From Scarcity to Security:

Managing Water for a Nutritious Food Future

Ertharin Cousin and A.G. Kawamura
Cochairs

Mark W. Rosegrant
Principal author

March 2019

Sponsored by

THE CHICAGO COUNCIL ON GLOBAL AFFAIRS

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Cover Photo: Rice fields on terraced mountain in Thailand. Credit: istock/af_istocker

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Foreword

The fundamental starting point for food and for life is water. Over the past century, our understanding of water management and agriculture enabled us to dramatically decrease hunger, malnutrition, and poverty. We have developed new knowledge and technology that allow us to harness this precious resource and manage life systems, creating unprecedented abundance for much of humankind. Despite this progress, some clear lessons emerge from the pages of history. First, inequity continues to coexist alongside abundance and prosperity—that is the sharp truth for 821 million food-insecure people and 150 million malnourished children in the year 2019. Second, as water scarcity intensifies, we must remember that without water, there is no food, and without food, there is no security.

This report, *From Scarcity to Security: Managing Water for a Nutritious Food Future*, examines the urgent challenges created by water scarcity and the impact on food security. More importantly, it offers an evidence-based pathway forward. Aligning clean water development with agricultural development can yield multiple benefits and is crucial to producing enough nutrient-rich food for a growing global population. The report reminds us that agriculture is fundamentally a response to the need of 7.8 billion people to eat every day, 365 days a year. Sustainably producing food and the act of eating food cannot be separated.

The areas of food, water, and energy have been significantly transformed over the past 100 years, and new solutions to age-old problems leap from impossibility to feasibility to reality. Technological advancement creates a sense that no problem is too big for our collective innovation potential as long as we invest appropriately in research and development. But we must not ignore or diminish the need for collective action to solve structural and often systemic problems. We also must not underestimate the urgency of the challenge. The cost of inaction can quickly destabilize communities when water and food are at stake. Good-quality water is projected to become short in supply, creating significant strain on food production systems already challenged by changing weather patterns. The increased demands from rapidly growing urban populations create an even more alarming scenario, where water scarcity leads to increasing levels of insecurity around the world.

With the clock ticking, now is the time to strengthen our national and global capacity to identify, assess, and address these critical issues in the face of known and unknown challenges. This report explores these conundrums and ultimately concludes that we know how to address the challenge. It offers a timely set of solutions and principles we must pursue if we hope to achieve a world of truly equitable opportunity and abundance. Whether through hindsight or foresight, the facts will require all of us to acknowledge that sustainable, resilient food systems maintain a peaceful prosperous civilization.

As cochairs for the report, we would like to thank our fellow task force members for their insight, guidance, and commitment throughout this process. Each individual brought their expertise to this effort, effectively collaborating to shape the report's consensus-based findings and recommendations. We would also like to thank Dr. Mark Rosegrant, lead author, who brought his great wealth of knowledge and thought leadership to develop the report's content, as well as the numerous subject matter experts who provided valuable input. Finally, we would like to express our appreciation to the Bill & Melinda Gates Foundation for its generous support, which made this report possible.

Ertharin Cousin and A.G. Kawamura

Cochairs, 2019 Global Food Security Report

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EXECUTIVE SUMMARY

Tanzania. Credit: Greg Garrett

The world is running out of clean, fresh water to feed—and nourish—a growing global population. Approximately 2.4 billion people—more than one-third of the global population—currently live in water-scarce regions, and projections indicate that by 2050 over one-half of the world's population could be at risk due to water stress. At the same time, global demand for water will continue to increase, driven by population growth, rising consumption, urbanization, and energy needs.

The stakes are high for protecting and effectively managing this vital resource, as increasing water scarcity threatens to undermine the progress that has been made on global food and nutrition security. Failure to treat water as a strategic, valuable, and limited resource will accelerate water insecurity, even for historically water-secure populations, and may threaten the economic and political security of nations, including the United States.

Agriculture depends on a reliable source of water, which will be severely tested by changing climate patterns, unpredictable water supplies, and increased demand for diverse, nutritious diets. Smallholder farmers, who largely rely on rainfall for their water supply, are at the greatest risk of total crop failure in the face of these challenges. Yet if they can manage water effectively, these farmers could be well positioned to produce the high-value crops needed to meet consumer demand and lift themselves out of poverty.

With the potential for severe economic, political, and humanitarian consequences, bold action and a commitment from all stakeholders is needed to address this critical issue. A combination of careful management strategies, technological innovations, investments, and policies around water are imperative to advance a sustainable, resilient global food system in the face of increasing water scarcity. In partnership with national governments, the private sector, and civil society, the United States must continue to lead in these efforts. With thoughtful planning and a commitment to sustainability, it will be possible to meet the water and food demands of current generations—while laying the groundwork for a nourishing food system in the future.

Competition for water

Water touches every aspect of our lives: food, health, environment, industry, and leisure. The competition for water resources is increasing between people and the natural environment as well as between cities and rural areas. Adding to this pressure, rising incomes are increasing demand for diverse, nutritious diets—including fruits, vegetables, legumes, nuts, healthy oils, and animal-source foods—which require more predictable supplies of water to produce at a time when changing climate patterns are making these supplies even less predictable.

By 2050 the global population is expected to increase to 9.8 billion, with 86 percent living in less developed countries and 70 percent living in rapidly growing urban areas. Farmers will need to improve their food production capacity to meet the needs of the growing populace, while expanding urban areas will also demand more water from a steadily decreasing supply. Global demand for water is generally projected to increase by 30 to 50 percent by 2050.

The fresh water necessary to produce crops and livestock accounts for the largest percentage of water usage among all sectors (71 percent), followed by industrial use (20 percent), and then domestic uses, including drinking water and sanitation (9 percent). Agriculture is expected to remain the largest user of freshwater resources in all regions in the foreseeable future, despite rapidly growing industrial and domestic demand. Competition for water among its many users is only going to intensify.

Threats to food and water security

Intensifying sectoral competition and water scarcity problems—combined with declining reliability and quality of water supplies and increased degradation of ecosystems—are major challenges to future food and nutrition security. Greater variability in precipitation and increases in temperature will disrupt agricultural production, further threatening water, food, and nutrition security. These impacts will likely be felt most intensely in regions with the least resources to adapt to it.

Agricultural production in low- to middle-income countries is more vulnerable to adverse weather shocks due to lower coping capacity. Expanding access to sustainable irrigation methods can increase both productivity and climate resilience: while only 20 percent of all cultivated land is irrigated, this land accounts for about 40 percent of agricultural production. But irrigation also has costs and environmental impact if poorly managed, including overuse, groundwater depletion, soil degradation, and increased vulnerability.

As nonagricultural demand for water increases, water will be increasingly transferred from use for irrigation to other uses in many regions. This will create the potential for conflict as well as the loss of farm production and income, especially among smallholder farmers. The reliability and quality of both agricultural and nonagricultural water supplies will decline without significant improvements in water governance, management strategies, policy, and investment.

Strategies to move the world toward greater water, food, and nutrition security

Successful, sustainable water management in agriculture is imperative to achieve the food and nutrition security goals of a rapidly growing, urbanizing world. Several existing strategies can be used to address the challenge posed by increasing water scarcity. These include:

1. improving overall water resource governance through institutions that are transparent, accountable, efficient, responsive, sustainable, and geographically contextualized;
2. allocating water more efficiently through water rights, regulations and quotas, water pricing, water trading, and subsidy reform;
3. improving crop and livestock productivity per unit of water and land through agricultural research, development, technology, extension, and financing;
4. shifting diets and diversifying agriculture to reduce the demand for water; and
5. increasing the supply of managed water and expanding the irrigated area through investment in infrastructure.

In addition, expanding urban and periurban agriculture and focusing on effective international agricultural trade policies, including trade in “virtual” water, will further support water productivity. Ensuring that these solutions reach smallholder farmers and that women and girls are empowered in the process is not only essential to increasing water productivity but will improve livelihoods and contribute to greater water, food, and nutrition security.

Continued US leadership and alignment of water and food security programs is needed to ensure future prosperity

At home, the United States has been at the forefront of addressing agricultural water management by empowering entrepreneurial farmers through technological advancements, research, and innovative implementation models. Globally, legislation like the Senator Paul Simon Water for the Poor Act of 2005 and the Senator Paul Simon Water for the World Act of 2014 are two examples of how US leadership is essential to catalyze innovations necessary to achieve global water, food, and nutrition security. While current efforts on both water and food assistance are to be commended, a multilayered and multidimensional approach is needed to reach the nation's stated foreign policy, national security, and humanitarian goals. Water challenges will only get worse if left unaddressed, and the incredible development gains of the past 50 years could be lost. Solutions to water scarcity and water access cannot be considered outside of the context of food production and the increasing food and nutritional needs of growing populations. As a global leader in both food security and water access efforts, the United States has the expertise, knowledge, and capability to ramp up solutions. It will take bold action and a commitment from all actors to work together toward the common goal of a water-secure and food-secure future.

This report lays out four key actions that can be taken by the US government—in partnership with national governments, the private sector, and civil society—to advance successful, sustainable water management in agriculture to achieve a nourishing food system for all.

Recommendation 1: Strengthen the environment for cooperation and communication between water development and food and nutrition security

- Create a formal, integrated, and multilayered process for communication and collaboration between implementers of the Global Water Strategy and the Global Food Security Strategy to improve whole-of-government efforts to expand sustainable agricultural development and water resource management simultaneously.
- Congress should permanently authorize the Global Food Security Act, in alignment with the authorization for the Water for the World Act, to give projects, grants, and research adequate time to come to fruition.
- Congress should request a comprehensive report from the administration on the impact of food and water insecurity on regional stability.
- Bolster the new Bureau for Resiliency and Food Security by increasing interdisciplinary efforts and requiring increased accountability and engagement.

Recommendation 2: Ease the challenges that hinder greater private-sector investment to expand sustainable water development for food and nutrition security

- Assess the use of artificial intelligence and expansion of the National Agriculture Imagery Program (NAIP) at USDA for solving major development issues such as water resource scarcity.
- As a part of the restructuring of the bureau, USAID should establish an interagency policy working group to formalize and coordinate a holistic approach that will make development finance tools available to local private-sector investors, from small businesses and farmers to multinational corporations.
- Congress should ensure the new US International Development Finance Corporation includes opportunities for short- and long-term investment in agriculture and water.
- The administration should support the development of an enabling environment for business through a standardization of regulations and support for rule of law.
- The administration should pilot collaborations with the private sector and civil society to design programs or innovations that build demand for nutritious diets.
- NOAA should continue to maintain current investments in digital mapping of water resources, and incentives should be introduced to increase sharing of critical data by commercial entities on this common platform.

Recommendation 3: Leverage US expertise and influence to improve water resource governance and sustainability

- In the face of rising investment from countries like China, the administration should employ all foreign policy tools available, with emphasis on technical assistance for water sustainability, to maintain US global leadership in strategically important regions.
- The administration should include education on water resource management at the state and national level as part of fellowships and academic exchanges.
- The administration should support active engagement with traditional multinational development institutions engaged in water management and development.

Recommendation 4: Strengthen support for agricultural R&D and interdisciplinary research at the nexus of water, food, and nutrition.

- The administration should coordinate and Congress should fund a significant challenge fund for water scarcity issues that encourages private-sector innovation.
- Support the creation of a USAID innovation lab at a land-grant university or expand existing innovation lab efforts to advance uptake and improvement of wastewater management and reuse for agriculture.
- Advance innovative new agricultural approaches to combat the impacts of a changing climate through targeted research.
- The administration should affirm and support greater research and development opportunities that are interdisciplinary and target the nexus of food, water, and nutrition.

African girl takes water from the river, Ethiopia. Credit: istock/hadynyah

INTRODUCTION

Akosua Nhyira Mireko, Ghana. Credit: Jennifer Winter

The world is running out of clean, fresh water to feed—and nourish—a growing global population, ensure sustainable human development, and maintain the health of our planet. Approximately 2.4 billion people—more than one-third of the global population—currently live in water-scarce regions, and projections indicate that by 2050 over one-half of the world's population could be at risk due to water stress.[1] Competition for water among its many users—including food and agriculture production, the environment, energy, industry, and individual consumers—is going to intensify. Increased competition over highly stressed, shared water sources, combined with weak governance and increased weather variability, can lead to migration and even violence. Failure to treat water as a strategic, valuable, and limited resource will accelerate water insecurity, even for historically water-secure populations, and may threaten the economic and political security of nations, including the United States.

Sufficient water for agriculture is at risk

Growing water scarcity, along with increasing degradation of ecosystems and poor water quality, is a major challenge to future food and nutrition security. The fresh water necessary to produce crops and livestock accounts for the largest percentage of water usage among all sectors (71 percent), followed by industrial use (20 percent) and then domestic uses, including drinking water and sanitation (9 percent).[2] Agriculture depends on a reliable source of water, which will be severely tested by expected changes in demand. By 2050 the global population is expected to increase to 9.8 billion, with 86 percent living in less-developed countries and 70 percent in rapidly growing urban areas.[3]

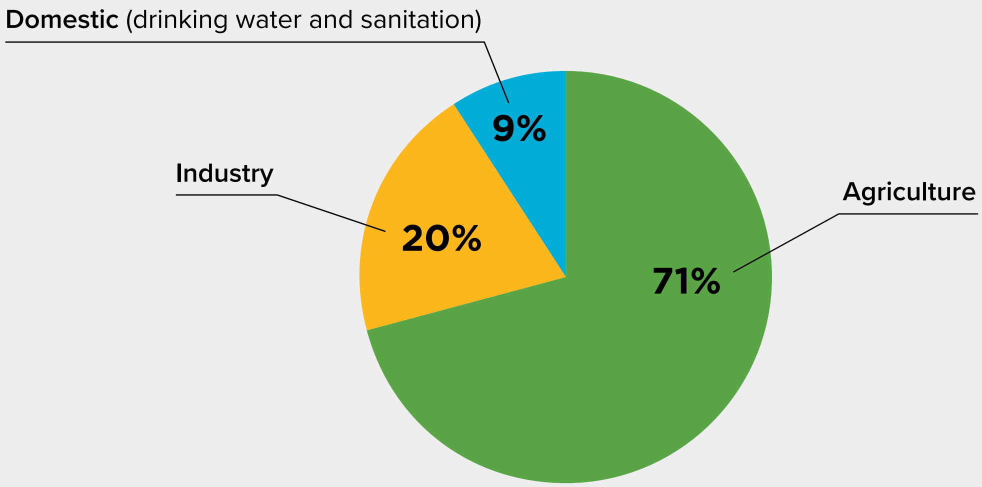
Failure to treat water as a strategic, valuable, and limited resource will accelerate water insecurity, even for historically water-secure populations.

Farmers will need water to improve their food production capacity to meet growing demand, while expanding urban populations will also demand more from a steadily decreasing supply. Climate change further threatens water for agriculture, as greater variability in precipitation and increases in temperature make supplies increasingly unreliable. Water challenges will likely be felt most intensely in regions with the least resources to adapt to it. Smallholder farmers, who largely rely on rainfall for their water supply, are at the greatest risk of total crop failure in the face of increased climate variability.

Adding to this pressure, rising incomes are increasing demand for diverse, nutritious diets—including fruits, vegetables, legumes, nuts, healthy oils, and animal-source foods—which tend to be more water-intensive to produce and require more predictable water supplies at a time when changing climate patterns are making these supplies even less predictable. Meanwhile, water and sanitation services are inadequate for billions of people, threatening health and nutritional status. More than 80 percent of wastewater is discharged without adequate treatment or reuse, threatening supplies for agriculture and other sectors.[4]

Despite rapidly growing industrial and domestic demand, agriculture is expected to remain the largest user of freshwater resources in all regions for the foreseeable future.

Figure 1 – Water usage by sector



Source: Wada et al. 2011

As nonagricultural demand for water increases, water will be increasingly transferred from irrigation to other uses in many regions. This will create the potential for conflict as well as the loss of farm production and income.

At the same time, subsidies and distorted policy incentives are encouraging conflicting water uses. Aquifers are being depleted of groundwater, and the reliability and quality of both agricultural and nonagricultural water supplies will decline without significant improvements in water governance, management strategies, policy, and investment. Although the domestic and industrial sectors use far less water than agriculture, the growth in water consumption in these sectors has been rapid. Globally, domestic and industrial water withdrawal, defined as the total volume removed from a surface water or groundwater source, quadrupled between 1950 and 1995, compared with agricultural water withdrawal, which slightly more than doubled.[5]

Water, food, and nutrition security depend on effective water management

The stakes are high for effectively developing and managing water because of its fundamental importance to food and nutrition security. Water, when reliably available to farmers throughout the year, increases the volume and diversity of food that can be produced. It allows for the greater production of micronutrient-rich foods such as fruits, vegetables, animal-source foods, and dry season crops. Expanding access to sustainable irrigation methods can increase both productivity and climate resilience: while only 20 percent of all cultivated land is irrigated, this land accounts for about 40 percent of agricultural production.[6] Irrigation contributes to increased food production, farm income, and improved resilience against weather variability.

If smallholder farmers can manage water effectively, these farmers could be well positioned—through their proximity to growing markets and potential competitiveness—to produce the high-value crops needed to meet consumer demand and lift themselves out of poverty. Scaling up sustainable irrigation methods can help smallholder farmers build resilience and protect against variable rainfall patterns, providing the control and access to water resources that are often out of reach or increasingly unpredictable.

But irrigation also has costs and an environmental impact if poorly managed, including groundwater depletion and soil degradation. Without thoughtful planning and a commitment to sustainability, water may be overused and contribute to increased vulnerability and instability within food systems and communities. Ensuring the affordability of improved irrigation technologies is also critical for smallholder farmers, and especially women, who disproportionately bear the physical burden of cheap forms of irrigation, like hand watering, which are the most labor-intensive.[7] Reducing these labor burdens would free up their time for more productive uses and contribute to poverty reduction. A combination of careful management strategies, technological innovations, investments, and policies is required to ensure that water demand pressures today do not undermine food security, human health, and peace of future generations but spark the innovations and investments necessary to lay the groundwork for a nourishing food system for all.

An Egyptian farmer holds a hose to pump water from a well to irrigate his land. Credit: REUTERS/Mohamed Abd El Ghany

Cooperation between the agriculture and the water, sanitation, and hygiene (WASH) sectors is vital

The WASH sector is also critically important for achieving food and nutrition security. The burden of disease from unsafe water, coupled with time spent collecting water, is a significant drag on the economies of low- and middle-income countries (LMICs). Women and girls are disproportionately affected, since they often bear primary responsibility for providing drinking water and sanitation for their families and for taking care of the sick. The consequences of their time and labor burdens are often borne out in girls' access to education and women's livelihood opportunities. Distant water access points can have negative impacts on health. Analysis of the Demographic and Health Surveys found that a 15-minute decrease in one-way walk time to the water point was associated with a 41 percent reduction in the prevalence of diarrhea, an 11 percent reduction in child mortality, and improvement in child nutritional status.[8]

In many LMICs, water facilities are multiuse, providing for both irrigation and for WASH needs. This influences the overall water environment in and around the household, potentially reducing exposure to fecal contamination and the risk of infectious diseases. Access to safe water is associated with reduced incidence of enteric infection and reduced incidence of disease in pregnant women, lowering maternal and neonatal mortality rates. Access to safe water can also reduce stunting among children under the age of five and improve nutrition in the first 1,000 days of life.[9]

A woman fetches water in a flood-affected village in Sonitpur district in the northeastern state of Assam, India. Credit: REUTERS/Anuwar Hazarika

Given that water quality issues cut across agriculture and WASH, conducting interdisciplinary research and integrating policies between these sectors opens vital new pathways for health and nutrition. This includes improvements in the proximity and cleanliness of water sources and in technologies for water extraction to support women's empowerment through time savings and improved health conditions. It also includes design and research on nutrition-sensitive irrigation programs and the integration of behavior change communication in agricultural water efforts.[10] Moreover, access to sanitation for women and

Successful, sustainable water management in agriculture is imperative to achieve the food and nutrition security goals of a rapidly growing, urbanizing world.

girls is particularly crucial for preserving basic dignity and improving access to education and economic opportunities.[11] A stronger emphasis on the need for policy coherence and alignment—as well as adequate water resource management between multiple users in a community—is crucial to achieve the goals of both the agriculture and WASH sectors.

