of deployment



Breakthrough 5

A retrofitted filter to reduce particulate matter exhaust from old heavy-duty vehicles

Outdoor air pollution primarily comes from fuel combustion, mainly from mobile sources such as vehicles, and to a lesser extent from stationary sources such as power plants. Most air pollution in cities in developing countries is attributed to vehicle emissions (UNEP, 2014). This is due to the large number of older vehicles coupled with poor vehicle maintenance, inadequate infrastructure, and low fuel quality. Vehicles in developing countries are typically older than those in industrialized countries. The average age of the vehicle fleet in Tanzania is about 15 years, and in Kenya and Uganda it is about 13 years (UNEP, 2009). Some vehicles, especially heavy-duty diesel-powered trucks and buses, sometimes operate for over 40 years. These older vehicles are responsible for a high percentage of air pollution, despite their low fleet numbers. These vehicles continue to operate because of the high cost of new vehicles and the existence of maintenance and supply lines for older technology. Due to the inherently slow turnover of a vehicle fleet, and the limited economic means of many truck and bus owners to obtain cleaner replacements, existing heavy-duty fleets are likely to remain in operation for many years.

In the longer term, many improved technologies may enable cleaner urban transport systems. These include electric battery and fuel-cell vehicles, and prioritized rapid urban transit with light rail or other modes. These require an appropriate regulatory framework, and involve economic and behavioral trade-offs. Most sources of outdoor air pollution are beyond the control of individuals, and require action by cities, and perhaps national and international policymakers. Policies and investments are needed to support cleaner transport systems as a means to reduce urban outdoor air pollution. In the shorter term, cleaner fuels (with reduced sulfur and lead content) should be used, and official incentives toward renewal of the heavy-duty vehicle fleet could be imposed, such as inspection and maintenance regimes. However, many authorities are reluctant to force older heavy-duty vehicles off the road, because of the economic importance of the services they provide.

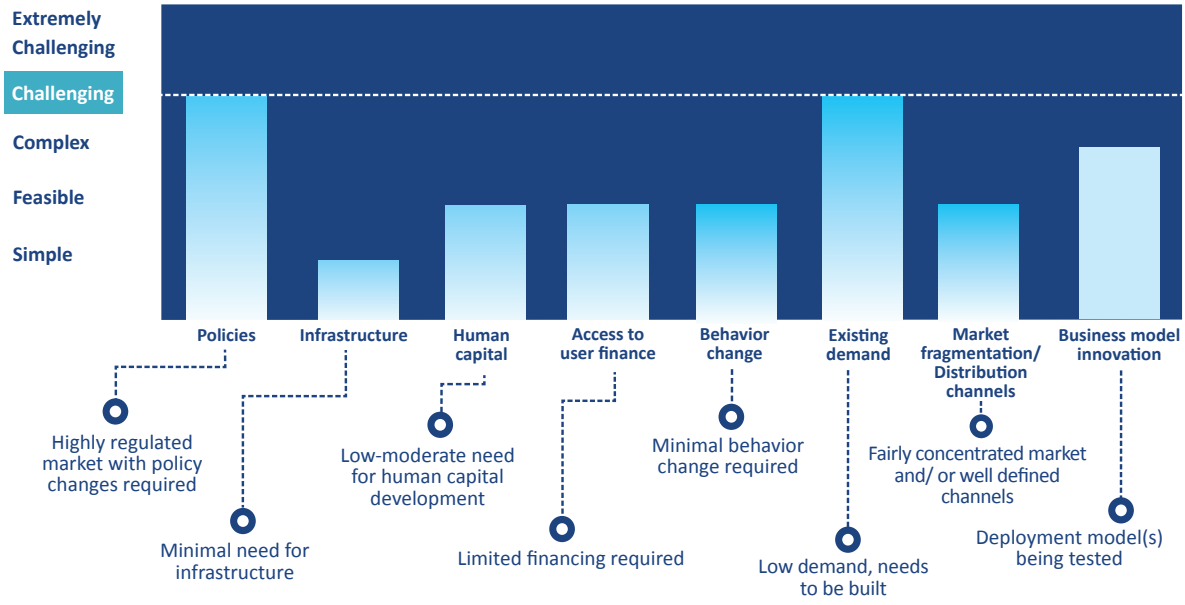
Urban air pollution could be significantly improved if these older vehicles could be easily and