Several strategies are essential to moving the world toward greater water, food, and nutrition security

Successful, sustainable water management in agriculture is imperative to achieve the food and nutrition security goals of a rapidly growing, urbanizing world. Several strategies can be used to address the challenges posed by increasing water scarcity. These include:

1. improving overall water resource governance through institutions that are transparent, accountable, efficient, responsive, sustainable, and geographically contextualized;
2. allocating water more efficiently through water rights, regulations and quotas, water pricing, water trading, and subsidy reform;
3. improving crop and livestock productivity per unit of water and land through agricultural research, development, technology, extension, and financing;
4. shifting diets and diversifying agriculture to reduce the demand for water; and
5. increasing the supply of managed water and expanding the irrigated area through investment in infrastructure.

In addition, expanding urban and periurban agriculture and focusing on effective international agricultural trade policies, including trade in "virtual" water, will further support water productivity. Ensuring that these solutions reach smallholder farmers and that women and girls are empowered in the process is not only essential to increasing water productivity, but will improve livelihoods and contribute to greater water, food, and nutrition security.

PART I

A man walks near a dry field, West Java, Indonesia. REUTERS/Willy Kurniawan

THE THREAT OF WATER SCARCITY

Rising global population, income, and urbanization are causing strong growth in food and water demand and intensified competition for water. More than one-third of the global population—approximately 2.4 billion people—already live in water-scarce regions, or river basins with annual water withdrawals greater than 40 percent of total renewable water. Twenty-two percent of the world's gross domestic product (GDP), US$9.4 trillion, is produced in these water-short areas, including 39 percent of cereal production.

In the absence of focused efforts to develop or increase the supplies of accessible, high-quality water, just over half (52 percent) of the global population—or 4.8 billion people—and 45 percent of total GDP (US$63 trillion) are projected to be at risk due to water stress by 2050. This includes 49 percent of global grain production.[12]

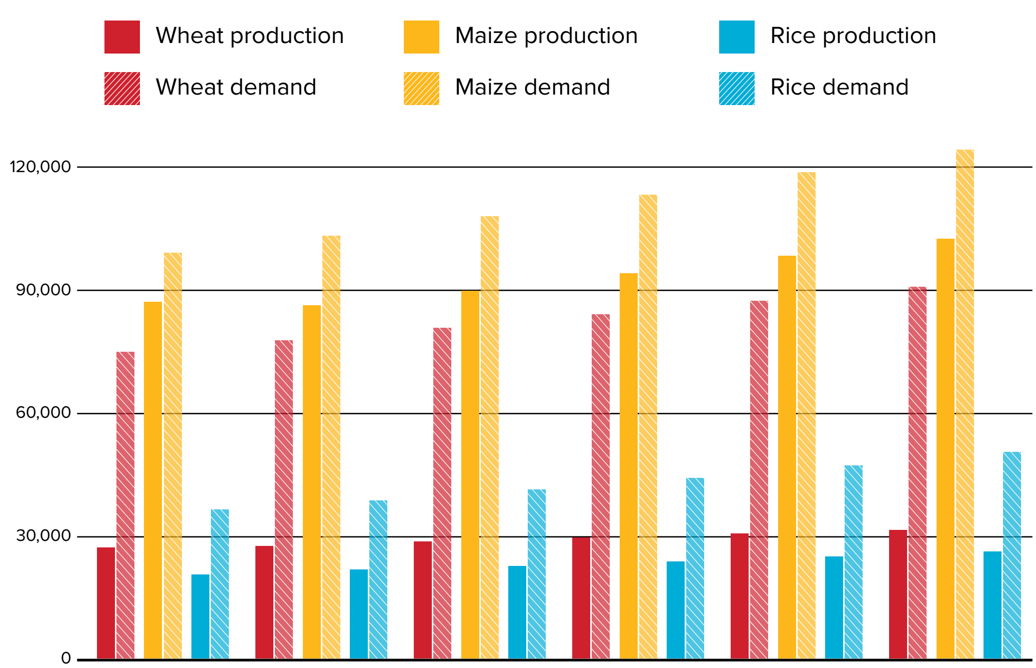
Food production and water demand are growing amid increasing water scarcity

Global demand for water is generally projected to increase by 30 to 50 percent by 2050.[13] Agricultural demand for water is a significant part of this, driven by growing populations and demand for food and agricultural products. The International Food Policy Research Institute (IFPRI) projects that global production of cereals will increase by 37 percent between 2010 and 2050, meat by 66 percent, and fruits and vegetables by 85 percent.[14] The projected rapid growth in livestock production is contributing to increased agricultural water demand, particularly for growing crops such as maize, other coarse grains, and soybeans to feed livestock and fish.

Accounting for constraints in future water supplies, it is projected that agricultural water consumption will grow 21 percent by 2050. A 29 percent increase in total *consumptive use* of water across all sectors is expected between 2005 and 2050.[15] Total water withdrawals are projected to increase by 45 percent from 3,800 km^3 in 2000 to 5,500 km^3 in 2050, falling thereafter to 5,000 km^3 by 2100.[16]

Agricultural and urban claims on water can create competition. A quarter of cities, with a total of US$4.2 trillion in economic activity, are classified as water-stressed. In these

Figure 2 – Projected gap between demand and production of key crops (2017 to 2027)



Source: OECD Stat - FAO Agricultural Outlook cities, 150 million people live with perennial water shortages, defined as having less than 100 liters per person per day of sustainable surface water or groundwater.[17] In the coming years, population growth and continuing urbanization will bring a 50 to 70 percent rise in the demand for water in cities.[18] Industrial and domestic consumption of water is projected to increase 61 percent between 2005 and 2030, doubling by 2050.[19]

Climate change and variability further threaten water resources and agricultural production

Historically, most human infrastructure—urban and agricultural alike—is built near reliable water resources. Climate change threatens to reduce this reliability and change the geography of dependable water resources. According to Intergovernmental Panel on Climate Change (IPCC), global average temperatures have risen by roughly 0.13°C per decade since 1950, and a faster pace of about 0.2°C per decade over the next two to three decades is expected. Substantial changes in mean annual stream flows, the seasonal distribution of flows, melting of snowpack, and the increased probability of extreme high- or low-flow conditions are likely. Specifically, climate change impacts on water resources include:

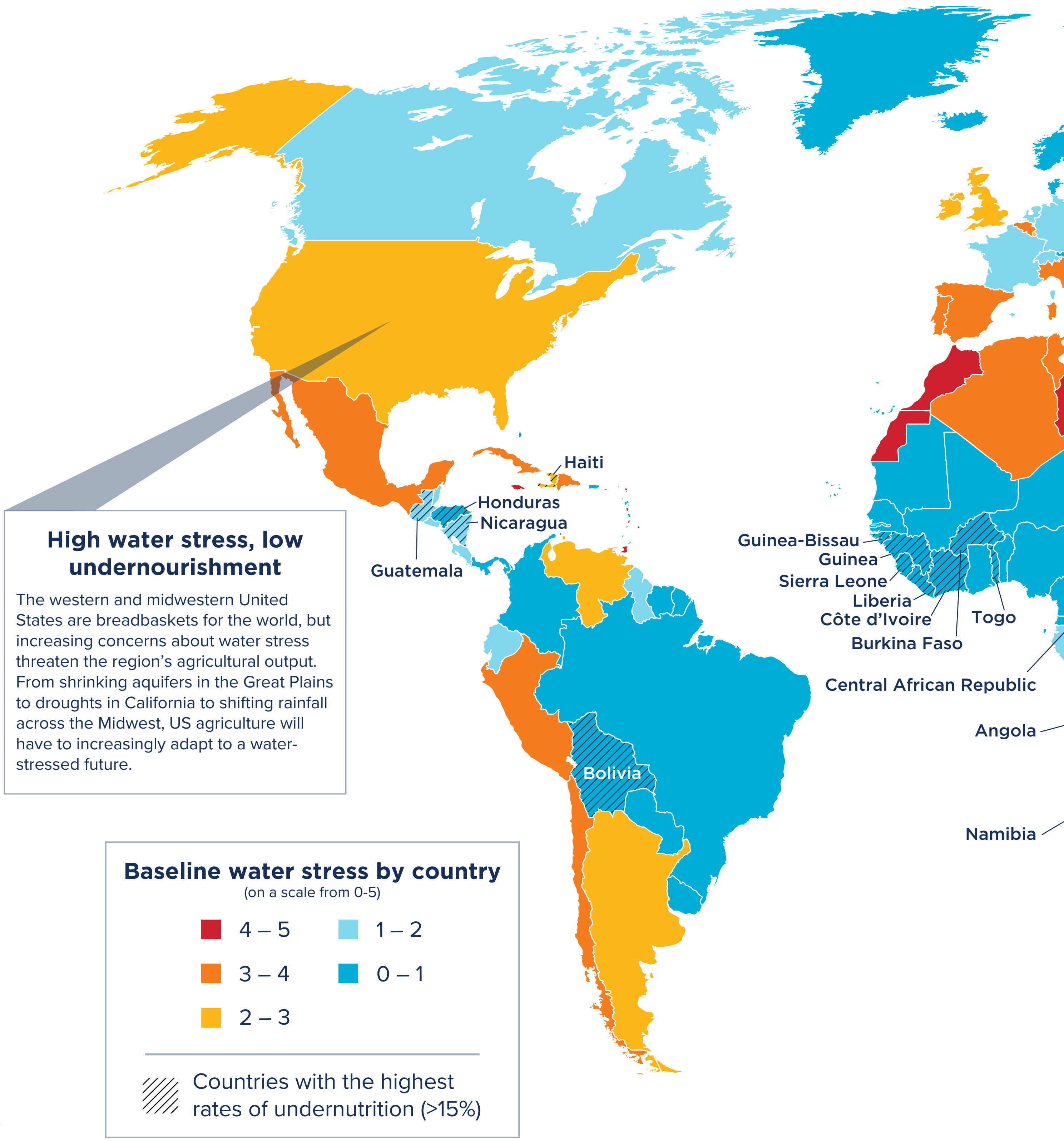
Climate change is projected to reduce food production growth and slow progress on food and nutrition security.

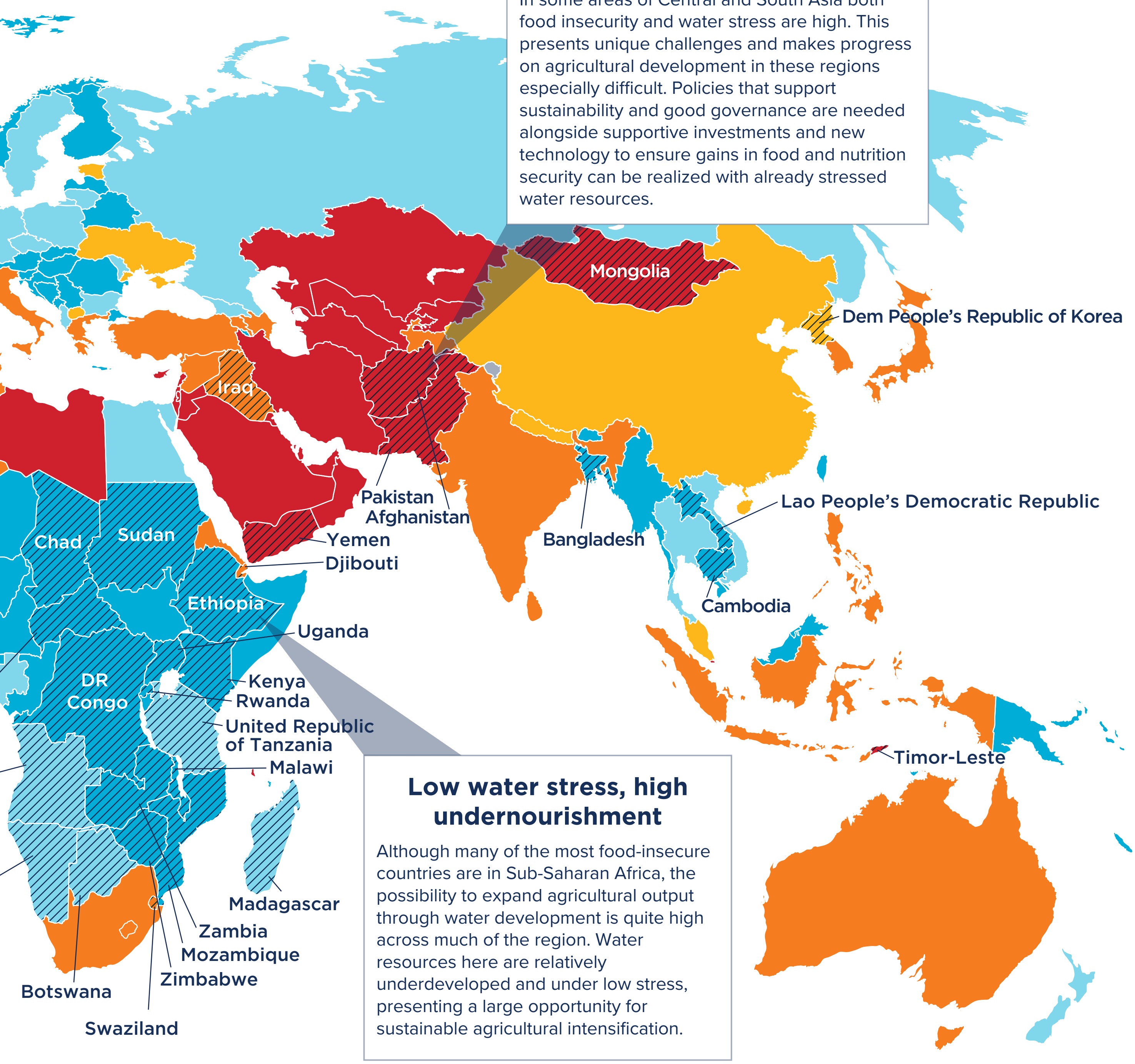
- changes in the timing of water availability due to changes in rainfall and snowpack and diminishing glaciers;
- changes in the timing and intensity of water demands due to increased temperatures, evaporation, and changes in surface water availability and groundwater storage;
- an increased number and intensity of extreme climatic events (droughts and floods);
- changes in water quality; and
- sea-level rise, which will lead to inundation and saltwater intrusion in existing irrigated areas.

Increased temperatures will also influence the length of crop-growing seasons. In temperate areas, growing seasons are likely to lengthen with climate change. However, warmer weather helps pests survive longer, which can increase damage to crops. Rising temperatures are expected to contribute to a shift in which areas are most agriculturally productive and what crops grow there. In tropical areas, rising temperatures will result in reductions in suitable plant-growing days, and this will be most pronounced in countries that are among the poorest and most highly dependent on plant-related goods and services.[20]

While altered patterns of precipitation are certain, the ultimate outcomes of climate change and its effect on water availability and variability are not. Unknowns include the locations where impacts will be the most significant, the degree of change in amounts of precipitation and their intensity, and whether changes will occur within the next five years or over multiple decades. Shifting precipitation patterns and warming temperatures

Figure 3 – Prevalence of hunger and water stress





High water stress, high undernourishment

In some areas of Central and South Asia both food insecurity and water stress are high. This presents unique challenges and makes progress on agricultural development in these regions especially difficult. Policies that support sustainability and good governance are needed alongside supportive investments and new technology to ensure gains in food and nutrition security can be realized with already stressed water resources.

Low water stress, high undernourishment

Although many of the most food-insecure countries are in Sub-Saharan Africa, the possibility to expand agricultural output through water development is quite high across much of the region. Water resources here are relatively underdeveloped and under low stress, presenting a large opportunity for sustainable agricultural intensification.

Source: FAOSTAT 2018; World Resources Institute 2013 could increase water scarcity in some regions, while increased soil moisture could expand opportunities for agricultural production in others.[21]

Despite improvements in water resources in some areas, climate change will make it more challenging to manage the world's water because it affects the entire water cycle.[22] Warming speeds up the hydrological cycle, increasing precipitation. In some areas, flooding and inundation of croplands could reduce crop yields and increase the need for drainage. Increased evaporation will make drought more prevalent in many regions of the world by the middle of the 21st century.[23] Even with significant projected increases in agricultural production growth, dependence on food imports will increase in regions with large populations such as parts of Africa, the Middle East, and Central America that are already net

Hunger is expected to rise about 10 to 20 percent by 2050 due to climate change relative to a no-climate-change scenario.

food importers. These likely increases in imports highlight the importance of a fair and open agricultural trade regime capable of providing the needed imports.

Other areas where average annual runoff is expected to decline sharply include major agricultural-producing regions such as much of Europe and parts of South America, North America, and Australia. The average number of consecutive dry days could increase by up to 20 in many of these regions. Moreover, the intensity of precipitation is expected to rise in almost all areas, regardless of whether total precipitation is decreasing or increasing. Drainage of excess rainfall quickly from croplands will be critical to prevent reduction of crop yields.[24]

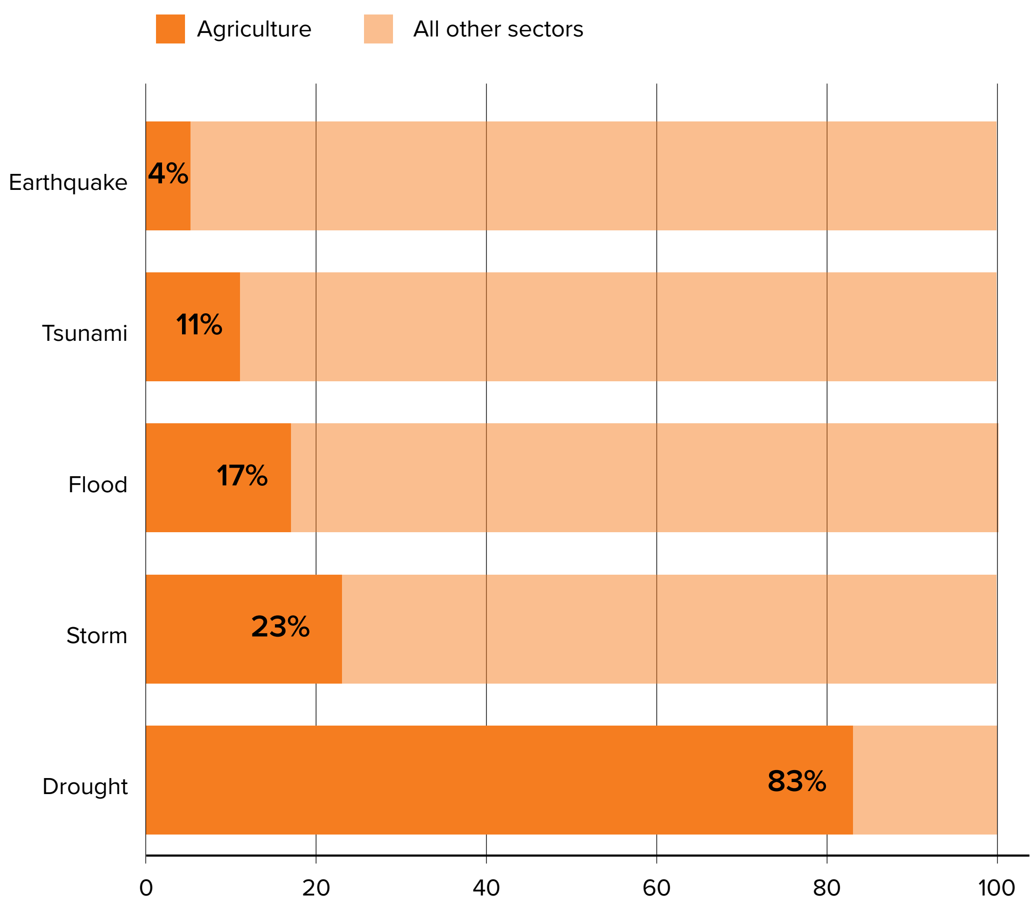
With its impact on both water and temperature, climate change is projected to reduce food production growth and slow progress on food and nutrition security. Modeling shows that climate is already affecting production. For instance, global maize and wheat production declined by 3.8 and 5.5 percent, respectively, from 1980 to 2008 relative to a no–climate change scenario. The estimated difference in crop production excluding and including carbon dioxide fertilization translates into average commodity price increases of 18.9 and 6.4 percent, respectively.[25]

Results from a climate model comparison exercise using 10 of the leading global economic models suggest that conditions will worsen under climate change. These models account for the initial biophysical impacts on crop yields, but they also account for the subsequent economic responses that tend to dampen the initial crop-yield impact. While there is a great deal of variation across models, the average impact in 2050 on yields across models and scenarios compared to a reference scenario that assumes no climate change is -13 percent for coarse grains (mainly maize), -9 percent for rice, and -10 percent for wheat. Prices are projected to increase on average by 12 percent for maize, 14 percent for rice, and 16 percent for wheat.[26] An earlier review of economic models showed slightly higher increases in food prices, ranging from 10 to 30 percent by 2050, with a median estimate of around 20 percent.[27] Hunger is expected to rise about 10 to 20 percent by 2050 due to climate change relative to a no–climate change scenario. Expected shifts in available water resources via changing precipitation and runoff are an important cause of the yield losses.

Extreme hydroclimatic events such as floods and droughts—caused by climate change and naturally occurring water or hydrologic variability—damage crops, hurt livelihoods, and adversely affect economic growth.[28] Owing to agriculture's strong dependence on climate and water resources, management of water is a key concern for food production. Extreme weather events can lead to cascading food system shocks and are responsible for lower long-term production potential. Globally, droughts and extreme heat alone reduced national cereal production by 9 to 10 percent between 1964 and 2007.[29] Moreover, agricultural production in LMICs is more vulnerable to adverse weather shocks due to the region's lower coping capacity. In recent years, almost one-fourth of weather-related damage has been in the agricultural sector in LMICs.[30] Existing and growing uncertainties regarding precipitation are adversely affecting investments in agricultural productivity.[31]

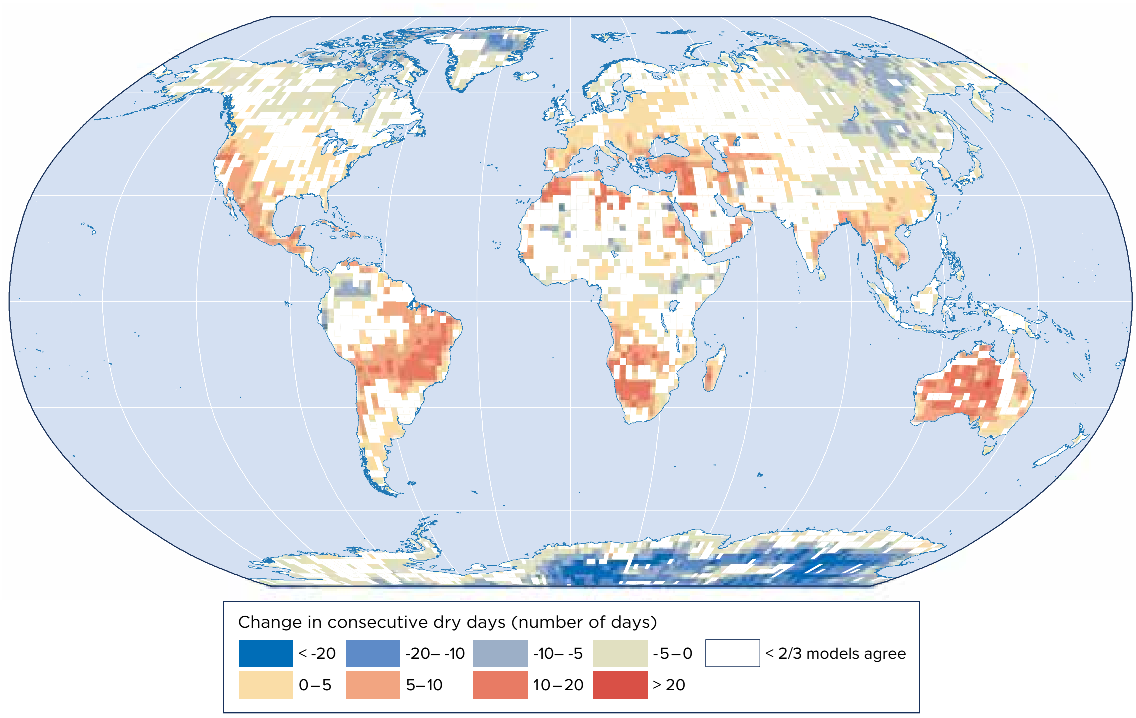
Figure 4 – Droughts are uniquely harmful to agriculture

Damage and loss to agriculture as a share of total damage and loss across all sectors by type of disaster



Source: FAO, The State of Food Security and Nutrition in the World 2018

Figure 5 – The world will experience both longer dry spells and increasingly erratic rainfall



Source: World Bank 2009

Groundwater is being rapidly depleted

Groundwater, housed naturally in specific rock formations called aquifers, plays a major role in irrigation and food production globally. More than one-third of the world's 301 million hectares of irrigation-equipped area relies on groundwater, and about 38 percent of the 252 million hectares of net irrigated area benefit from groundwater access.[32] In addition, groundwater accounts for 43 percent of total consumptive irrigation water use.[33] Eleven of the top 15 countries using groundwater are in Asia. India alone uses more than 250 km^3 of groundwater annually—double that of any other country. Of that, 89 percent (223 km^3) is used for irrigation. The next highest users are China, the United States, and Pakistan. Irrigation accounts for 54 and 71 percent of total groundwater use in China and the United States, respectively.[34]

Intensive groundwater pumping for irrigation has caused groundwater depletion in many arid and semiarid agricultural regions, leading to declining groundwater tables. Many of the depleted aquifers overlap with the world's most important breadbaskets.[35] Sustained groundwater overdraft puts future irrigated food production at risk and leads to undesirable environmental consequences, including land subsidence (sinking of the land) and saltwater intrusion, which can often have significant social and environmental impacts such as contamination of agricultural and drinking water.

Groundwater is typically a common pool resource, accessible to any users with appropriate technologies. Overexploitation of groundwater is intrinsically linked to this. Moreover, in certain regions of the world, including some parts of India, electricity for agricultural use, including the pumping of groundwater, is subsidized or provided without charge. Without better governance and other incentives for farmers to conserve water, the recent introduction of solar panels for pumping groundwater in South Asia could further aggravate water drawdown.

Water pollution and poor water quality contribute to water challenges

Water pollution affects human health, economic development, and the environment. It leads to increased competition among water users for the shrinking supplies of unpolluted water. Pollutants can be both human-induced (e.g., microbiological contamination, eutrophication and excess nutrients, acidification, metal pollutants, toxic wastes, saltwater contamination, thermal pollution, and increases in total suspended solids) and natural (e.g., salinization, arsenic, and fluoride). Water pollution reduces agricultural production and increasingly constrains agricultural and economic development in densely populated regions where water is already scarce and wastewater treatment is poor. Water pollution also threatens aquatic life. Salinity is one of the largest water-quality problems facing the agricultural sector. Freshwater biodiversity and associated fisheries are on the decline in almost all LMICs, reducing the availability of protein, healthy fats, and micronutrients that are often deficient in specific segments of poor populations.[36]

Fertilizers

Inorganic fertilizer has been a driving force of agricultural production growth. Together with irrigation expansion and the spread of modern varieties of rice and wheat, increased fertilizer use was a foundation of the Green Revolution that led to rapid growth in agricultural production and farm income in Asia and Latin America beginning in the 1960s. However, in some regions in the world, fertilizer is now used in excess, resulting in runoff that can pollute irrigation and drinking water. Fertilizer-contaminated runoff can also cause eutrophication, which results in excess algae growth and oxygen depletion in lakes and streams. Because polluted water is, in general, less productive than fresh water and requires the use of fresh water to leach the pollutants, water pollution also reduces the effective water supply.

Because polluted water is, in general, less productive than fresh water and requires the use of fresh water to leach the pollutants, water pollution also reduces the effective water supply.

Water pollution from agricultural crops occurs when fertilizers and other agrochemicals are applied more heavily than crops can absorb them, or when they are washed away during storms. Fertilizer subsidies, particularly for nitrogen fertilizers, are a key reason for overapplication of nitrogen fertilizers. More efficient application of fertilizer and manage-

Box 1 – Good governance is the key to managing conflicts over water

Growing populations in water-scarce regions have long raised fears of widespread violent conflict over water. Research to date on the causes of water conflict, however, suggests that chronic scarcity alone does not inevitably lead to conflict. There are few, if any, historical examples of war fought exclusively over water resources.

Weather variability, rather than chronic scarcity, seems to precipitate more conflict. Militant activity in East Africa, for instance, rises after periods of both especially high and low rainfall. In general, water conflict is more likely when regions with weak governance and institutions experience sudden shocks to available water supplies. In other words, poverty, food insecurity, and other vulnerabilities make an unreliable water supply more dangerous (see map).

If, as predicted, climate change makes rainfall more erratic, this could lead to more conflict than from increased water scarcity alone. The Pacific Institute has recorded hundreds of water conflicts globally, and the frequency is steadily growing. Most of these are between communities in the same nation that share a water source or between communities and their own governments. Neighboring communities show greater rates of conflict if they perceive unequal access to water.

In areas with existing instability and conflict, water insecurity can make the problems much worse. For instance, in October and November of 2004, four people were killed and over 30 injured in the Sri Ganganagar district of India near the Pakistan border during protests over the allotment of water from the Indira Gandhi Canal. Conflict over this water still continues.

Between 2004 and 2006 a drought affected an estimated 11 million people across East Africa, killing large numbers of livestock. This forced the governments of Kenya and Ethiopia to send the military and police to intercede in scores of skirmishes over water in their countries.

In northeastern Syria, droughts between 2006 and 2011 caused 75 percent total crop failure and 85 percent livestock loss. The resulting rural-to-urban migration of more than a million unemployed Syrians added to the domestic instability that underpinned the country's ongoing civil war.

In all these cases, good governance can make the difference between conflict and stability. Serious shocks to the water supply may be unavoidable, but resilience is possible through policy and watershed-level planning.

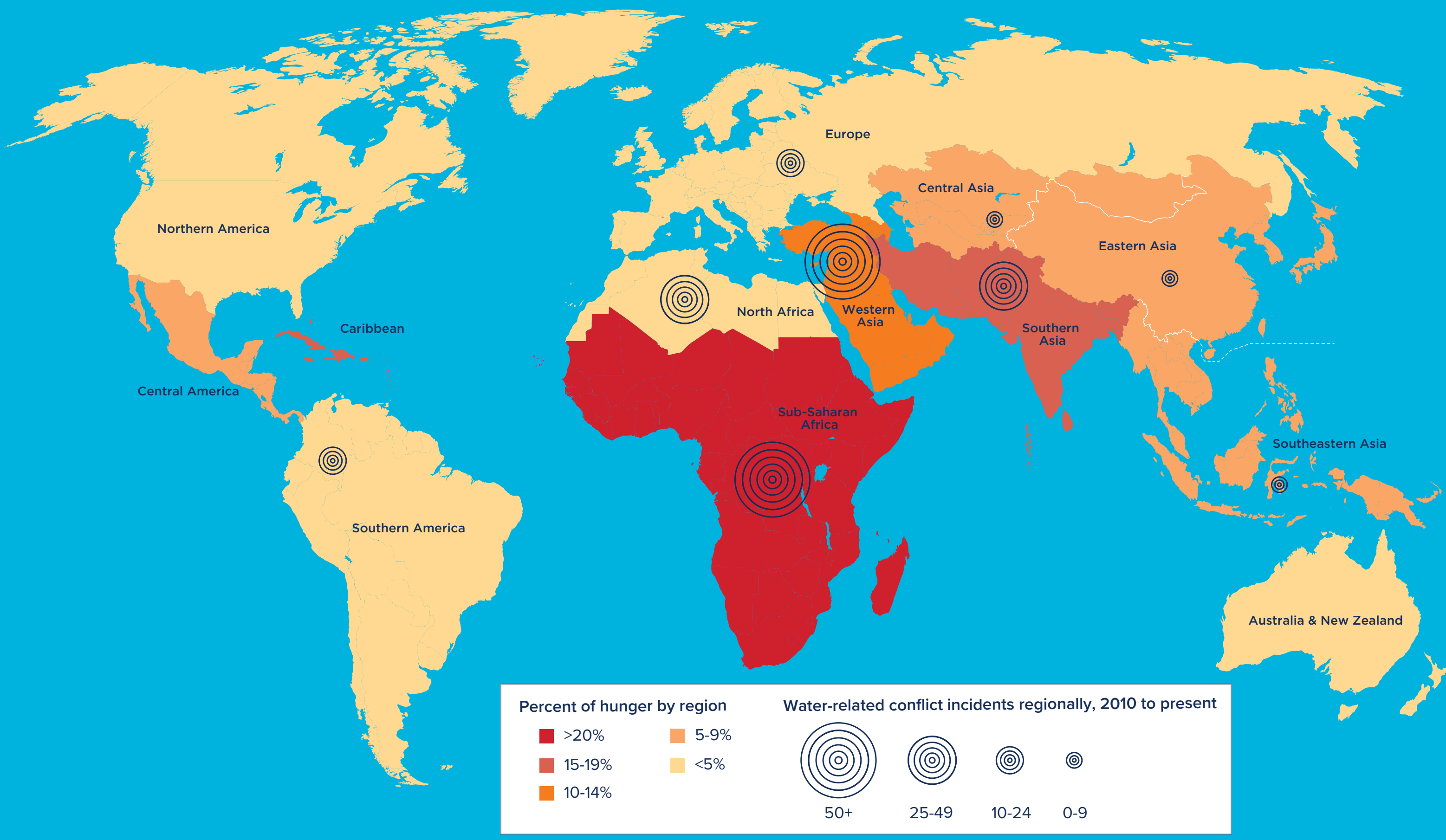
The importance of cooperation

Proactive governance, an emphasis on cooperation, and mechanisms for adapting to change will have to become more common practice. International cooperation over water—in the form of treaties and transboundary watershed agreements—is fairly common. However, only about half of formal agreements include basic monitoring provisions, and many lack clear dispute resolution or authority. Negotiating joint management of water resources is almost always deeply contentious. Success requires transparent, adaptive transboundary watershed management institutions and clear legal mechanisms for conflict resolution. Even long-standing treaties like the Indus Waters Treaty between India and Pakistan signed in 1960 are still a source of political conflict.

Emerging development patterns further test these established agreements. New, large-scale hydropower dams, for instance, provide needed access to electrification, but they can cause environmental damage, population displacement, and reduced water access for downstream countries. Conflicts over unilateral infrastructure construction are ongoing between China and India, India and Pakistan, and Ethiopia and Egypt. Changing weather patterns may also undermine progress made on transboundary water cooperation.

Even though the links between water scarcity and violence are not linear, it is now well established that investments in water security and good water governance are investments in peace and security.

Figure 6 - Hunger and water-related conflict



Sources for text: Kraemar 2013; Wolf 2003; Salehyan and Hendrix 2014
Sources for map: FAOSTAT 2018; Pacific Institute 2018

ment of water can greatly reduce both water and fertilizer loss. The biggest challenges are applying adequate amounts of nitrogen and phosphorus to achieve a healthy crop without using excessive amounts of fertilizer. In contrast to regions in much of the world, very low levels of inorganic fertilizer use in much of Sub-Saharan Africa have contributed to soil infertility, as nutrients are lost over the harvest period through leaching, erosion, or other means and not replenished with fertilizer. Increased use of inorganic fertilizer, together with organic fertilizer applications, would improve nutrient management and generate higher crop yields. Promising organic technologies include incorporation of leguminous trees and shrubs into improved fallow systems, planting of leguminous cover crops, and application of manure and compost. These techniques should be complemented with higher inorganic fertilizer use.

Crop protection

The application of pesticides (crop protection tools) is also rapidly growing. Crop protection technologies (pesticides, fungicides, and herbicides) have also played an important role in boosting food production and reducing the vulnerability of crops to pests and diseases.

As is the case with fertilizer use, runoff and deep percolation of agricultural chemicals into water bodies and aquifers may result from poor irrigation and land management prac-

Currently, severe pathogen pollution affects around one-third of all river stretches in Africa, Asia, and Latin America, putting the health of millions of people at risk.

tices. Improved formulations of pesticides—together with farming practices such as tillage, crop rotation, and intercropping; plant genetics (pest resistant or pest-tolerant crop varieties); biological control organisms; and synthetic pesticides—can sustain crop protection while reducing negative environmental impacts.[37]

Urban and agricultural pollution

Urban water pollution also adversely affects food and nutrition security. A report by the CGIAR Research Program on Water, Land and Ecosystems summarizes much of the recent information.[38] More than 330 km^3 of pathogen-laden municipal wastewater—equivalent to four times the Nile River—is being discharged globally into rivers, lakes, and seas every year, most of it untreated.[39] Currently, severe pathogen pollution affects around one-third of all river stretches in Africa, Asia, and Latin America, putting the health of millions of people at risk.[40] Rapidly growing livestock and aquaculture sectors, especially large-scale operations, produce wastes that further damage ecosystems.[41] Freshwater fish and marine fish are threatened by pollution from wastewater and nutrient runoff from agriculture, which can threaten food quality for the significant proportion of people globally who rely on fish for protein and essential nutrients. Nearly 17 percent of protein comes from fish consumption.[42]

When affordable drinking water is not available in LMICs, polluted water is often used for food processing and food preparation, which can result in foodborne illnesses.[43] A comprehensive review of evidence on the use of untreated wastewater for the irrigation of crops shows that this practice has caused high levels of disease incidence in countries around the world.[44] The global burden of foodborne disease was 33 million disability-adjusted life years in 2010, and 40 percent of the foodborne disease burden is among children under five. Foodborne diarrheal disease agents cause 230,000 deaths per year, particularly nontyphoidal *Salmonella enterica*.[45]

Credit: Greg Garrett

PART II

Credit: Marilyn Shapley/Mercycorps/Niger

STRATEGIES TO ENHANCE WATER, FOOD, AND NUTRITION SECURITY

As the largest user of global water supplies, agriculture has a critical role to play in sustainable water solutions that allow it to meet growing production demands while enhancing water security. In general, agriculture can become more water secure either through making existing water usage more productive or by finding new sources of water.

These five strategies offer the potential to reduce water scarcity and improve food and nutrition security:

1. improving overall governance and institutions for effective water management;
2. incentivizing efficient water use through effective policies such as those for water rights, regulations, enforcement, water pricing, water trading, and reform of water subsidies;
3. improving crop and livestock productivity—and value chain efficiency—per unit of water and land through agricultural research, development, technology, and financing;
4. shifting diets and diversifying agriculture to reduce the demand for water and improve nutrition; and
5. increasing the supply of managed water for domestic and industrial uses and expanding sustainably irrigated area through investment in infrastructure.

In addition, expanding urban and periurban agriculture and focusing on effective international agricultural trade policies, including trade in "virtual" water, will further support water productivity. Agricultural commodity price policies also have substantial impacts on water use decisions across crops. Agricultural trade and price distortions should be removed to provide a level playing field. Ensuring that these solutions reach smallholder farmers and that women and girls are empowered in the process is not only essential to increasing water productivity, but will improve livelihoods and contribute to greater water, food, and nutrition security.