inexpensively retrofitted with a technology to reduce particulate matter emission. A number of retrofit emission technologies currently exist for heavy-duty diesel vehicles, such as catalyzed diesel particulate filters, which remove 95% of particulate matter from exhaust but cost up to $10,000 per vehicle (UNEP, 2009). Current particle emission controls are too expensive for widespread adoption.

The answer lies in a robust, low cost technology that can be retrofitted onto old heavy-duty vehicles to reduce particulate matter exhaust. This engineered solution must be inexpensively produced—less than $1000—with simple retrofitting onto existing fleets of trucks and buses. Operation of the device must not impose significant load on the vehicle, in terms of exhaust back pressure or electricity demand. A successful breakthrough technology would use inexpensive and abundant materials (i.e. no expensive catalysts), would require only simple installation and maintenance, and would produce no harmful byproducts (such as NO_2).

Assuming adequate level of support to achieve this breakthrough, we expect that it would take less than 5 years to be market ready. A major deployment challenge is the lack of demand within the current market structure. Some level of policy incentive must be created to encourage vehicle owners to install such a device. The difficulty of deployment in this case would be CHANLLENGING.

Breakthrough 5 – Difficulty of deployment



Breakthrough 6

Low cost, distributed monitoring sensors to identify environmental toxins and their concentrations

Human health is threatened by exposure to a diverse range of environmental toxins such as heavy metals and persistent organic pollutants (POPs). Reducing exposure to environmental toxins is complex due to the variety of chemicals, exposure pathways, and time horizon of effects. Progress towards reducing exposure and improving health outcomes is hindered by the sparseness of data on the presence and concentrations of various toxins throughout the environment. A breakthrough is needed to develop a robust and affordable monitoring technology to identify health threats due to local exposure to

toxins, and make the data publicly available and comparable. This may lead to increased regulatory accountability, reduced emissions of toxic agents, improved knowledge of critical remediation sites, and decreased long-term health risks.