> *Ensuring that solutions reach smallholder farmers and that women and girls are empowered in the process is essential to greater water, food, and nutrition security.*

Improving governance and institutions for effective water management

Water is allocated through a variety of mechanisms, including government management, community or user-based management, and market-based management. In many cases, water allocation is carried out through a combination of these. Water allocation systems are fundamentally influenced by the historically prevailing institutional and legal frameworks and water infrastructure.[46] Government-managed water allocation is widely used because larger systems are built with public funding, and the government is often the only institution that has jurisdiction over water users in all sectors. Community or user-led allocation requires effective collective action, institutions with the authority to make decisions on water rights, and strong water rights, whether formal or customary.

Water allocation through tradable water rights also requires well-defined water rights. For such markets to function effectively, the original allocation of water rights needs to be well defined. An institutional and context-specific legal framework for trade and the basic infrastructure for water transfers also needs to be in place.[47] Given growing water scarcity, the mix of appropriate mechanisms for water allocation may need to change, requiring a flexible, enabling framework for making such shifts.

Reforming public irrigation agencies can improve water system performance

Approaches to improving water use efficiency and productivity include making the public sector more efficient, devolving more responsibility to community or user groups, and involving the private sector. Institutional reform of public irrigation agencies holds some promise for long-term improvements in system performance. Possible reforms include shifting from top-down management systems to semi-independent or public utility–type systems and applying financial criteria to ensure irrigation agencies are viable. Franchising the operation of publicly constructed irrigation facilities, discussed in more detail on page 51, can strengthen accountability, including providing farmer oversight of operating agencies.[48]

Ultimately, reform requires fundamental change in the function of these agencies that manage water. These agencies may need to improve their performance and expand their efforts in activities such as river basin planning, watershed management, water resource

The participation of women in WUAs needs to be greatly expanded because existing power relations and formal and informal norms rules have often excluded women.

allocation, environmental monitoring and enforcement, groundwater monitoring and control, and technology transfer and/or advisory services to water user associations (WUAs).[49] Farmers' participation in irrigation management at the secondary and tertiary levels has been widely promoted by governments to improve local management. The level of success depends on farmer cooperation and their incentives to take on an expanded role.[50]

According to a comprehensive review of case studies on WUAs in Sub-Saharan Africa, local socioeconomic and agricultural conditions shape the ability of WUAs to deliver expected results, including improved governance, equitable participation, and improved cost recovery in an irrigation scheme. National-level laws or regulations or ensuring that WUAs create bylaws, by contrast, do not lead to these outcomes because external institutions and actors cannot as easily create the necessary conditions for success. The review concluded that development assistance to WUAs should emphasize improved water delivery services rather than just user-pay mechanisms. The participation of women in WUAs needs to be greatly expanded because existing power relations and formal and informal norms rules have often excluded women. Getting better service through infrastructure and technology would provide users an incentive to pay and participate. User participation in the design process can help users, irrigation managers, and officials find affordable infrastructure and management solutions that include technological innovations and mechanization.[51]

Box 2 – International Water Management Institute (IWMI) takes an interdisciplinary approach to water, land, and ecosystems

The International Water Management Institute (IWMI) is a research center within the Consultative Group on International Agricultural Research (CGIAR), a global research partnership for a food-secure future. Founded in 1983 with initial support from the Ford and Rockefeller Foundations, IWMI focuses on sustaining and improving developing countries' water and land resources with the goal of a water-secure world. IWMI spearheads the Water, Land, and Ecosystems Program (WLE), which combines the resources of the FAO, the RUAF Foundation, and many other partners to promote new approaches to sustainable intensification that have natural resource management principles at the core. In 2012 IWMI received the Stockholm Water Prize for their efforts to improve "crop per drop" and policies that support sustainable water usage for agriculture. IWMI also builds bridges for wastewater management, aquaculture, clean drinking water, and overall water resilience, recognizing the need for collaboration across sectors. In the wastewater recovery area, 24 business models for reusing waste products from urban centers have been developed. Support for this integrated work is key to finding crossdisciplinary solutions and policies for shared water resources that will support farmers' and consumers' water and food needs.

Source: IWMI

Integrated water resources management (IWRM) can be a successful approach but should not inhibit pragmatic solutions

Integrated water resources management (IWRM) has been a prominent guiding ideal over the past three decades. IWRM supports the principle that "good water governance requires clear legal frameworks, comprehensive water policies, enforceable regulations, institutions that work, smooth execution and citizen-based mechanisms of accountability as well as strong interconnections between these entities."[52] Institutions should be accountable, efficient, responsive, and sustainable.[53] Some successes have been achieved through formal adoption of IWRM.

For example, rapid development in the Liao River Basin in China in the 1980s resulted in water shortages and severe water pollution. Water-use efficiency was very low in urban and industrial areas and for irrigation. Untreated industrial and urban wastewater polluted the streams, destroying the river's ecology. As part of a new IWRM institutional framework, the EU-Liaoning Water Resource Planning Project Office was established. This office was responsible for developing and implementing an IWRM plan. As a result, pollution loads were reduced by 60 percent, and the quality of the water in the river improved considerably. Deforestation declined, drinking water within the basin was safeguarded, and ecosystems along several river stretches were restored. Groundwater pollution decreased, and the public became more aware of the need to manage their water use and pollution risks.[54]

These principles and best practices are valuable, but fully integrated and holistic water management is often costly and politically difficult or impossible to implement. Adherence to formalized IWRM principles and organizational structures can become an end in itself and thus drive out more pragmatic solutions. Decision makers should, therefore, focus on solutions to specific problems rather than on universal approaches. This involves understanding the physical, social, and especially political context of the challenge.[55] "Ideal" solutions may not be possible, and even if they are, they may not have the desired result

It is preferable to adopt workable solutions that are cheaper to implement … than to try for better yet unrealistic solutions that can never be effectively implemented.

within the social, economic, and political context. Second-best water governance solutions may go against apparent norms, but they can still push communities and nations toward desired results. It is preferable to adopt workable solutions that are cheaper to implement and that align incentives between various interest groups, taking into account local conditions, than to try for better yet unrealistic solutions that can never be effectively implemented.[56]

An important example of pragmatic problem solving is the Zhang He River Basin in China. The Zhang He reservoir was designed for multiple uses: irrigation, flood control, domestic water supply, industrial use, and hydropower generation. As demand for non-agricultural water use increased, system operators used a top-down approach, allocating more water to cities and less to farmers for irrigation. Reduced supplies to farmers forced a response, including the construction of small reservoirs within the irrigated area to capture runoff and to capture return flows from rice cultivation. The system was among the first in China to introduce volumetric pricing at the village level. Cost savings were prorated to the individual farmers. Farmers were encouraged to shift from flooded paddy fields to alternate wetting and drying to save water, which was achieved without loss in yield or profit.[57] Crop production remained steady despite much less water being delivered from the main reservoir to rice farmers, and systemwide water productivity increased.[58] The Zhang He example shows how policies, system management, and changes in technologies and farm practices can be used together to reallocate and improve the efficiency of water use.

Incentivizing efficient water use through effective water policies

As a scarce resource, water should be treated as a valuable strategic good that has a "price," but the unique aspects of water, described below, have made this difficult. Establishing a price for water can be done through a range of policy instruments that incentivize efficient water use, recover investment costs from those who benefit, and provide a revenue stream for investors. Examples include tariffs for water supply and sanitation, abstraction charges, pollution taxes, value-capture mechanisms, and payments for ecosystem services. But improving willingness to pay for water management and water services requires a clear explanation of how revenue will be used to benefit users. Robust alloca-

Box 3 – Clear and secure water rights are critically important for farmers

Water rights are the moral and legal claims that people have to gather the water they need. The United Nations has established the right to clean, safe water as a human right. While some nations—South Africa and India—have constitutional entitlements to water, the general legal force of the human right to water is inconsistent globally.

Typically, legal rights to water follow two basic doctrines: the riparian doctrine and the appropriation doctrine. The riparian doctrine is common in wetter areas and gives users adjacent to a water source the right to take water as long as they return it in good quality and do not reduce access for downstream users. The appropriation doctrine, more typical in dry areas with strong legal systems, provides for water rights in the order they are claimed, with the oldest claims filled first. Often these claims are tied to land ownership.

Water rights are generally managed formally through legal and bureaucratic systems. But there are many places in the world where these entitlements are managed informally or by traditional cultural practice. Clear and secure water rights are critically important for farmers and can encourage efficiency.

Market exchanges for the trading of water rights between farmers can incentivize water efficiency by raising the cost of permits. These exchanges need to be transparent, monitored, and supported by a fair system of adjudication when there are disagreements. Farmers who know they have a legal claim to the water they need can plan with greater certainty, which can encourage them to invest in their farms with more confidence.

Stronger water and land rights are especially important for the large portion of female smallholders around the world. Women account for 60 percent of agricultural production in Sub-Saharan Africa, but they own a far smaller percentage of the land (13.1 percent sole ownership and 37.8 percent joint ownership). For water rights to be effective tools, all the users in a system must be able to participate. Irrigation, for instance, raises land value, but where rights are not equally accessible to women, the benefits will tend to favor men. Gender equity in rights and in access to productive resources is therefore an important element of policies aimed at reducing hunger and raising farm productivity.

Sources: FAO 2011; World Economic Forum 2019; The World Bank 2018

Credit: Marilyn Shapley/Mercycorps/Niger tion arrangements can help shift water on the margin from cereal crops toward higher-value uses and provide flexibility to adjust to changing conditions.[59]

Long-standing practice and political, cultural, and religious beliefs have treated water as a free good. Typically, water is subsidized, and secure water rights have not been established. However, insecure water rights, low water charges, and poor cost recovery threaten the efficient maintenance of existing water infrastructure and investments in future water development projects. These factors also encourage wasteful use of water, including excess agricultural irrigation. Agricultural pricing policies can cause overuse and misallocation of water as well. Crop-specific price interventions, such as price supports for rice in India combined with input subsidies, resulted in excess use of water and environmental degradation.[60]

Water rights are the foundation of effective water management

Secure water rights are the key to establishing incentives for irrigation management. They empower water users—individuals or communities—by requiring user consent to any reallocation of water and compensating the user for any water transferred. If well-defined rights are established, water users have the incentive to invest in water-saving or income-enhancing technology.[61]

> *If well-defined water rights are established, water users have the incentive to invest in water-saving or income-enhancing technology.*

Although some system of formal or informal water rights can be found in virtually any setting where water is scarce, systems that are not formally recognized or grounded in statutory law and enforced are likely to be more vulnerable to expropriation.[62] The establishment of formal water rights should follow transparent procedures that protect small- and microscale users and enable them to negotiate the sharing of benefits or compensation. In order to effectively prevent and resolve conflicts among the many medium-, small-, and microscale users, formal processes should also recognize customary arrangements and rights.[63] The establishment of formal water rights will not be effective if it ignores existing customary arrangements.[64] Secure land rights are also essential to provide producers the incentives to invest in farm improvement, new crop varieties, better crop management, and appropriate inputs to make water management more effective.

Low water use efficiencies are often cited as evidence that very large savings in water use are possible. However, an increase in water use efficiency for an individual farmer does not necessarily save water in the river basin or irrigation system. Much of the water that is “wasted” by inefficient farm-level upstream irrigation is recovered through downstream use of drainage water and recharge of groundwater that can be used for irrigation.[65] Thus, less potential exists for generating water savings than farm-level water use efficiency figures imply. Nevertheless, if secure water rights and incentives for efficient agricultural water use can be effectively implemented, there is considerable potential for economic gains through reallocation of a greater portion of water to higher-value uses such as fruits and vegetables and by improving water quality by reducing the number of withdrawals.

Water pricing is challenging in low- and middle-income countries

Administered water pricing, or set pricing that is not based just on market forces, can incentivize more efficient water use. In high-income countries, farmers can respond to higher water prices by decreasing the water used on a given crop, adopting water-conserving irrigation technology, shifting water applications to more water-efficient crops, and changing the crop mix to favor higher valued crops. But in LMICs, farmer demand for irrigation water is likely price inelastic because the above options are either unavailable or too costly. Prices high enough to induce significant changes in water allocation (or recover capital costs) will severely reduce farm income.[66] Moreover, in existing irrigation systems, the value of prevailing water rights (formal or informal) has already been capitalized into the value of irrigated land. Rights holders correctly see the imposition of administered pricing as expropriation of those rights, which would lead to capital losses on established irrigation farms.[67]

Attempts to establish administered efficiency prices are thus met with strong opposition from established irrigators, which makes it difficult to institute and maintain an efficiency-oriented system of administered prices.[68] In addition, measurement and monitoring to support administered efficiency pricing may be prohibitive. Irrigation in many LMICs consists of large systems that serve many small farmers. Efficiency pricing at the farm level will be difficult because the measurement of deliveries to large numbers of end users, as would be required to charge by volume of water use, is too costly.

Water trading requires improved measurement and monitoring

Water markets that allow farmers to trade water and water rights can overcome the appropriation issue, but they share some of the same measurement constraints as direct pricing. In addition, entrenched interests benefit from the existing system of subsidies and administered allocations of water.

Effective development of well-defined water rights and trading in LMICs would be enhanced by improvements in irrigation technology for conveyance, diversion, and metering. Improved management of irrigation systems would also help, as would development

An initial focus on realistic allocation of water on a seasonal basis, together with registration of rights based on shares, would be a major first step.

of community organizations to manage water allocation. However, development of water trading beyond a local level is likely to be a long-term process in most LMICs. An initial focus on realistic allocation of water on a seasonal basis, together with registration of rights based on shares, would be a major first step.[69]

Innovative water pricing offers an attractive solution

Despite these constraints, innovative water pricing can be implemented to introduce incentives for efficient and higher-value water use while protecting farm income, improving the economic value of water, and recovering—at a minimum—operations and management costs. Instead of imposing direct water prices on farmers, this system would pay farmers to use less water based on the charge-subsidy approach for pollution control. Irrigation agencies or a river basin authority would establish base water rights at major turnouts and broker water transfers at those turnouts. Allocation downstream of the turnouts would be handled by WUAs or farmer organizations, which have localized knowledge of water allocation. For demand greater than the base water right, an efficiency price based on the value of water in alternative uses would need to be charged to the users. For demand below the base right, the same efficiency price would be paid to the water users. The sum of the base water rights establishes a cap on total water use in the basin or system, allowing basin-wide water use to be maintained or reduced. This system establishes nonpunitive incentives for more efficient water use, with farmers paying only for additional water above the base water right and having the option to sell water if they reduce water consumption.[70]

Generalized subsidies should be reduced

Government subsidies for water, energy, and fertilizer have been prominent policies in LMICs. Subsidies are often justified as the provision of public goods; an incentive to adopt

> *Generalized water, energy, and fertilizer subsidies have high fiscal costs that only rarely generate commensurate benefits and often encourage degradation of natural resources.*

new technologies, promote food security, and provide income support to smallholder farmers; and a counterbalance to poor infrastructure.

But in practice, governments often end up providing large subsidies for private goods (such as water, energy, fertilizer, and credit), displacing the supply of public goods (investment in research, roads, and education).[71] Free or cheap irrigation water leads to excessive use and might trigger increased planting of thirsty crops.[72] When subsidies are broad-based, most of the benefits do not go to poor farmers but to larger farmers who utilize more water, fertilizer, and energy.

Moreover, in addition to reducing the supply of infrastructure and other public goods and encouraging overuse of water, energy, and fertilizer, public expenditures on subsidies often result in underinvestment in sanitation and environmental protection. Reducing the share of subsidies for private goods, therefore, has a large, significant, positive impact on rural per capita income, reduces certain undesirable environmental effects associated with output growth, and contributes to poverty reduction.[73]

Generalized water, energy, and fertilizer subsidies have high fiscal costs that only rarely generate commensurate benefits and often encourage degradation of natural resources.[74] Yet they remain politically attractive as a means of support to farmers. Where subsidies continue to exist, they should be reduced to a moderate amount of national agriculture budgets with a clear exit strategy and should be combined with complementary expenditures.[75] Fiscal savings from the reduction of subsidies can be invested in increased agricultural R&D and nondistorting income support to small farmers, which can generate greater benefits than general subsidies. Concerns about the impact of loss of income for smallholder farmers can be addressed by using some of the saved funding to compensate

Box 4 – Feed the Future's Naatal Mbay project in Senegal issues rain-index insurance

In southern Senegal, farmers producing rain-dependent crops traditionally lacked the ability to withstand shocks brought about by extreme weather such as drought or flooding. These days however, Senegal's National Agriculture Insurance Company (CNAAS) is filling this gap by offering rain index insurance products for farmers—thanks to support from the USAID-funded Feed the Future Senegal Naatal Mbay project, implemented by RTI International and Global Affairs Canada in partnership with Senegal's National Agency for Civil Aviation and Meteorology (ANACIM).

The insurance products address a critical challenge: if rainfall is insufficient, erratic, or excessive, farmers risk losing their investment in production inputs or, even worse, they risk defaulting on input loans, reducing their ability to access credit for future seasons. To reduce this risk, the project works with a national insurance company and institutional reinsurers to craft and sell affordable rain-index insurance plans tailored to farmers, distributed by producer networks and financial institutions.

In support of the effort, ANACIM has installed 88 solar-powered, automated rain gauges throughout the southern zone, which allow insurers like CNAAS to quickly access rainfall data and accurately determine farmers' losses to then compute rain-index insurance payouts.

Equipped with this risk mitigation tool, smallholder farmers are more likely to invest in quality inputs that yield more and produce better-quality products demanded by buyers. More than 10,500 producers subscribed to agricultural rain-index insurance in 2018, up from 3,087 in 2015 when the Naatal Mbay project began, a 240 percent increase.

Source: RTI International

A solar-powered, automated rain gauge in Kolda, Senegal. Credit: Xaume Olleros/RTI International them for the losses. With rapidly increasing access to ICT, smart cards or phones can be used for efficient funds transfer to small farmers.

"Smart subsidies" can incentivize desired outcomes without causing permanent market distortions

Given the potential for negative effects of subsidies, are there appropriate uses for them? Carefully selected and implemented, small-scale "smart" subsidies to achieve specific goals have a role to play in facilitating the adoption of new technology and promoting environmental services. These subsidies could come in the form of loans or targeted subsidized prices on equipment for smallholder farmers to invest in improved practices such as drip irrigation. Temporary subsidies during the early stage of input and technology adoption may be effective in overcoming the fixed costs related to the adoption of new

Carefully selected and implemented, small-scale "smart" subsidies to achieve specific goals have a role to play in facilitating the adoption of new technology and promoting environmental services.

technology and in inducing farmer experimentation and learning during periods of rapidly changing technological potential. Such smart subsidies should be temporary and phased out as adoption and appropriate use become widespread. But the phase-out of subsidies becomes difficult once they are in place and develop political support.[76]

Examples of potentially effective smart subsidies include payments for environmental services (PES) and subsidies for solar-powered irrigation pumps linked to the electric grid. These targeted smart subsidies have potential environmental and economic benefits. However, they also have potential negative effects such as increased groundwater mining if implemented poorly. PES consist of payments to farmers or landowners who agree to manage their land or watersheds for environmental protection (e.g., to protect and improve water resources or reduce greenhouse gas emissions).