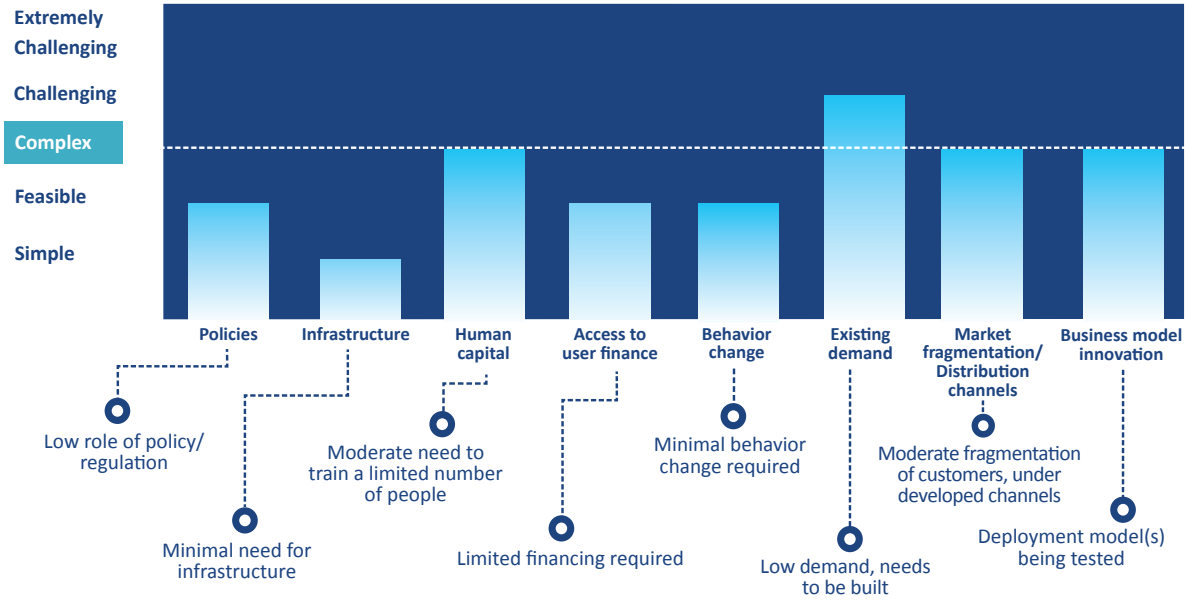
Current monitoring techniques to identify environmental toxins are inadequate. The analysis is typically done in a laboratory, meaning that samples must be collected and transported to a centralized location. After various pre-treatment steps, the samples are analyzed with techniques such as chromatography to determine their makeup. This process can take several days from sample collection to results, and can cost up to $1000 per sample (Ho, et al., 2005). Separate analyses are typically required for each toxic material under investigation. Conventional electrochemical sensors for detecting heavy metals must be used by skilled operators (Aragay, et al., 2011). These methods are not scalable to allow widespread identification of overall toxic health risks throughout the world, including in developing countries.

A new generation of environmental monitoring technology is needed to accurately and inexpensively identify the presence and concentrations of a range of toxic substances. Rather than bring the samples to the laboratory, this breakthrough would take the laboratory to the field and allow widespread in situ measurement of major environmental toxins in realtime. The technology would be flexible enough to analyze samples of water, soil, food or other media, after simple preparation steps. It would identify levels of inorganic materials (such as mercury, lead and arsenic), synthetic organic chemicals (such as dioxin, PCBs and some pesticides), and volatile organic compounds (such as benzene and formaldehyde). Where feasible, the use of appropriate biomarkers would allow determination of actual human health risk, rather than mere occurrence of a toxin in the environment (Lam, 2009). The initial cost of the hardware would be modest (<$500), perhaps taking the form of a plug-in sensor device that leverages the computing power of an existing mobile device. Cost of consumables would be low (~$1 per test), allowing ubiquitous monitoring even in remote sites in developing regions.

To maximize its effectiveness, this sensor technology would be integrated with a web-based platform to allow collection and comparison of environmental toxicity risks over time and place. The linking of improved toxin sensor technology with mobile communications technology would lead to a system for realtime, spatially-explicit, multi-agent exposure monitoring that would create an unprecedented understanding of global toxic health risks and pathways toward their reduction. Once identified, areas of high risk could be assessed in more detail, and critically contaminated sites in need of remediation can be flagged. On a broader and longer-term level, this monitoring technology may lead to advances in green chemistry and life-cycle product design to permanently eliminate the dangers of toxic exposure.

Progress is being made rapidly in the field of environmental monitoring, though there appears to be no focused effort towards the integrated technology we envision here. If sufficient resources were allocated to allow the necessary research and development efforts, we expect that it will take 5 years for this breakthrough to be ready for use. A significant deployment challenge is the lack of consumer demand for environmental monitoring. Therefore, deployment is likely to be COMPLEX.

Breakthrough 6 – Difficulty of deployment



REFERENCES

Aragay, G. et al., 2011. Recent trends in macro-, micro-, and nanomaterial-based tools and strategies for heavy metal detection. Chemical Reviews.

Baligar, V.C. et al., 2001. Nutrient use efficiency in plants. Communications in Soil Science and Plant Analysis.

Blacksmith Institute, 2013. The World's Worst 2013: The Top Ten Toxic Threats. [Online]. http://www.worstpolluted.org/2013-report.html

Boden, T., Marland, G & Andres, R., 2013. Global, Regional, and National Fossil-Fuel CO2 Emissions. Carbon Dioxide Information Analysis Center.

Branch, T. et al., 2013. Impacts of ocean acidification on marine seafood. Trends in Ecology & Evolution.

Chatham-Stephens, et al., 2013. Burden of disease from toxic waste sites in India, Indonesia, and the Philippines in 2010. Environmental Health Perspective.

Collen, B. et al., 2008. Monitoring change in vertebrate abundance: the Living Planet Index. Conservation Biology.

Cordell, D., Drangert, J. & White, S., 2009. The story of phosphorus: Global food security and food for thought. Global Environmental Change.

Daly, H.E., 2005. Economics in a full world. Scientific American.

Dasgupta, S. et al., 2009. The impact of sea level rise on developing countries: A comparative analysis. Climatic Change.

Dawson, C. & Hilton, J., 2011. Fertilizer availability in a resource-limited world: Production and recycling of nitrogen and phosphorus. Food Policy.

Diaz, R. & Rosenberg, R., 2008. Spreading dead zones and consequences for marine ecosystems. Science.

Dirzo, R., et al., 2014. Defaunation in the Anthropocene. Science.

D'Odorico, et al., 2013. Global desertification: Drivers and feedbacks. Advances in Water Resources.

Ericson, J., et al., 2006. Effective sea-level rise and deltas: Causes of change and human dimension implications. Global and Planetary Change.

Food and Agricultural Organization of the United Nations, 1997. Wildlife and Food Security in Africa. FAO Conservation Guide 33. [Online]. http://www.fao.org/docrep/w7540e/w7540e00.htm

Food and Agricultural Organization of the United Nations, 2010. Global Forest Resources Assessment. FAO Forestry Paper 163. [Online]. http://www.fao.org/forestry/fra/en/

Food and Agricultural Organization of the United Nations, 2012. The State of World Fisheries and Aquaculture. [Online]. http://www.fao.org/docrep/016/i2727e/i2727e00.htm

Food and Agricultural Organization of the United Nations, 2012. World Agriculture Towards 2030/2050: The 2012 Revision.

Food and Agriculture Organization, 2014. FAOSTAT: Live Animals. [Online]. http://faostat3.fao.org/

Fritzmann, C. et al., 2007. State-of-the-art of reverse osmosis desalination. Desalination.

Frye, C.A. et al., 2012. Endocrine disrupters: A review of some sources, effects, and mechanisms of actions on behaviour and neuroendocrine systems. Journal of Neuroendocrinology.

Global Alliance for Clean Cookstoves, 2011. Igniting Change: A Strategy for Universal Adoption of Clean Cookstoves and Fuels. [Online] http://www.cleancookstoves.org/resources/fact-sheets/Igniting_Change.pdf

Global Alliance on Health and Pollution, 2013. The Poisoned Poor: Toxic Chemical Exposures in Low- and Middle-Income Countries. http://www.gahp.net/new/wp-content/uploads/2013/09/GAHPPoisonedPoor_Report-Sept-2013.pdf

Gleason, T. et al., 2012. Water balance of global aquifers revealed by groundwater footprint. Nature.

Godfray, H. & Beddington, J. et al., 2010. Food security: The challenge of feeding 9 billion people. Science.

Green, P. et al., 2004. Pre-industrial and contemporary fluxes of nitrogen through rivers: A global assessment based on typology. Biogeochemistry.

Hall, C.A.S. et al., 2014. EROI of different fuels and the implications for society. Energy Policy.

Harmsen, J.H.M. et al., 2013. The impact of copper scarcity on the efficiency of 2050 global renewable energy scenarios. Energy.

Ho, C.K. et al., 2005. Overview of sensors and needs for environmental monitoring. Sensors 5.