PES are most likely to succeed when there is a clear demand for environmental services that have financial value to one or more stakeholders; the services needed are feasible; there are effective brokers or intermediaries; land and water rights are clear and contracts can be enforced; and the outcomes can be independently monitored and evaluated. For example, in Quito, Ecuador, and smaller cities in Honduras and Costa Rica, the water utility and electric power companies pay local people to conserve the watersheds from which water is drawn. In Venezuela the power producer CVG Edelca pays to support the preservation of the Rio Caroni watershed. The Water Producer Program of the National Water Agency in Brazil compensates farmers for safeguarding critical headwaters for the São Paulo metropolitan region.[77]

Managing groundwater to prevent aquifer depletion is also essential

Groundwater use in much of the world has increased rapidly in a short period, particularly in Asia, following the availability of cheap pumps, often combined with subsidized energy and water. While the expansion of groundwater use has been highly beneficial for agricultural productivity, overdrafting is excessive in many instances, causing land subsidence,

Box 5 – Targeted subsidies for solar pumps are being piloted

Targeted subsidies for smallholder farmers to purchase solar irrigation pumps in India and Bangladesh are showing promise in pilot studies. Bangladesh, the Nepal Terai, and eastern India have abundant groundwater, but it is costly for smallholder farmers to access the water through diesel pumps. The Bangladesh Infrastructure Development Company Limited piloted a pro-poor irrigation service market by offering private companies or investors a 50 percent government subsidy and 35 percent loan to purchase solar pumps to sell irrigation service to small farmers for an affordable fee. Three hundred of pumps were in operation in 2016.

A pilot in Bihar by the International Water Management Institute (IWMI) also organizes farmers to create a pro-poor water market. In both Bihar and Bangladesh, there is evidence of a 40 to 60 percent fall in water prices compared to diesel pumps. This has resulted in the rapid expansion of solar pumps in pro-poor irrigated agriculture. The key motive in both programs is to promote affordable groundwater irrigation for the poor where there are abundant water resources.

Another IWMI pilot in Dhundi village in water-scarce Gujarat seeks to promote co-usage of solar irrigation pumps for irrigation and solar energy. In this pilot well owners gave up grid power connections for subsidized solar irrigation pumps of equivalent capacity. The small irrigation pumps are formed into a microgrid managed by a cooperative of their owners. The utility buys all surplus solar power from the cooperative at a single metered point.

The pilot seeks to promote lower greenhouse gas–emitting irrigation, reduce the farm power subsidy, reduce technical and commercial losses in serving grid power, give farmers an additional source of risk-free income, and incentivize farmers to economize on energy and groundwater. Before the sale of solar power began in May 2016, farmers used all of their solar generation to irrigate their own and their neighbors' fields. But since then they have sold as much power as possible and used only 35 percent of their solar generation for pumping groundwater.

Source: Jayan 2018; Kishore et al. 2004; Kumar and Goel 2018; Rai 2018; Shah et al. 2009; Shah et al. 2018

salinization, and other degradation of land and water quality in the aquifer. The principles of groundwater management are essentially the same as described in the previous section, but they are even more complex to implement than in surface systems due to the invisibility of the resource, the lack of data on safe yield or availability, and groundwater movement. Elements of successful groundwater management include recognized user rights, monitoring processes, means for sanctioning violations, and procedures for adapting to changing conditions.

Key elements of effective groundwater governance include local governance that is trusted and has the ability and willingness to set and enforce rules. This requires a portfolio of approaches, sufficient budget and time, the ability to collect data, and enough state-level oversight.[78] Again, the institutional capability to establish such systems is the major challenge throughout most of the world, including in LMICs, which suffer the most from failures to address governance. Measuring groundwater and establishing clear rights would be an important step forward. In order to be successful, these governance structures must be agreed upon and managed by the water users, responsive to local conditions, operated with available data and information, and adaptable to the evolving environment.[79]

Ending groundwater overdraft has been contemplated for some of the world's most severely depleted aquifers, but this could increase food prices and lead to increases in food insecurity, especially in regions where the population is at risk of hunger. Complementary policies to prevent this would need to be implemented.[80] To address groundwater degradation, countries have started to develop legislation to regulate drawdown. For example, in response to severe drought, California passed the Sustainable Groundwater Management Act in 2014 to establish a framework for sustainable local groundwater management for the first time in the state's history.[81]

Policies to address pollution and water quality will improve health and increase water, food, and nutrition security

Reducing pollution and improving water quality requires both economic and regulatory instruments. The regulatory approach to water pollution gives authorities control over what environmental goals can be targeted and when. Economic instruments such as taxes on

Key elements of effective groundwater governance include local governance that is trusted and has the ability and willingness to set and enforce rules.

pollutants provide incentives to polluters to modify their behavior in support of pollution control and provide revenue to finance pollution control activities. Such financial penalties are most relevant for pollution in urban areas rather than for nonpoint source pollution in agriculture. Effective management of water pollution will often require a combination of regulations and incentives that target the specific constraints that govern a particular water allocation system.[82]

Several measures need to be taken to support both regulatory and economic approaches. Investing in water quality monitoring should be scaled up, and water quality standards for different uses that are both measurable and feasible must be established. Additionally, water quality standards should be incorporated into water rights systems and enforced by national and district agencies. Enforcement will pose perhaps the greatest challenge: those who pollute water must be made to pay regulatory fines, and the use and discharge of low-quality water must be discouraged. Enforcement will provide incentives for adopting better clean-water technologies as well as wastewater treatment and recycling solutions. Education and outreach on appropriate technologies and management systems would have substantial benefits.

Increasing water productivity through investment in agricultural research, development, and technology

An important key to better water productivity is not directly part of the water sector: investment in agricultural R&D to generate productivity gains for irrigated and rainfed agricul-

Box 6 – Improving water efficiencies in animal agriculture is critical to sustainability

The importance of livestock

Livestock are one of the building blocks of agricultural development. The "livestock ladder" is an essential part of the economic trajectory that helps lift smallholder farmers out of poverty, achieve food and nutrition security, and bridge the gap between farming and small- and medium-sized enterprise. Globally, it is estimated that 1 billion low-income people derive at least part of their livelihoods from livestock.

Livestock, land, and water

Animal agriculture requires significant natural resources. Globally, 26 percent of all land is used for livestock grazing, and 33 percent of global cropland is used to grow feed crops for livestock. Indeed, 99.8 percent of the total water used in raising livestock is green water used to grow animal feed. Accounting for the water used to grow feed crops, livestock consume approximately 10 percent of global annual rainfall either directly (blue water) or indirectly (green water). This accounts for approximately 24 to 32 percent of the world's total agricultural water use.

Improving water efficiencies

Improving water efficiencies in animal agriculture is critical to building sustainability in the food and agriculture system, where even small improvements can have magnified impacts on water resource management. Deliberate management of animal movements and land access can improve soil health and green water retention. Improvements in animal nutrition, veterinary care, and animal genetics, for example, can allow animals to grow larger and faster on less feed.

It is imperative that animals eat feed grown with a lower water cost of production. One way to do this is to better incorporate the nongrain portions of maize, teff, and sorghum plants grown for human consumption into animal feeds. This provides feed for animals at no additional water cost. Likewise, in water-scarce areas where grain is used to feed livestock, importing feedstuffs from areas with less water stress can improve water efficiency.

Integrating sustainable irrigation development with animal husbandry is another way to maximize water efficiency. Across Africa, the highest livestock densities are in areas that also have large-scale irrigation, which often generates abundant crop residues and nutritional supplements that can sustain meat and dairy production.

Pastoral livestock systems in Africa

Pastoral livestock systems play an important role in many low-income countries. In Africa, these systems occupy an area of 3.66 million square kilometers across the Sahel, the Horn of Africa, and Southern Africa. The systems contains 37.5 million cattle, contributing to the livelihoods of the 33.4 million people in this region.

Yet pastoralists are facing ever-growing challenges, from low pasture productivity to vulnerability to climate change and the fragmentation of rangelands, causing conflict between pastoralists and other agriculturalists. Pastoral systems overall struggle to overcome poverty and improve education and health.

Water management is a key factor in livestock mobility and pasture consumption, and appropriate interventions can contribute to more sustainable use of rangeland. For example, early warning systems and drought predictions could help herders better manage the complex interactions between herd size, feed availability, and rainfall. Interventions should focus not only on developing water "hardware" facilities, but on promoting water governance, management, and technical support. Governance structures need to empower pastoralists to effectively conserve water resources. A regional perspective should be taken in managing pastoral resource use and conflict within and across national borders.

In addition, road building that does not interfere with migration routes can provide market access, reduce marketing costs, promote social capital, and insure against distress sales. Microcredit and index-based livestock production insurance could provide some protection against risks.

Diversification of incomes is likely to be essential, given the challenges facing pastoralism and limits to expansion of productivity in these systems. Providing social services, including education, health, and social protection, will assist pastoralists in boosting incomes, reduce their income risks, and improve livelihood prospects outside herding.

Sources: Nicol et al. 2015, Haileslassie 2009; Herrero et al. 2015; de Leeuw et al. 2019; Lore 2013; National Research Council 2009; Nyachieo et al. 2016; Thornton 2010;

Cows and cattle in the Omo Valley of Ethiopia. Credit: istock/CanY71 ture as well as livestock.[83] While basin efficiency has contributed to the increase in water productivity (crop yield per meter of applied water), the major contribution over previous decades has come from increases in crop productivity per unit of water and land.[84] Importantly, progress on rainfed crop yield per hectare and per unit of water would not only improve rainfed water efficiencies, but also reduce irrigation pressure, increasing water productivity even further.

Achieving productivity gains in the livestock sector is also important (see box 6). The sustainable expansion of livestock production to meet the growing demand for animal-source foods must allow poorer consumers to benefit from a nutritional perspective while simultaneously addressing the impact on the environment. This means balancing trade-offs among food and nutrition security, poverty, equity, environmental sustainability, and economic development. Key innovations are needed in breeding and feeding programs that will focus not only on productivity but also on product quality, animal welfare, disease resistance, reduced water and land use, lower greenhouse gas emissions, and reduction of other environmental impacts.[85]

Areas for R&D include optimizing livestock diets to reduce the environmental impacts of production, improving feed digestibility, improving water management, developing

The sustainable expansion of livestock production to meet the growing demand for animal-source foods must allow poorer consumers to benefit from a nutritional perspective while simultaneously addressing the impact on the environment.

high-quality grain concentrates, and improving pasture quality. Other areas include improved waste management, use of by-products for energy production, and recycling. Integrated management of mixed livestock–crop systems could provide substantial water savings and livestock productivity. Innovative, intensive grazing practices that lead to soil creation and soil health are exciting strategies for enhancing soil moisture retention and fighting desertification.

Adoption of engineering solutions and technology are essential to improving water productivity of irrigated agriculture

General improvements in agricultural productivity and overall water allocation and management systems will set the stage for improved water productivity in irrigated agriculture. Yet significant increases in water productivity will also rely on the adoption of engineering solutions and technology in the field. These include water-saving irrigation methods such as deficit irrigation and proper deficit sequencing; modernization of irrigation systems, including improved irrigation technology such as drip and sprinkler irrigation; real-time management of irrigation systems; and advanced crop and water management such as enhanced water harvesting and water mapping through the use of satellite technology, artificial intelligence, and blockchain tools.

Precision farming, or farming that is guided and managed through these advanced digital and other technologies, is an area that is developing rapidly and holds significant promise for enhanced water productivity and food and nutrition security (see box 7).

Box 7 – Advanced technologies hold great promise for improved water, land, and crop productivity

Advanced technology offers the potential for LMICs to leapfrog older technology and develop faster. Mobile phones have begun to transform the delivery of market, financial, and weather information as well as the agricultural, health, and educational services that reach the poor.

Many other valuable mobile applications are also being developed. For example, recent pilot projects in India of picture-based weather insurance using smartphones show significant potential for reducing the cost of weather-based index insurance for smallholder farmers.

Precision agriculture, or agriculture guided and managed by advanced digital technologies, is another area that is developing rapidly. For example, remote sensing technologies have the potential to improve farming systems and irrigation management for water and food security. Satellite imagery is often the only option available in remote, sometimes insecure areas that are persistently experiencing food insecurity. Plus, the technology offers a dependable, ongoing source of data globally for understanding changes over time and assessing the efficacy of policy interventions.

Remote sensing applications are in development or being used in areas such as the measurement of water quality, water surface mapping, monitoring of area under crops and crop health, and adoption of good agricultural practices. For example, the Africa Regional Data Cube is a new tool that harnesses the latest earth observation and satellite technology to help Ghana, Kenya, Senegal, Sierra Leone, and Tanzania address food security and issues relating to agriculture, deforestation, and water access.

Satellite imagery has the potential to be even more powerful if combined with information from airplanes, drones, and ground-truthing (verifying the interpretation of satellite images) through surveys and sensors. Aided by remote sensing and big data, continued development of precision agriculture will allow farming management based on observing and responding to intrafield variations. With satellite imagery and advanced sensors, farmers can optimize returns on inputs and minimize greenhouse gas emissions while preserving resources. Further field-level understanding of crop variability, geolocated weather data, and precise sensors for soil water availability and nutrients should allow improved decision making from improved productivity.

Precision agriculture has mainly been for large-scale farming and has the potential to further disadvantage smallholder farmers due to lack of expertise and financial start-up costs. Thus, it is important to develop precision technologies suited to smallholder farmers.

Source: Aker and Mbiti 2010; Ceballos et al. 2018; Global Partnership for Sustainable Development 2018

Box 8 – Healthy soil improves water productivity and provides a carbon sink

The health of the world's soils is critical to food and nutrition security and sustainability. Water stored in the soils—called green water—supports 90 percent of global agricultural production. Soils' ability to absorb rainwater and hold moisture in the form of green water, is directly related to the overall health of those soils. Healthy soils are more fertile, act as a "sponge" when it rains, and hold more nutrients. Poor soils, conversely, hold fewer nutrients and less water, supporting less agricultural activity and increasing the risk of flooding and erosion.

Soils also act as a global carbon sink. The topmost meter of the world's soils contains three times as much carbon as the world's vegetation and almost twice as much as the atmosphere. The healthier the soil, the more vegetation it can support and the more atmospheric carbon it can sequester. Even small declines in soil health can have measurable impacts on carbon dioxide levels in the atmosphere.

Today, one-third of our global soils are moderately or highly degraded. Agricultural soil management practices can help reverse this trend.

Groundswell International, a nonprofit organization focused on agroecological innovations, for example, is using farmer-to-farmer training in Burkina Faso to expand the use of zai pits, a traditional planting method in which pits are dug during the preseason to catch water and concentrate compost. The pits create a microenvironment that improves soil's ability to absorb green water and hence rehabilitate abandoned land.

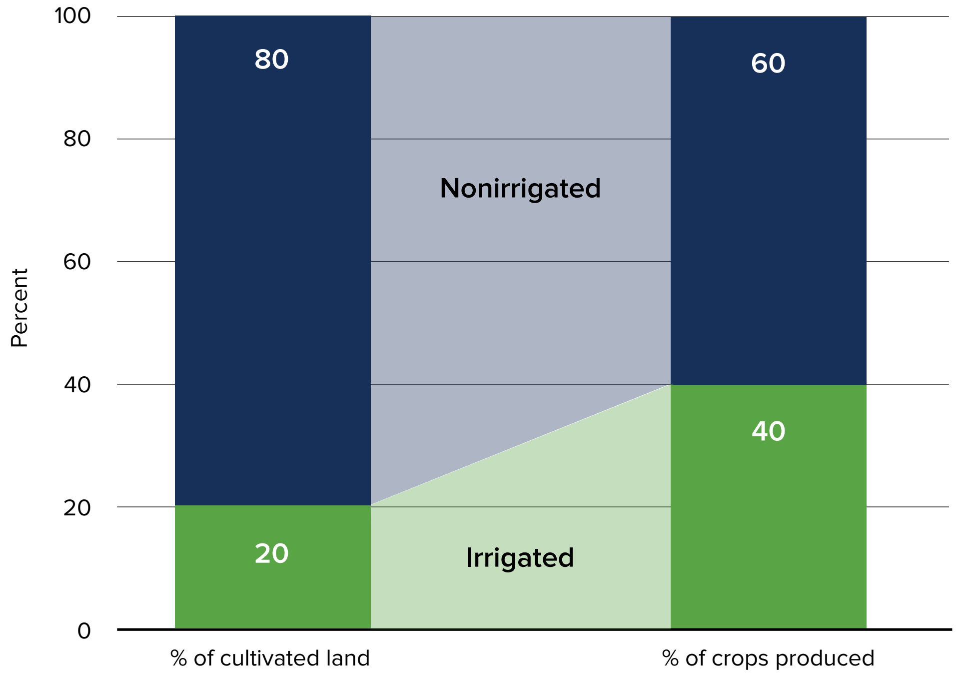
In Ethiopia, researchers are using enset, a deep-roots plant native to that country, in conservation efforts to not only conserve green water in soils by reducing runoff, but to provide water to plants that are grown around them. Organizations such as Self Help Africa and the American Association for the Advancement of Science are working to increase awareness about the important role of enset and to directly educate Ethiopian farmers. Ultimately, these efforts are aimed at bolstering soil health to strengthen soils' capacity to hold green water, helping increase crop yields, protect against drought, and promote the health and well-being of farms and local ecology.

Sources: Rockström et al. 2009, Groundswell International, FoodTank

Improving water distribution from flooded irrigation methods by land leveling can significantly reduce water waste and improve crop yield. Recent experimental results from drip irrigation methods in paddy fields show significant water savings. However, because of the interconnected nature of water, runoff from one water user is often available to other users through return flows. Thus, the actual savings of water and improvement in water user efficiency at the river basin level are frequently small, even when these new technologies are put in place. In such circumstances, well-intentioned investments in such technologies upstream can result in water transfers from downstream users, as occurred in the Indus River Basin in Pakistan.[86] The adoption of new technologies can even induce *increased* water use by making irrigation more profitable for individual farmers who expand its use rather than save water.[87]

However, even when there are limited basin-wide and system-wide water savings, there are many reasons for farmers to adopt advanced irrigation technology. These include increased income from higher-value crops, higher yields from more precise irri-

Figure 7 – Productivity gap: irrigated vs. nonirrigated agriculture



Source: ODNI 2015

gation during critical growth periods, farmer convenience and labor savings, and lower pumping costs. A water allocation system that recognizes these hydrological realities can promote the potential benefits of new technologies and farming systems. Well-specified water rights and allocations have the potential to significantly improve water, food, and nutrition security and to tap the potential gains of these technologies. Physical controls on water usage, which can include rationing or quotas through enforcement of water rights, are needed to maintain or reduce basin-wide water use after the introduction of new technologies.

Rainfed agriculture can benefit from improved technologies across the value chain

Rainfed agriculture accounts for around 60 percent of total crop production. It accounts for more than 95 percent of farmed land in Sub-Saharan Africa; 90 percent in Latin America; 75 percent in the Near East and North Africa; 65 percent in East Asia; and 60 percent in South Asia. In many regions, productivity remains significantly lower than in irrigated areas due to less access to water and often poorer soil and agroclimatic conditions as well as inferior access to roads and markets. As in irrigated areas, improved technologies and farming systems, together with logistics, including roads, cold chains, and storage solutions, can boost the production of food from rainfed areas.

There are two broad strategies for increasing yields in rainfed agriculture when water is scarce:

1. capturing more water
2. using the available water more efficiently by increasing the plant water uptake capacity and/or reducing nonproductive soil evaporation

There are a range of integrated land and water management options for achieving these aims. Most techniques such as water harvesting systems focus on capturing more water. Others focus on increasing water productivity (e.g., drip irrigation and mulching). Management approaches aimed at capturing more water often lead to higher water productivity, as denser crop canopies shadow the soil and thus reduce soil evaporation.[88]

Water harvesting

Water harvesting involves concentrating and collecting rainwater or runoff for productive purposes. Runoff can either be diverted directly and spread on the fields or collected and stored locally to be used later. Local water harvesting techniques include external catchment systems, microcatchments, and rooftop runoff collection. The last of these is used almost exclusively for nonagricultural purposes. External catchment water harvesting involves the collection of water from a larger area that can be a substantial distance from the

Water harvesting can increase the rainwater available for transpiration from 20 to 50 percent.

area where crops are being grown. Water harvesting can increase the rainwater available for transpiration from 20 to 50 percent.[89] Supplemental irrigation (adding a little irrigation from water harvesting or other sources in critical stages to supplement rainfall) can also increase the productivity of water.[90]

While many water harvesting case studies and experiments have shown increases in yield and water use efficiency, constraints remain for the widespread use of these technologies. Construction and maintenance costs of water harvesting systems, particularly the labor costs, are very important in determining if a technique will be widely adopted by farmers. The initial high labor costs of building the water harvesting structure often provide disincentives for adoption.

Green water management

Managing green water, or rainwater stored in the soils' root zone, is critical for controlling water lost through evaporation and reduces the demand for new water sources. Options include dry planting, direct seeding, conservation agriculture, and mulching.[91] Integrated nutrient management (INM), which combines application of chemical fertilizer and organic matter and use of other organic soil fertility practices (such as intercropping with agroforestry, soil erosion control, and tillage methods) can also improve soils' water-holding capacity and the productivity of water and land.

Integrated nutrient or soil water management requires new expertise, and the benefits often come years after the initial adoption as soil quality gradually improves, making it less attractive to farmers. Broader adoption of these techniques will require better extension, credit, and incentives such as payment for soil conservation services.

While expansion of rainfed areas can lead to a decrease in desertification, it can also take water from other uses such as forests, grasslands, and rivers. Expanding agriculture upstream through better rainfall and runoff harvesting and artificial storage systems can,

Box 9 – The Household Water Insecurity Experiences (HWISE) scale is a valuable tool

Problems with water have been identified as one of the most pressing global issues by global institutions like the United Nations and the World Economic Forum. However, scholarship and policy on this critical issue have been stymied due to an inability to sufficiently quantify water problems.

To understand the issue, household-level metrics are necessary. National-level data mask heterogeneity in water availability within regions and subpopulations and fail to capture whether available water is accessible or sufficient for household use.

To provide the needed data on household water use, the Household Water Insecurity Experiences (HWISE) scale was developed. Informed by survey data from 8,231 households in 28 sites around the world, the HWISE scale provides a simple, 12-item scale for measuring household water insecurity in any low- or middle-income setting. The HWISE scale is comprised of straightforward questions about water in the past month, from worrying about having enough water to going to sleep thirsty. With the HWISE scale, it is now possible to quantify the prevalence and determinants of household water insecurity and understand how household water insecurity impacts well-being across cultures.

The value of the data generated by this scale is manifold. The data will address the type and severity of problems with water, when they occur, and who is affected by them. This data is actionable and can be used to identify appropriate interventions. Solutions to poor water quality such as filters and chlorination, for example, are far different than solutions for water shortage such as storage containers and drip irrigation.

The data are also useful for targeting water interventions at times of scarcity, like dry seasons, or to populations at heightened risk, like pregnant women or the elderly. If water insecurity is not solvable, some of the consequences of water insecurity, like nutritional insecurity, may be mitigated.

The data will also make it possible to know if water interventions have a demonstrable impact on water security and are useful for politicians, journalists, program planners, and community leaders to demonstrate the burden of water insecurity, show the value of water interventions, and advocate for change.

Source: Young et al. 2019

as with irrigation technologies described above, also reduce downstream flows supporting other uses downstream.[92]

Additional solutions will further contribute to efficient water use

Plant breeding

Plant breeding can increase water productivity and improve crop resilience by yielding plants that require less water and that have improved salt and flood tolerance. Although it is a challenging breeding goal, improvement in crop yield per unit of water continues to show progress and has further potential.[93]

Agronomic and soil management

Seed priming, seedling age manipulation, direct- or wet-seeded rice, proper crop choice, integrating agriculture and aquaculture, increasing soil fertility, addition of organic matter, conservation tillage, and soil mulching can also contribute to improved water productivity.[94]

Reducing agricultural water pollution

A combination of technologies, management, and policy can also reduce the growth of agricultural water pollution. A wide range of options is at farmers' and policymakers' disposal to address the challenge, but few measures are being effectively implemented. In many regions, fertilizer subsidies should be modified to reduce the excessive use of cheap fertilizer. In addition to rationalizing fertilizer subsidies, a range of agricultural technologies exist or are being developed to help reduce agricultural water pollution. These include crop breeding for increased nutrient efficiency as well as enhanced fertilizer application methods. An example of this is fertigation, the application of fertilizer with irrigation water, used for a growing number of crops and irrigation methods. It is also possible to increase the use of precision agriculture methods such as slow-release fertilizer and yield monitors to apply fertilizers (and pesticides) where they are needed most or where they generate the highest yields.

Further, enhanced extension and information systems focused on balanced fertilizer applications and judicious application of pesticides can be provided. No-till or reduced tillage and other conservation measures such as terraces, soil or stone bunds, or buffer strips along water bodies have been shown to dramatically reduce erosion and thus protect water bodies from the adverse effects of runoff. Crop rotations with nitrogen-fixing (cover) crops are a further measure that can be applied in both large- and small-scale irrigation systems.[95] The effectiveness of any of these tools depends on increased farmer training and access to information about proper use.

The rapid dissemination of appropriate water-related technologies and information on their proper use is critical to realizing water productivity gains.

Improving extension services

The rapid dissemination of appropriate water-related technologies and information on their proper use is critical to realizing water productivity gains. Given that many of the new technologies are knowledge-intensive, extension services, education, and training will be crucial. Education can focus on strengthening human resource capacity, especially within local government agencies, to improve the delivery of rural services and extension. In addition, for agricultural extension programs to be effective and efficient, local government agencies should be given active roles in increasing the adaptive capacity of vulnerable farmers through training and other capacity-building activities. Innovative forms of extension—through radio, mobile phones, and other advanced information and communication technologies (ICT), for example—should be implemented. Public, private, and NGO extension efforts should be better coordinated.[96]

Improving value chains and reducing postharvest losses

Value chains from farm to table have important implications for water, food, and nutrition security. Millions of low-income people participate in agricultural value chains as producers, small-scale traders, processors, retailers, and consumers. The high costs to farmers and other actors of poor infrastructure, lack of information, insufficient credit, and policy distortions reduce the efficiency of value chains and impede producers' ability to connect to markets.[97] These costs and inefficiencies lead to postharvest losses that also waste the water used to produce and process food; to poor food quality; and to unsafe food. Improving the performance of value chains, therefore, can potentially benefit large numbers of people and help save water.

Food losses can occur at any point in the value chain—from production (crop damage, spillage) and postharvest processing (attacks from insect or microorganisms during storage) to distribution (poor infrastructure, cold storage), retail sale, and consumption (e.g., spoilage, table waste). In LMICs losses are mainly the result of inefficient harvesting methods and techniques, lack of storage and/or cooling facilities, and poor marketing and transport systems. In middle- to high-income countries, the biggest losses occur mainly after food reaches retail outlets, restaurants, and consumers where food is often thrown away due to spoilage and sell-by date expiration.[98]

It is hypothesized that waste is as much as 20 to 30 percent for cereals, pulses, meat, milk, and fish; 40 percent for roots and tubers; and 50 percent for fruits and vegetables.

But the elongation of supply chains, as well as the increase in consumption of perishables, has raised concerns internationally that waste and loss in LMIC countries' food supply chains are even more substantial. For example, it is hypothesized that waste is as much as 20 to 30 percent for cereals, pulses, meat, milk, and fish; 40 percent for roots and tubers; and 50 percent for fruits and vegetables.[99] A recent review of empirical studies showed lower rates: 16 percent for cereals, 19 percent for oilseeds, 24 percent for roots and tubers, and 27 percent for fruits and vegetables.[100]

The amount by which postharvest food losses can be reduced remains uncertain. But even loss rates of about 5 to 10 percent for grains, 10 to 15 percent for roots, tubers, and pulses, and 20 to 25 for fruits and vegetables indicate that there is potential for reducing food losses, which can also save the water used to produce that food.

Innovative financing and investments can propel water productivity initiatives forward

Innovative and sustainable funding mechanisms are needed to finance actions aimed at alleviating water scarcity in agriculture. For example, options such as green and blue bonds are emerging as a source of funding worth considering. Cooperatives have experience in facilitating access to financing for their members. Payment models for ecosystem services can be adapted for water interventions. Financing through new sources such as the Green Climate Fund can also be explored. Funding through Grand Challenges, the Global Water Fund, or Development Innovation Funds should also be tapped, since these sources have

Box 10 – Collective corporate action for water management is required for sustainability

Corporate actors have a significant vested interest in water sustainability since lack of access to affordable, clean water can disrupt the bottom line. In each of the World Economic Forum's last five Global Risk Reports, which survey companies on their risk perceptions, water crises have been listed as a top risk in terms of likelihood and impact. As a likely result of this, corporate actors are working alongside civil society and with each other to drive corporate stewardship of water resources.

One example is the CEO Water Mandate, a special initiative of the UN Global Compact, implemented in partnership with the Pacific Institute, an independent think tank focused on water. Over 140 companies, ranging from food and beverage companies to agricultural and mining companies, have all agreed to improving water availability and quality and ensuring access to water, sanitation, and hygiene. The mandate asks for action and accountability at the CEO level across six core areas: direct operations, supply chain and watershed management, collective action, community engagement, public policy, and transparency and disclosure.

The mandate allows companies to share best practices and work together to reduce water risks in specific geographies and sectors. The Water Action Hub, which is also associated with the CEO Water Mandate, widens the net of opportunity for collaboration to government, civil society, and research actors, each of which can map their water-related activities. Currently, over 600 organizations have catalogued water projects in over 2,700 locations, enabling greater transparency and partnership to improve sustainability.

The CEO Water Mandate is also facilitating an exchange of tools for taking action, including short online courses on specialized areas relating to water sustainability, open data sets, case studies, and guidelines for improving any number of indicators affecting water quality or quantity.

Source: Congress.gov; USAID 2018

Credit: A plantation worker walks pasts water sprinklers over rows of seedlings at nursery in Indonesia. Credit: REUTERS/Vivek Prakash quicker funding cycles designed to account for rapid technology advances and the ability to iterate and scale.

Another funding option is a mix of grants, loans guaranteed by governments, and contributions by beneficiaries. Blended finance, which strategically uses development finance or public funding to mobilize additional resources toward sustainable development in LMICs, is a promising approach for scaling up private-sector financing for water.[101] These alternative financing mechanisms need to be assessed for their relevance to water scarcity in agriculture and for how they can be accessed for this purpose.

Private-sector financing or investment in the irrigation sector of LMICs, however, has been limited mainly to groundwater development and, to a lesser extent, smaller commercial surface water systems growing high-valued crops. Experts highlight five reasons why the private sector hesitates to allocate significant budget to irrigation development. These include: (1) relatively low rates of return, (2) high financial risks, (3) political interference during project management that leads to water fees below sustainable levels for private investors or banking sectors, (4) government's concern that the private sector might sell water to industries rather than to agricultural users or domestic water suppliers in order to

Blended finance, which uses development finance or public funding to mobilize additional resources toward sustainable development in LMICs, is a promising approach for scaling up private-sector financing for water.

reap higher rates of return, and (5) failure to consider the irrigation sector as a commercial venture.[102] For these reasons, it is likely that financing of larger-scale water systems will continue to be mainly the domain of the public sector for the foreseeable future.

There is, however, strong interest in finding ways to better mobilize private investment in smaller-scale, farmer-led irrigation systems. One option is the franchise model in which a private company is granted a concession to develop water and associated land resources and then can earn a profit from the provision of water-related services to users.[103] There are a number of potential advantages to this approach. First, the mobilization of private capital relieves pressure on public development budgets. Second, the same entity designs, constructs, and operates the scheme, so there are incentives for efficient and cost-effective solutions. Finally, there are also incentives to recover both capital and operational costs.[104]

Yet there are also challenges in using this scheme. Potential rates of return on investment must be attractive, cultivators must be able to pay the costs needed for the private investor to recover costs, and government must regulate without seeking excessive rent or strangling the effort through bureaucratic challenges.[105] Morocco and Tunisia have implemented with some success the franchise approach to attract private concessions for the development and sale of irrigation water for high-value crops. In such cases the ability to charge an economically viable price is crucial. Where there are good prospects of profitability, there may be scope for using risk-sharing instruments (e.g., guarantees by public agencies) to stimulate private lending and investment.[106]

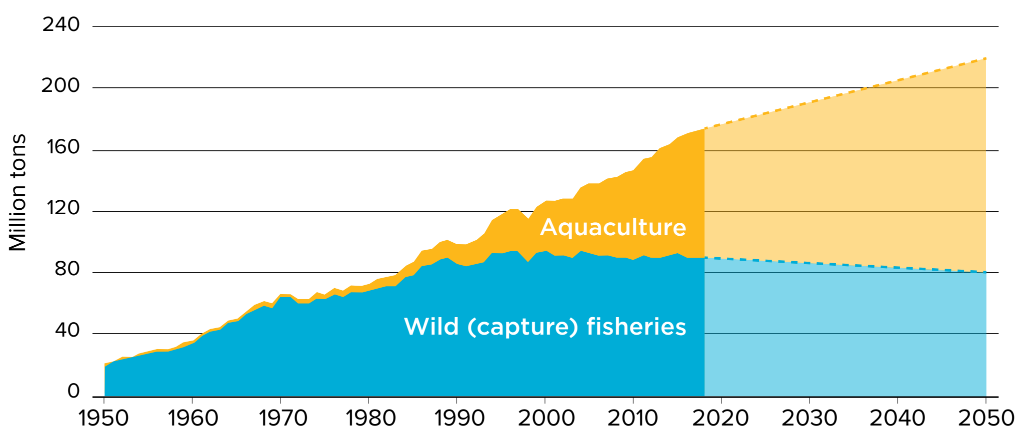
Shifting diets and diversifying agriculture to reduce demand for water and improve nutrition

Dietary shifts, supported by agricultural diversification, are another strategy that can potentially reduce water use and improve food and nutrition security. A strategy around shifting diets, however, must be based on what constitutes sustainability in a particular local context. Changes can impact livelihoods, and there may be unforeseen opportunity costs associated with shifting diets that should be heavily weighed before policies are implemented. Accounting for water use throughout the value chain, meat and cereals in general use more water per capita than higher-value crops such as fruits and vegetables. They also have lower use on the farm per kilogram of food produced, although this can vary by region and production and processing methods.[107] Meat uses large amounts of water due mainly to the cereals, soybean, and pasture that are used to feed livestock. Data show that most fruits and vegetables are more productive per unit of water in crop yield and far more productive in value per unit of water.[108]

In high meat-consuming countries, diets that shift consumption away from meats and cereals toward higher-value foods therefore have the potential for reducing water use over time. But for many LMICs in Africa and Asia, increased meat and dairy consumption has strong nutritional benefits. Cereals and other staple foods also remain essential. In LMICs, cereal crops—and the agribusiness and nonfarm rural economy that supports them—provide a large part of rural income that supports food consumption. In much of Africa, hunger driven by deficits in calories remains a major problem, and growth in consumption of cereals is needed.[109]

At a global level, and especially for high-income countries, the evidence on the impacts on water use—and greenhouse gas (GHG) emissions and land use—from shifting current dietary intakes to more environmentally sustainable dietary patterns has been systematically reviewed. The review included 210 diet scenarios from 63 studies, including 14 common sustainable dietary patterns, including vegetarian, vegan, pescatarian,

Figure 8 – Aquaculture production must continue to grow to meet world fish demand



Source: Historical data, 1950–2016; FAO (2017b) and FAO (2018), Projections to 2050; Calculated at WRI; assumes 10 percent reduction in wild fish catch from 2010 levels by 2050, linear growth of aquaculture production of 2 Mt per year between 2010 and 2050.
wri.org/sustfoodfuture | World Resources Report: Creating a Sustainable Food Future

Box 11 – Growth in aquaculture must be sustainable

Aquaculture is growing rapidly as demand for fish increases around the world and supplies of wild fish are being depleted. The output of the world's wild fisheries peaked in 1995, with all growth in seafood production since that time coming from aquaculture. As of 2016, aquaculture accounted for 47 percent of total seafood production.

Global per capita consumption of fish doubled between 1961 and 2015 to 20.2 kg per capita, accounting for 17 percent of consumption of animal protein. In the least-developed countries, fish accounted for about 26 percent of animal protein consumption, and it accounts for 19 percent of animal protein consumption in other developing countries. Many fish varieties are low in saturated fats, carbohydrates, and cholesterol and provide a wide range of essential micronutrients, including various vitamins, minerals, and polyunsaturated omega-3 fatty acids. Fish can also be an essential part of a nutritious diet for pregnant women and very young children, contributing to neurodevelopment during the most crucial stages of unborn and young child growth.

Aquaculture is projected to provide all the growth in fish production through 2030, with capture fishery production remaining near current levels. However, fish production faces sustainability challenges. Even without growth in capture fish production, the percentage of overfished fish stocks has continued to increase. As of 2015, 33 percent of fish stocks globally are classified as overfished. Poorly managed aquaculture causes many environmental problems, including destruction of mangrove forests; harm for marine organisms and human health due to excessive use of chemicals; transfer of viruses and parasites between farmed and wild fish; competition and interbreeding among farmed and wild fish, altering the overall pool of genetic diversity; increased levels of nutrients in the water from food and fish waste, leading to oxygen-deprived waters; and dependency upon fish meal and fish oil as feed puts pressure on capture fisheries.

But progress is being made in the implementation of more sustainable aquaculture. Production efficiency has improved, with a large decline in the use of fish meal and fish oil per unit of farmed fish. A 62 percent increase in global aquaculture production was achieved from 2000 to 2008 even though the global supply of fish meal declined by 12 percent. Integrated management of land, water, and other resources—together with upscaling of support to small-scale fisheries through education, extension of appropriate technologies, strengthening of fisheries organizations, and policy reform—can have high payoffs. Targeted incentives to encourage sustainable practices together with elimination of subsides that contribute to overcapacity and overfishing would also be beneficial.

Improving aquaculture will also require other investments. Like other agricultural sectors, fisheries suffer from high postharvest losses, as high as 27 percent between landing and consumption and 35 percent including losses prior to landing. To reduce these losses and improve quality and safety, investments are required in infrastructure and services, such as hygienic landing centers, electric power supply, potable water, roads, ice, ice plants, cold storage, refrigerated transport, and appropriate processing and storage facilities.

Source: FAO 2012; FAO 2018; Gustavsson et al. 2011; World Bank 2013; WWF 2018

Box 12 – Shifting diets will alter water and production needs

Evidence shows that as incomes rise, diets diversify, and, to some extent, people shift away from staple-food rich diets to eat more fruits and vegetables. In Taiwan, for example, rice consumption has fallen more than two-thirds in 50 years, and similar trends are visible in other parts of Asia with higher incomes. But other trends are also visible in wealthy economies, including overconsumption of food on the one hand and preference for "healthy" and sustainable foods on the other.

As populations grow and diets change, so do the water requirements to produce our food. But the water requirements of plants are also changing as plant genetics and farmers' practices improve. Optimizing the positive health, environmental, economic, and social impact of diets is no easy policy exercise. And shifting diets to align them to optimal production and consumption patterns is no easy behavioral task. Shifting production and livelihoods is yet another challenge, especially for smallholder farmers who live on less than $2 a day, requiring strong policy support, farmer education, and attention to constraints along the value chain.

So what impact will shifting diets have on current and future water use and how can we work collectively to ensure the best outcomes across crops and production zones? It starts with focusing on the needs for particular people and agro-ecologies and planning for the best ways to address the possibilities for that community. In the example of rice, that may mean promoting cultivation of water-efficient pulses in the fallow rice paddies after a rice harvest to boost household nutrition security, improve soil fertility, and increase income. In the medium term, it may mean supporting a conversion to the cultivation of vegetables or dairy as demand decreases. In every case there will be trade-offs across nutrition, natural resources, and livelihoods. Only monitoring, data collection, pilot testing, and R&D can help inform better policy both on the production side and on the consumer education side.