Horton, B. et al., 2014. Expert assessment of sea-level rise by AD 2100 and AD 2300. Quaternary Science Reviews.
Houghton, R. et al., 2012. Carbon emissions from land use and land-cover change. Biogeosciences.
International Energy Agency, 2013. Key World Energy Statistics. [Online].
http://www.iea.org/publications/freepublications/publication/KeyWorld2014.pdf
Intergovernmental Panel on Climate Change, Working Group1, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report. [Online].
https://www.ipcc.ch/report/ar5/wg1/
Intergovernmental Panel on Climate Change, Working Group 2, 2014. Climate Change 2014: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report. [Online]. https://www.ipcc.ch/report/ar5/wg2/
Intergovernmental Panel on Climate Change), Working Group 3, 2014. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report. [Online].
https://www.ipcc.ch/report/ar5/wg3/
Kissinger, G. et al., 2012. Drivers of Deforestation and Forest Degradation: A Synthesis Report for REDD+ Policymakers. Lexeme Consulting.
Lal, R., 2009. Soil and food sufficiency: A review. Agronomy for Sustainable Development.
Lam, P., 2009. Use of biomarkers in environmental monitoring. Ocean & Coastal Management.
Lee, B. et al., 2012. Resources Futures: A Chatham House Report. Chatham House.
Lu, C., Warchol, K. & Callahan, R., 2014. Sub-lethal exposure to neonicotinoids impaired honey bees winterization before proceeding to colony collapse disorder. Bulletin of Insectology.
MacDonald, A.M. et al., 2012. Quantitative maps of groundwater resources in Africa. Environmental Research.
MEA, 2005. Millennium Ecosystem Assessment. [Online].
http://www.maweb.org/en/index.aspx
Meybeck, M., 2003. Global analysis of river systems: from Earth system controls to Anthropocene syndromes. Philosophical Transactions of the Royal Society.
Montgomery, D.R., 2007. Soil erosion and agricultural sustainability. PNAS.
Murphy, D., 2014. The implications of the declining energy return on investment of oil production. Philosophical Transactions of the Royal Society.
Norgate, T. et al., 2007. Assessing the environmental impact of metal production processes. Journal of Cleaner Production.
Olsen, R. & Hasan, M., 2012. A limited supply of fishmeal: Impact on future increases in global aquaculture production. Trends in Food Science & Technology.
Pimentel, D., 2006. Soil erosion: A food and environmental threat. Environment, Development and Sustainability.
Pimentel, D. & Burgess, M., 2013. Soil erosion threatens food production. Agriculture.
Pimm, S. et al., 2014. The biodiversity of species and their rates of extinction, distribution, and protection. Science.
Pongratz, J. et al. 2008. A reconstruction of global agricultural areas and land cover for the last millennium. Global Biogeochemical Cycles.
Prüss-Ustün, A. et al., 2011. Knowns and unknowns on burden of disease due to chemicals: A systematic review. Environmental Health.
Ramankutty, N., & Foley, J.A., 1999. Estimating historical changes in global land cover: Croplands from 1700 to 1992. Global Biogeochemical Cycles.
Roberts, T, 2007. Right product, right rate, right time and right place: The foundations of best management practices for fertilizer. Fertilizer Best Management Practices, IFIA, Paris.
Robertson, G. & Vitousek, P., 2009. Nitrogen in agriculture: Balancing the cost of an essential resource. Annual Review of Environment & Resources.
Sathaye, J. et al., 2011. Renewable energy in the context of sustainable development. Chapter 9 in: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. [Online].
http://srren.ipcc-wg3.de/report
Schultz, B., 2001. Irrigation, drainage and flood protection in a rapidly changing world. Irrigation & Drainage.
Sharma, B. M. et al., 2014. Environment and human exposure to persistent organic pollutants (POPs) in India: A systematic review of