Source: Chandran 2018; FAO 2018; CGIAR 2018

Credit: Greg Garrett

Food	Fish	Dairy	Vegetables
Nutritional contribution	Fish currently supply roughly 17 percent of global protein and provide essential fatty acids.	Milk can provide affordable, essential micronutrients such as calcium, magnesium, and B vitamins in addition to protein to help combat child stunting.	Vegetables are an important source of dietary fiber and micronutrients, particularly calcium; iron; magnesium; A, B, and C vitamins; and phytochemicals such as antioxidants.
Livelihoods	Fishing, aquaculture, and fishery operations employ roughly 120 million people full time and provide income directly and indirectly for up to 820 million people through the production and sale of inputs, farming and harvesting, processing, and distribution.	There are an estimated 150 million dairy farms across the world, directly and indirectly providing income for roughly 1 billion people.	Out of the world's estimated 570 million farms, roughly 90 percent are family owned, often cultivating vegetables for their own consumption or for sale to markets or both.
Threats & opportunities	Wild fisheries face unprecedented threats from overfishing: more than 30 percent of the world's existing fisheries are close to exhaustion. Aquaculture continues to grow with increased demand, but existing systems are endangered by climatic shocks, rising temperatures, and unsustainable water use.	In smallholder systems, productivity often averages less than 2 liters a day compared to 15 in high-income countries, using the same amount of water and feed. Genetic improvement of dairy animals is needed, along with feed sourcing with attention to water to improve water intensiveness.	Demand will continue to grow for animal proteins, fruits, and vegetables. Cultivation of higher-value vegetable crops will become more promising for smallholders. However, many of the more profitable vegetables require access to irrigation, are highly perishable, and difficult to transport.

Mediterranean, "recommended" diets, and various levels of reduction in meat consumption. It found reductions as high as 70 to 80 percent in GHG emissions and land use and 50 percent in water use, with medians of about 20 to 30 percent for each of these indicators across all studies, from adopting sustainable dietary patterns. The review also showed that health benefits are possible by shifting current Western diets to more sustainable dietary patterns.[110]

Looking specifically at reduced meat consumption, another assessment examined four scenarios in which the amount of protein from animal products was successively limited to 50, 25, 12.5, and finally 0 percent of total protein intake.[111] It was found that reducing the consumption of animal products in the diet would decrease global green water consumption by 6, 11, 15, and 21 percent in the four applied scenarios. For blue water, the reductions

Changing dietary patterns could result in reductions as high as 70 to 80 percent in GHG emissions and land use and 50 percent in water use, according to some studies.

would be 4, 6, 9, and 14 percent. The results vary widely across regions, depending on the initial diets and production methods in each region. However, even in India, which has low meat consumption, a modeling analysis showed that optimized diets that meet nutritional guidelines while minimizing changes from existing diets had up to 30 percent lower blue water use and generally contained lower amounts of wheat, dairy, and poultry and increased amounts of legumes.[112]

Governments in many parts of the world are already experimenting with policy instruments designed to shift or "nudge" diets due to different motivations. The effectiveness of policies to induce dietary shift, however, is uncertain. School feeding programs can emphasize healthier food and an awareness of the resources required to produce it. Pressure can be put on corporations to improve the nutritional content of convenience foods or to make healthy foods more affordable or accessible to marginalized communities. Economic policies can also be used, through direct carbon taxes that fall more heavily on meat than on crops, causing meat prices to rise relative to fruits and vegetables and other crops.[113] Whether these policies can become politically, economically, and ethically feasible—and be sustainably implemented—must be determined. Application of broad-based policies such as taxes would need to be carefully designed based on local circumstances, including how the tax revenues are distributed, and should also take into account the impacts of these taxes on livelihoods of consumers and livestock producers.

If significant dietary changes occur over time due to behavioral change and policy interventions, it is important to examine whether agricultural production systems can diversify to meet new demands. Water availability per se is not a primary constraint to diversification above and beyond the constraint on overall agricultural production. Fruits and vegetables are often considered to be more "water intensive" than cereals and other field crops because they are more dependent on well-controlled irrigation and do not do as well under rainfed or intermittent water conditions. Data on field-level water use by crop vary hugely depending on agroclimatic conditions, farming systems, and management. However, while these crops may be more irrigation dependent, they normally use less water per kilogram of output—and less irrigation water—than cereals and other food crops.[114] In specific regions, growing conditions, and farming systems, fruits and vegetables

While fruits and vegetables may be more irrigation dependent, they normally use less water per kilogram of output—and less irrigation water—than cereals and other food crops.

may require more water per kilogram of water. In either situation, high-quality, dependable irrigation is a key to diversification to fruits and vegetables and other higher-value crops that support dietary change.[115]

Increasing managed water supply and expanding irrigated area

Given the growing demand for food and agricultural production to support the world's booming population, increased water productivity will have to be combined with expanded supplies of fresh, clean water for use in irrigation. This can be done to some extent through artificial groundwater recharge, desalination, and wastewater reuse and recycling.

The potential for increased irrigation area is substantial in some regions

Because new investments in irrigation and water supply are increasingly expensive and politically sensitive, hard infrastructure investment has a reduced role globally compared with past decades when dam building and expansion of irrigated area drove rapid increas-

Women work in a cauliflower field in Kolkata, India. Credit: REUTERS/Rupak De Chowdhuri

Box 13 – Farmer-led irrigation offers a new approach to resilience and profitability

Irrigation will become an increasingly important strategy for farmers in rainfed agricultural areas in Africa because of the improved productivity and increased resilience it enables. The potential is great: only 6 percent of arable land is irrigated in Africa, compared to 14 and 37 percent in Latin America and Asia, respectively. As outlined in a recent report by the Malabo Montpellier Panel, 38 million hectares of farmland across Africa could be introduced to irrigation.

Governments and multinational lenders have had a historical preference for funding state-led irrigation schemes, such as centrally managed canal and dam infrastructure. But these projects have shown mixed results, and there is a growing shift in emphasis toward smaller-scale, distributed projects inspired by farmers' needs.

Farmer-led irrigation, according to the World Bank, is when "farmers drive the establishment, improvement, and/or expansion of irrigated agriculture." Since the 1970s, farmer-managed pump and pipe irrigation has become the leading irrigation option in South Asia and has resulted in more irrigation there in the past 50 years than in the last 250. Adoption has been significantly slower in Sub-Saharan Africa, but is happening. Farmer-irrigated area is, for instance, three times larger than state-irrigated area in Tanzania's Lower Moshi.

Supporting farmer-led irrigation means finding new ways to invest in sustainable irrigation systems and collectively manage resources in decentralized ways. This includes creating opportunities for private investment in small-scale irrigation systems and making irrigation technology affordable. But it also requires focused investments in markets, transportation infrastructure, cold-chain storage, legal support, and education.

During a side event to the 2018 African Green Revolution Forum convened by the World Bank, African Development Bank, and the Alliance for a Green Revolution in Africa, the Kigali Joint Statement on farmer-led irrigation was adopted by an assembly of African government officials, financial institutions, nonprofits, academics, agribusiness representatives, and members of farmer organizations. The World Bank believes that implementation of the Kigali Statement will lead to farmer resilience in the face of climate change and variability as well as making significant improvement toward achieving SDGs 1, 2, and 3.

Feed the Future, the United States' hunger and food security program, also supports Innovation Labs for small-scale irrigation. And influential groups like the Malabo Montpellier Panel and the Daugherty Water for Food Global Institute have produced reports detailing smart smallholder irrigation expansion strategies.

The Malabo Montpellier Panel

The Malabo Montpellier Panel report, *Water-Wise: Smart Irrigation Strategies for Africa*, summarizes what six African countries—Ethiopia, Kenya, Mali, Morocco, Niger, and South Africa—have done right as they implement cutting-edge irrigation schemes. The policies and practices identified in the report could spur agricultural growth and transformation in Africa while increasing resilience and improving livelihoods in rural communities. By adapting the practices to local contexts across the continent, African governments can significantly increase the chances of meeting their national and international commitments to agricultural growth and transformation.

Sources: World Bank 2018; AGRA 2019; Mutiro 2015; Woodhouse 2017; Malabo Montpellier Panel 2018 es in crop yields, particularly in LMICs.[116] However, with climate change creating water shortages in some regions, and greater variability in water for other regions, there may be renewed demand for increased investment in both large and small dams for storage to accommodate future changes in rainfall and runoff. Potential increases in demand for hydropower can also generate increased investment in multipurpose dams for energy and agriculture. Substantial potential for expanded irrigation still exists in some regions of the world. Harvested irrigated area is projected to increase by 16 million hectares in East Asia and the Pacific from 2010 levels of 142 million hectares; by 7 million hectares from 22 million in Latin America; by 6 million hectares from 28 million in the Middle East and North Africa; by 37 million hectares from 113 million in South Asia; and by 10 million hectares from 8 million in Sub-Saharan Africa.[117] These increases include both expanded area under irrigation and improvement in cropping intensities.

The potential is even higher if appropriate policies are put in place. The World Bank's Africa Infrastructure Country Diagnostic study concluded that Africa has the hydrological

Sub-Saharan Africa has the hydrological and economic potential to add up to 30 million hectares of profitable smallholder irrigation via motor pumps.

and economic potential to add at least 16 million hectares of profitable, large-scale irrigation and 7 million hectares for farmer-led irrigation. However, the internal rate of return was substantially larger for individual and farm-community managed systems.[118] An even larger potential was shown for profitable smallholder irrigation expansion in Sub-Saharan Africa, up to 30 million hectares for motor pumps.[119] The amount of this potential depends on policies, incentives, and local enabling conditions.

The supply of managed water can be increased in multiple ways

Recharging groundwater

Investment in artificial groundwater recharge, or increasing the amount of water in aquifers by diverting it from sources that would not normally reach it, can also increase water supplies. Both large- and small-scale artificial groundwater recharge has potential. SAB Miller India partnered with local stakeholders in Rajasthan, India, to implement a basin-wide groundwater management initiative to improve the sustainability of the local deep aquifer. This aquifer is the only reliable source of water for the agricultural, industrial, and municipal sectors in the semiarid region, together with the seasonal monsoon rainfall. The construction of six recharge structures resulted in 345,000 cubic meters per year of enhanced aquifer recharge and a 5.2-meter rise in the water table locally. Training programs for local farmers on water efficiency practices were also implemented to reduce withdrawal for agricultural purposes.

SamSamWater Foundation, in collaboration with the NGO Chamavita and the community in Kwemakame in Tanzania, successfully implemented a small-scale aquifer recharge scheme capturing rainwater runoff from the steep rocky slopes of the local Usambara mountain range. The area suffers from a reduced rate of water infiltration due to deforestation, resulting in higher runoff from exposed bedrock and an increase in water abstraction

Box 14 – Groundwater recharge can expand water supplies

Human activities are becoming increasingly groundwater intensive. Groundwater has the highest rate of extraction of any raw material on the planet, and rates of withdrawal are increasing at nearly twice the rate of population growth.

Groundwater is technically a renewable resource, but it can take a very long time for water to infiltrate and "recharge" the aquifer, making it an effectively limited resource. The best strategy for managing groundwater is a two-pronged approach that measures water usage carefully and uses policies that encourage diversification of water sources to conserve limited resources.

With technology, however, aquifer recharge can be deliberately sped up. Managed aquifer recharge (MAR) is the process of intentionally supporting recharge and involves putting water collected from the surface back into aquifers for later use. MAR is less expensive than desalination and can contribute to improved water quality and quantity. There are several methods of recharge currently used, including surface spreading, infiltration pits and basins, and injection wells that are deep underground.

Shallow infiltration acceleration methods like the Bhungroo used in India may be quite effective for farmers who live in seasonally wet places. Managing surface soil moisture may be a solution for farmers living in areas that would require much deeper wells, which are more costly.

Water recharge in action: Bhungroo

Bhungroo technology in India, invented by Biplab Ketan Paul, enables farmers to store of excess surface water underground and then extract it during the dry season for use in agriculture. Bhungroo combines technology and business model innovations that are now serving over 20,000 farmers, with substantial impact on water management, nutrition, basic food security, and biodiversity. In addition to direct farming benefits, the approach helps build environmental, economic, and social resilience.

During rainy season monsoons, water can be "banked" quickly and safely (also helping mitigate flood risks in some areas) and can then be extracted more slowly when the farmers need it. This extends the growing season each year and helps mitigate negative impacts of dry spells and weather fluctuations.

The technology has been used to trigger local planning and regenerative economic development in communities, with particular benefits for poor people and local ecology. This "localizing" process increases successful adoption of the technology and adaption across different geographies. As a result, Bhungroo now grants the technology rights primarily to poor women in new communities and then works with them and others to understand and adapt the technology to local conditions. Bhungroo now operates in India, Bangladesh, and Vietnam and has partnerships in 10 additional countries in Asia and Africa.

Source: Bhungroo, The National Groundwater Association 2018; Siebert et al. 2018; Sprenger et al. 2017; FEMA 2015 due to rapid population growth. It is estimated that this scheme saves 1,200 cubic meters per year at an initial capital cost of $29,300.[120]

Desalination

Freshwater supplies can also be increased by desalinating seawater or brackish water. Desalination provides around 1 percent of the world's drinking water, but this percentage is growing rapidly. An expected US$10 billion investment in the next five years would add 5.7 million cubic meters per day of new production capacity. This capacity is expected to double by 2030. At the end of 2015, there were approximately 18,000 desalination plants worldwide, with a total installed production capacity of 86.55 million cubic meters per day. Around 44 percent of this capacity is located in the Middle East and North Africa. While desalination in that region is projected to grow at a rate of 7 to 9 percent per year, the "hot spots" for accelerated desalination development over the next decade are expected to be Asia, the United States, and Latin America.[121]

Growth will be helped by technical developments, including energy-efficient filtering membranes, that are causing desalination prices to fall. Pilot schemes are powering desalination plants with renewable energy. Depending on the scale of the plant and the

While desalination has significant potential in coastal regions, it is energy and capital intensive and creates waste disposal problems.

technology—as well as the availability of the source water—fresh water can be produced for as little as US$0.50 per cubic meter.[122] However, typical costs in 2016 remained at US$0.80–$1.20 per cubic meter.[123] Even at US$0.50, water from desalination remains more expensive than conventional sources, so desalinated water will likely be confined to the highest-value uses such as urban water supply or tourism.[124] It also tends to be limited to coastal areas since the distribution of desalinated water inland would add to the costs. It is estimated that while the relative contribution of desalinated water is small, the volume of desalinated water will grow significantly due to technological change and reach approximately 250 cubic kilometers annually by 2100, which would be 5 percent of projected total water demand.[125]

While desalination has significant potential in coastal regions, it is energy and capital intensive and creates waste disposal problems. R&D and technological change to reduce the costs and handle the negative by-products such as brine that damages ocean ecosystems will be essential for realizing the potential.

Wastewater reuse and recycling

Reusing wastewater is another source of fresh water for agriculture. Municipal wastewater accounts for the majority of wastewater directly used in agriculture. Municipal water demand corresponds to 11 percent of global water withdrawal.[126] Out of this only 3 percent is consumed, with the remaining 8 percent discharged as wastewater. This is 330 cubic kilometers per year, much of which could potentially be used for agricultural irrigation.[127] However, there is no comprehensive inventory of how much treated or untreated wastewater is used in agriculture apart from the incipient efforts by institutions like AQUASTAT, an FAO initiative.

Inadequate wastewater treatment and the resulting large-scale water pollution suggest that the area irrigated with unsafe wastewater is probably 10 times larger than the area using treated wastewater, causing fecal contamination and accumulation of microbiological and chemical pollutants in crops, livestock products, soil or water resources and leading to severe health impacts for consumers and farm workers.[128] If wastewater can be tapped through appropriate treatment, it can make an important contribution to safe food

> *The use of wastewater can encounter strong public resistance due to a lack of awareness and trust with regard to human health risks.*

production. In the most optimistic projection, if all of the approximately 330 cubic kilometers of municipal wastewater generated every year could be effectively treated, it could potentially irrigate 40 million hectares (with approximately 8,000 cubic meters per hectare), or 15 percent of currently irrigated lands.[129]

Nevertheless, the evidence suggests that even in best-case scenarios of sanitation system investments, the majority of wastewater generated in LMICs will continue to be untreated. Given the projected growth in demand for food, this means that the risks to public health remain. In such cases, measures to avoid contamination of crops, prevent exposure of workers, and protect consumer health are necessary.[130] A more realistic goal would be providing clean, treated wastewater to areas that are currently being irrigated with raw and diluted wastewater, which is in the range of 5 to 20 million hectares globally.[131]

The use of treated wastewater for irrigation has the most potential in urban and peri-urban areas, where wastewater is more easily available and reliable and where there is a market for agricultural produce. In the absence of elevation-assisted gravitational flow, the transport of treated municipal wastewater to more remote agricultural areas for irrigation is uneconomical, likely greatly reducing the potential area claimed above. If wastewater is used in agriculture without the necessary safety precautions, the effects can be detrimental. However, if adequately treated and safely applied, wastewater is a valuable source of both water and nutrients, contributing to food and nutrition security and the improvement of livelihoods.[132]

The use of wastewater can encounter strong public resistance due to a lack of awareness and trust with regard to human health risks. Other factors include different cultural and religious perceptions about water in general and/or using treated wastewater. Whereas public health and safety concerns have traditionally been the main reason for public resistance to wastewater use, cultural aspects and consumer behavior seem to be the overriding factors in most cases today, even if the reclaimed water resulting from advanced treatment processes is entirely safe.[133] Increased efforts by large corporations to enhance wastewater reuse in high water risk areas may alleviate some of these concerns. For example, in several of PepsiCo's manufacturing facilities in Mexico, the company has installed membrane bioreactors coupled with reverse osmosis wastewater treatment technology, which enables water reuse and helps to deliver greater water-use efficiency.[134]

Water recycling also can provide opportunities for water supply expansion and water resource recovery, both on a large scale, for example in industrial parks where synergies in water recovery and recycling can be achieved, and on a small scale. Large-scale recycling plants tend to be energy intensive and produce sludge that is difficult to dispose.[135] Newer technologies may be able to alleviate these problems by developing new sludge by-products and moving toward recycling at net zero energy cost by capturing biogas.[136]

Smaller-scale recycling is exemplified by wastewater collection and recycling in the greenhouses of Sher Ethiopia, which produces roses for export and employs around 10,000 local people. Prior to recycling, wastewater was discharged directly into a nearby lake. With implementation of the recycling project, Sher Ethiopia has collected wastewater and treated it in constructed wetlands. The effluent is then stored in reservoirs and eventually added to the irrigation water of the greenhouses, dramatically reducing the environmental impact of the company.[137]

An alternative to recycling is to enhance the natural environment to improve water quality at the source, and to store more water, enhance water quality, reduce flooding, and provide other critical benefits.[138] Payments for environmental services, as discussed above, can help realize these gains.