recent and historical data. Environment International.
Siraj, A. S. et al., 2014. Altitudinal changes in malaria incidence in highlands of Ethiopia and Colombia. Science.
Smil, V., 2003. The Earth's Biosphere: Evolution, Dynamics, and Change. MIT Press.
Smith, B., 2011. General patterns of niche construction and the management of 'wild' plant and animal resources by small-scale pre-industrial societies. Philosophical Transactions of the Royal Society.
Smith, V., 2003. Eutrophication of freshwater and coastal marine ecosystems. Environmental Science & Pollution Research.
Subramanian, M., 2014. Deadly dinners. Nature.
United Nations Development Programme, 2009. Climate Change in the African Drylands: Options and Opportunities for Adaptation and Mitigation. [Online]. http://www.unccd.int/Lists/SiteDocumentLibrary/Publications/Climate%20Change%20Adaptation%20and%20Mitigation%20final.pdf
United Nations Environmental Programme, 2011. Decoupling Natural Resource Use and Environmental Impacts from Economic Growth. [Online]. http://www.unep.org/resourcepanel/Publications/Decoupling/tabid/56048/Default.aspx
United Nations Department of Economic and Social Affairs, 2012. World Urbanization Prospects: The 2011 Revision. [Online]. http://esa.un.org/unpd/wup/
United Nations Environmental Programme, 2009. Cleaning Up Urban Bus Fleets: With a Focus on Developing and Transition Countries. [Online]. http://www.unep.org/transport/pcfv/PDF/Retrofit.pdf
United Nations Environmental Programme, 2014. Urban Air Pollution. [Online]. http://www.unep.org/urban_environment/issues/urban_air.as
United Nations High Commissioner for Refugees, 2013. Populations of concern to UNHCR. [Online]. http://www.unhcr.org/
UN HABITAT, 2011. For a Better Urban Future. [Online].
http://www.unhabitat.org/
United States Geological Survey (USGS), 2014. Mineral Commodity Summary: Phosphate Rock. [Online].
http://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/
van der Sluijs, J. et al., 2014. Conclusions of the Worldwide Integrated Assessment on the risks of neonicotinoids and fipronil to biodiversity and ecosystem functioning. Environmental Science and Pollution Research.
van der Leeden, F., Troise, F. & Todd, D., 1990. The Water Encyclopedia. Lewis Publishers.
Vitousek, P., 1997. Human domination of Earth's ecosystems. Science.
Vörösmarty, C. J., & Sahagian, D., 2000. Anthropogenic disturbance of the terrestrial water cycle. BioScience.
Wada, Y. et al., 2012. Non-sustainable groundwater sustaining irrigation: A global assessment. Water Resources Research.
Watson, R. et al., 2013. Global marine yield halved as fishing intensity redoubles. Fish and Fisheries.
Werner, A. et al., 2013. Seawater intrusion processes, investigations and management: Recent advances and future challenges. Advances in Water Resources.
World Health Organisation, 2013. Lead poisoning and human health. [Online]. http://www.who.int/mediacentre/factsheets/fs379/en/
World Health Organisation. 2014. Burden of Disease from Household Air Pollution for 2012. [Online]. http://www.who.int/phe/health_topics/outdoorair/databases/FINAL_HAP_AAP_BoD_24March2014.pdf
Wilkinson, B., 2005. Humans as geologic agents: A deep-time perspective. Geology.
World Bank, 2012. Climate Change, Disaster Risk, and the Urban Poor. https://openknowledge.worldbank.org/handle/10986/6018
World Bank, 2012. Climate Change, Disaster Risk, and the Urban Poor. [Online]. http://go.worldbank.org/BPXUJ3ARJ0
World Bank, 2013. World Bank Open Data. [Online]. http://data.worldbank.org/indicator/all
WWF, 2014. Living Planet Report 2014: Species and Spaces, People and Places. [Online].
http://wwf.panda.org/about_our_earth/all_publications/living_planet_report/

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