Increasing urban and periurban agriculture

With rapid urbanization and changing population and dietary patterns, the role of urban and periurban agriculture is of increasing potential importance. Urban agriculture and periurban farming offer many attractive benefits as populations boom in these regions, including the use of hidden or underutilized urban natural resources; maintaining green spaces that also generate income; reducing the heat island effect in cities; and having direct access to relatively inexpensive treated wastewater.[139] Urban agriculture at a commercial level can provide competitive advantages for low-income people. For producing vegetables, for example, some of the advantages include easy access to inputs; highly segmented, accessible markets; openness of market information; and availability of multiple marketing channels depending on the scale of operations.[140]

Plastic containers are used to carry water from a well near the slum of Petare in Caracas, Venezuela. Credit: REUTERS/Carlos Garcia Rawlin

A global assessment of urban and periurban agriculture shows that these areas are an important resource.[141] The global area of urban irrigated croplands (within cities of at least 50,000 population) was estimated at about 11 percent of all irrigated croplands, or 24 million hectares. The global area of urban rainfed croplands was approximately 4.7 percent of all rainfed croplands or 44 million hectares. The distribution of urban and nonurban irrigated and rainfed croplands varies greatly across regions. South and East Asia comprise 49 percent of urban irrigated croplands and 56 percent of the nonurban irrigated area globally. These same two regions account for 26 percent of urban rainfed croplands and 22 percent of nonurban rainfed croplands. Developed countries account for 20 percent of irrigated urban croplands but 44 percent of urban rainfed croplands. Sub-Saharan Africa comprises less than 1 percent of urban irrigated and 3 percent of urban rainfed croplands but 14 percent of nonurban rainfed croplands.[142]

Such patterns contrast with much of Asia, where more croplands are located within urban boundaries.[143] However, even in Sub-Saharan Africa, urban agriculture is locally important. A survey of 11 cities and towns in Southern Africa showed that 22 percent of households are engaged in small to microscale urban agriculture, including crops and livestock. In 21 cities and towns in West Africa, this ranged from 20 to 50 percent of households.[144]

The total area of irrigated croplands within 10 and 20 kilometers of urban boundaries is 40 and 60 percent of total irrigated cropland, respectively, or 87 and 130 of 214.5 million hectares. Such an expansive definition of periurban agriculture subsumes a substantial area of what would normally be considered rural agriculture, subject to the same recommended policies, technologies, and investments.

The total area of irrigated croplands within 10 and 20 kilometers of urban boundaries is 40 and 60 percent of total irrigated cropland, respectively, or 87 and 130 of 214.5 million hectares.

Significant constraints to urban and periurban agriculture also exist. Lead and heavy metals in the soil, air, and water are major contaminants that can collect in the leaves of certain green leafy vegetables and cause health issues. Regular testing of all foods is necessary to ensure a safe food supply, and any foods unfit for human consumption should be destroyed.[145]

Efforts should be made to convince health agencies to include urban agriculture in existing programs. In many cities, especially in LMICs, farmers use drainage runoff and raw sewage to irrigate. While public health laws exist to prevent this practice, implementation is varied.[146] As a complement to large-scale systems, sewage can be treated through pond systems that are relatively inexpensive and low in maintenance.[147] Ensuring the safety of these systems, however, can be a substantial challenge. Successfully meeting this challenge can bridge agricultural production and sanitation management.

Poorly managed animal production in urban and periurban areas can also cause risks to public health. Accumulation of fecal materials can provide breeding grounds for harmful pathogens as well as the insect vectors that carry them. Credit and extension services are often limited or nonexistent, exacerbated by the lack of land rights and changing zoning and construction that constantly change the availability of land for urban farming.

Box 15 – Israel is a leader in water innovations for arid environments

Water insecurity can trigger social tensions, but with the investment of resources, R&D can also lead to impressive innovations. Israel, for example, is 60 percent desert, yet the population has grown tenfold since 1948, requiring considerable attention to water management.

Early constraints on water, a rapidly growing population, and overexploitation of aquifers meant that Israel needed to engage in a massive R&D program for reusing treated wastewater. Additionally, certain policies gave farmers strong incentives to use treated, reclaimed wastewater for irrigation instead of fresh water. Reused wastewater now accounts for over 40 percent of the country's irrigation needs. This innovative system has almost entirely closed the urban water cycle, with 87 percent of wastewater reused.

Israel also led early development of efficient, low-volume irrigation technologies such as drip irrigation and miniature sprinklers. Considerable support has been provided to regional irrigation companies by the Agricultural Extension Service. Israel has made a special effort to promote innovations in the water sector, with the establishment of a unique ecosystem combining business and industry, water utilities, and research universities to support the development of innovative water technologies. Widespread development of efficient irrigation technologies, together with growing access to treated wastewater, has made it possible for the agricultural sector to continue to irrigate despite a sharp reduction in the amount of available fresh water. In addition, limited groundwater resources sparked the development of large-scale desalination systems, many of which were developed through public-private partnerships. Desalinated water now accounts for 85 percent of domestic urban water consumption.

Source: FAO AQUASTAT 2016; Juanico and Friedler 1999

Irrigation system in Isreal. Credit: istock/avian75

Urban farmers in most cities continue to struggle against existing regulations, agencies, and financial disincentives. Local government recognition of the role of urban agriculture, together with relatively small investments in personnel, capital, and legislative and regulatory change, could significantly improve the prospects for urban farming.[148]

Leveraging international agricultural trade policies and the virtual water trade for improved water resource management

International trade, including trade in "virtual water," has been shown to impact the water sector and can be used to improve water and food and nutrition security.[149] Virtual water is the volume of water used to produce a good or service, including agricultural commodities. It is measured in crop water depletion or in irrigation water depletion.[150]

By substituting cereal and other food imports for irrigated agricultural production (providing virtual import of the water embodied in the food), countries can effectively reduce their agricultural water use, saving water for other uses. Moreover, when agricultural exporters are more water efficient in production than importers, global water savings take place.[151] With much of world cereal exports coming from highly productive irrigated and rainfed systems in the United States, Canada, and Brazil, substantial water savings are generated.[152]

International trade is driven by economic and political forces rather than by water scarcity. Trade protection and domestic support for agricultural production (e.g., tariffs, duties, agricultural commodity price support, and subsidies) influence the movement of virtual water.[153] OECD countries generally have the highest agricultural trade barriers (although Australia, for example, has open trade policies). Yet many LMICs have also maintained barriers to agricultural trade to protect domestic agriculture from international competition.[154]

Available evidence shows small to substantial increases in virtual water flows due to trade liberalization.

Trade liberalization can potentially have large, positive impacts on the economies of many countries, especially in LMICs, although the increases in international commodity prices due to liberalization can also increase pressure on LMICs' water resources. However, available evidence shows small to substantial increases in virtual water flows due to trade liberalization.[155] Trade liberalization also tends to reduce water use in water-scarce regions and to increase water use in relatively water abundant regions such as the United States and Latin America.[156] An analysis of the virtual water trade in Africa finds that undernourishment tends to decline with increased virtual water trade openness. The potential for implicit "infrastructure sharing" is shown by countries with small dam storage capacity obtaining a higher fraction of their agricultural water requirements from virtual water imports.[157]

There is a need to integrate water and development issues, including their environmental effects, in trade and development policy. The import of food and its embodied virtual water can be important in water-scarce areas to improve food and nutrition security.

Box 16 – US leadership for global water and food security

Several pieces of bipartisan legislation and policymaking have underpinned the US approach to global development policy on water. First among these is the Senator Paul Simon Water for the Poor Act of 2005 (WfP), which designated water access, sanitation, and hygiene (WASH) as important foreign policy priorities for US national security interests. The legislation created conditions for the US administration to help millions of people gain better access to water resources by increasing the US government's capacity to implement WASH programs, target resources to communities in need, and develop a comprehensive strategy for addressing a critical challenge for the most vulnerable. It is estimated that 31 million gained access to water and 12 million gained improved sanitation under WfP from 2005 to 2014.

Building upon the success of the 2005 act, the 2014 Senator Paul Simon Water for the World Act specified criteria for high-priority countries for assistance; required reports to Congress no later than every five years; and authorized the establishment of water coordinators at USAID and the State Department with overlapping, coordinating, but independent roles. This legislation ensures that all US government agencies focusing on WASH issues are working closely together to maximize impact.

The USAID water coordinator implements water programs, focuses on economies of scale and efficiency, identifies country "capacity, capability, and commitment" to determine countries likely to make significant sustainable improvements, and is required to develop and utilize appropriate metrics and evaluation. Water management is included as a component of the role, which is more applicable to agriculture than other aspects of WASH.

The State Department water coordinator manages resources related to "intra- and transboundary conflicts over water resources consistent with national interests" and represents the United States in key international fora.

Water for the World Act high-priority countries

- Afghanistan
- Democratic Republic of Congo
- Ethiopia
- Haiti
- Indonesia
- Jordan
- Kenya
- Lebanon
- Liberia
- Nigeria
- South Sudan
- Uganda

Source: Report to Congress, Senator Paul Simon Water for the Poor Act

PART III

Credit: Marilyn Shapley/Mercycorps/Niger

ENSURING THAT WATER SOLUTIONS REACH SMALLHOLDER FARMERS

To ensure that farmer-led irrigation can thrive in Sub-Saharan Africa and other regions requires a conducive policy environment, affordable technologies, infrastructure, institutions to support irrigation management, and investment in research and extension services.

Conducive policy environment

A conducive policy environment includes secure and equitable water and land rights, economic incentives to use water more efficiently, and improved governance for more sustainable (ground)water use. Improvements in agricultural policies are also needed such as trade and agricultural input and output support policies, plant breeding programs, revived extension systems, and enhanced microfinance and credit policies. Agricultural trade policies can harm local food systems, including farmer-led irrigation, if they favor crops from large-scale production over those from small-scale systems. The attractiveness of investing in irrigation technologies and services is related to import policies, currency exchange rates, the competitiveness of input and output markets, and regional trade policies.[158] Numerous studies have identified these policy areas as major impediments to investment and therefore major opportunities to encourage investment.[159]

Many governments in Sub-Saharan Africa and Asia have been using agricultural input subsidies to support agriculture. As noted above, generalized subsidies should be modified, and the funds saved should be reallocated to targeted subsidies for smallholder farmers that would encourage the uptake of advanced irrigation and other technologies. Investing in more research on crops adapted to irrigated microenvironments and in outdated extension systems would also be beneficial.

Affordable technologies

Affordable technologies for irrigation management such as low-cost precision agricultural technologies are rapidly increasing in availability and declining in cost. However, while available in international markets, such technologies have yet to reach farmers in more remote, rural areas. Thus, it is essential to develop precision technologies suited to smallholder farmers as well as credit and contracting services for precision equipment. Establishment of clear land rights would also facilitate the consolidation of farms into larger operations, if necessary, without depriving smallholder farmers of ownership.

It is essential to develop precision technologies suited to smallholder farmers as well as credit and contracting services for precision equipment.

Solar-powered irrigation pumps are one technology that is rapidly increasing in Sub-Saharan Africa and will likely provide further rapid boosts to farmer-led irrigation. This technology must be combined with sound groundwater (and surface water) governance as well as farmer training programs with adequate incentives to ensure success and avoid rapid water depletion and degradation that would be likely in many parts of Africa's drylands.

Precision agriculture for the smallholder

One example is Hello Tractor, which features small-scale tractors designed to be economical, yet still meet the needs of the typical farmer in Nigeria and similar countries. These three-wheel "smart tractors" are equipped with GPS technology and the ability to monitor maintenance application intervals for inputs like fertilizer, making crop management easier for owners. Nearby farmers who have a need for a tractor can send a text message to Hello Tractor describing the service they need and sending an electronic payment. The company identifies a tractor owner nearby, and the owner provides the tractor.

With lower costs for the use of farm machinery through Hello Tractor, more farmers can access the tractors to increase their productivity and meet ideal timelines for each stage of the crop cycle, thus improving their yields. This system also allows tractor owners to offset the initial cost of their equipment, making it more feasible for small-scale farmers in Africa to own their own tractors.[160]

A similar approach has been used for irrigation. The need for upfront irrigation investment has led to the emergence of a rental market in Sub-Saharan Africa, where entrepreneurs either rent pumps to farmers by the day or season or provide an irrigation service themselves. By monitoring such developments, donors and NGOs can help create an enabling environment in ways other than simply providing pumps.[161]

Aerial images from satellites or drones, weather forecasts, and soil sensors are making it possible to manage crop growth in real time.

Aerial images from satellites or drones, weather forecasts, and soil sensors are making it possible to manage crop growth in real time. Zenvus, a Nigerian precision farming start-up, measures and analyzes soil data like temperature, nutrients, and vegetative health to help farmers apply the right fertilizer and optimally irrigate their farms. The system can improve farm productivity and reduce input waste by using analytics to facilitate

Satellite imagery: India wheat. Credit: © DigitalGlobe 2019 data-driven farming practices for small-scale farmers. UjuziKilimo, a Kenyan start-up, seeks to use big data and analytic capabilities to transform farmers into a knowledge-based community with the goal of improving productivity by adjusting irrigation.

SunCulture, which sells drip irrigation kits that use solar energy to pump water from any source, can make irrigation affordable.[162] Two examples of precision agriculture for irrigation in Africa are FruitLook, which is used by farmers in the Western Cape in South Africa as a state-of-the-art information technology that helps deciduous fruit and grape farmers become water efficient and climate smart. The Chameleon and Wetting Front Detector Sensors have enabled small-scale farmers in Mozambique, Tanzania, and Zimbabwe to dramatically cut irrigation frequency and double productivity.[163]

Financial solutions

Beyond precision farming, financial solutions designed for farmers are blossoming. FarmDrive, a Kenyan enterprise, connects unbanked and underserved smallholder farmers to credit, while helping financial institutions cost effectively increase their agricultural loan portfolios. Kenyan start-up M-Farm and Cameroon's AgroSpaces provide pricing data to remove price asymmetry between farmers and buyers, making it possible for farmers to earn more.[164] Scaling up these innovations will be a critical next step for achieving large benefits.

Value chain improvements

In addition to pricing services, advanced technologies can help value chains better serve smallholder farmers in other ways. Sensors linked to digital information systems have the potential to improve links between farmers and processors, reduce postharvest losses (reducing water used in producing the food) with digitally enabled harvest loans and digitally warehoused receipts, inform on-farm harvest practices, monitor storage conditions

Innovation is especially important to integrate sensor technology and data applications into locally appropriate products and services that address problems affecting smallholder farmers.

along the value chain, track provenance for supply chain optimization and grading, reduce the cost of transport, increase transport options for farmers, and increase access to timely information so that farmers know if and when transport is arriving.[165]

Progress is, therefore, being made to turn the potential of sensors and digital information systems into reality for agriculture and water management. Yet major efforts are still required to achieve large-scale adoption in developing countries. The prices of sensor technologies remain high for most developing country applications. Both the market and donors have a role to play in speeding up cost reductions for sensors and related technologies and in supporting local development partners in testing and refining technologies for context-specific applications. Innovation is especially important to integrate sensor technology and data applications into locally appropriate products and services that address problems affecting smallholder farmers. Donors, entrepreneurs, and development and private-sector actors all have a role to play in promoting adoption by creating and disseminating actionable information to smallholder farmers and others along the agricultural value chains.[166]

Infrastructure

Access to rural roads and proximity to markets are essential for farmer-led irrigation. Sub-Saharan Africa has made substantial investments in road infrastructure over the last two decades. Access to a source of energy for irrigation is also essential. Energy is often

Innovative, public-private financial instruments to support the entire irrigated agriculture value chain should be scaled up in collaboration with local banks, cooperatives, and farmers' organizations.

needed to pump water from the ground and sometimes surface sources. Energy is increasingly needed to distribute water in the field, for heat removal and cold storage, for the packing or processing of vegetables and fruits, and for transporting surplus irrigated products to markets.

While investments in rural infrastructure such as roads and electricity are critical, investments in emerging ICTs are also paramount to ensure market and credit access. Import tariffs on motor pump technologies have been identified as a factor slowing farmer-led irrigation, as have poorly developed supply chains for the pumps. Problems include highly centralized supply chains, highly variable prices across locations, poor training, and few support and repair facilities for pumps.[167] It is difficult for smallholder farmers to afford the few hundred dollars required to purchase a pump, and small, local agribusinesses also struggle to obtain operating capital to stock equipment and spare parts and develop and implement new services for irrigators. Innovative, public-private financial instruments to support the entire irrigated agriculture value chain should be scaled up in collaboration with local banks, cooperatives, and farmers' organizations.[168]

Institutions to support irrigation management

Monitoring irrigation users through registries, which should also record water rights, is essential. This would ensure that small-scale irrigation is acknowledged in a way that can be properly supported with policy and that overall agricultural water is appropriately managed on a larger scale. It would also prevent adverse impacts such as water depletion, pollution, and degradation. Such systems are currently underdeveloped in much of the world. Generally speaking, governments do not monitor farmer-led irrigation development. While African irrigation agencies do not have technologies in place to reliably monitor very small irrigated plots through remote sensing, rapid advances in satellite data and applications make this a possibility in the near future and should be further explored.

To ensure that crops from farmer-led irrigation can be exported, aggregating mechanisms need to be put in place, for example, through cooperatives that can help ensure that economies of scale for inspection, packaging, food safety regimes, and quality management are achieved competitively. Such cooperatives can also lower costs for agricultural inputs such as seeds and chemicals and can also support microfinance services.

Investment in research and extension services

The level of investment in agricultural R&D in Africa is extremely low and to date has had very little impact on crop productivity compared to R&D in other regions.[169] Applied research is especially lagging in agricultural water management, including irrigation. African governments and the private sector should increase funding for applied agricultural research, especially water management, and create an institutional support system that will encourage evidence-based innovation. External funders could contribute to this by offering attractive, long-term cofunding.[170]

Extension services need to rely not only on government agencies but on NGOs and the private sector. A promising private-sector initiative in Africa is Farm Business Advisors (FBAs), a network of commission-based entrepreneurs who provide four basic services to farmers: (1) inputs and equipment such as drip irrigation kits, (2) agricultural advice and installation and servicing of equipment, (3) advice on output markets, and (4) advice and

African governments and the private sector should increase funding for applied agricultural research, especially water management, and create an institutional support system that will encourage evidence-based innovation.

assistance in obtaining loans. International Development Enterprises, a nonprofit international social enterprise, has pilot-tested this model in Zambia. Over time, the cost of fielding FBAs has declined as the number of clients increased, and both the FBAs and farmers have profited financially. Factors contributing to this success include a built-in data feedback loop, sales training for FBAs, and adaptive, flexible management.[171]

Use of affordable smartphones is expanding rapidly in rural areas of Africa, further improving access to market and crop information. Smartphones can also allow for the transfer of funds, and they can provide access to weather forecasts and online software to make irrigation more precise and cost effective. Farmerline, a social enterprise that uses mobile technology to connect farmers to information and services, provides daily weather updates, assistance on getting seeds and fertilizer on credit, and access to market prices in local languages in 11 African countries.[172]

Access to assets for women

Women's access to the same rights and resources as men is critical to improving agricultural productivity along with food and nutrition security. The same is true for water security. Improvements to farm water infrastructure may reduce women's disproportionate exposure to time-consuming and often dangerous water collection tasks. But access to legal water and land rights, support services, and education are also essential to achieve these physical security goals. The establishment of cooperatives and collective action can also be beneficial.

Improvements to WASH and drinking water infrastructure continue to be of critical importance. Water collection in LMICs is gendered and often hazardous. More than 263 million people, almost entirely women and girls, travel at least 30 minutes from home simply to get water for drinking, bathing, cooking, and other household needs.[173] In a study of 25 countries in Sub-Saharan Africa, UNICEF estimated that women there spent 16 million hours collecting water each day. Women in a recent study in Kenya reported spending an average of 4.5 hours fetching water per week, causing 77 percent to worry about their safety while fetching and preventing 24 percent from caring for their children.[174] The time lost to collection represents a loss of productive capacity for women who already face the "time poverty" of uncompensated labor necessary for managing a household and caring for dependents. Closer safe water sources would reduce these risks and free up women's time for more productive activities.

African woman from Maasai tribe collecting water, Kenya, East Africa. Credit: istock/hadynyah

Women also have key roles in labor-intensive, manual irrigation methods, including the use of buckets, bowls, and their hands to distribute water to fields. Even within the same household, husbands and wives may be using different small-scale irrigation technologies on different plots that they manage separately. With heavy domestic work obligations, women struggle to fit in irrigation duties as well.[175] Affordable, non-human-powered irrigation technology would benefit these women, make their farms more productive, and allow them to grow more crops per year.

Part of making this technology affordable for women, however, lies in strengthening female farmers' access to legal rights, financial assets, and education, far beyond the domain of water management. The gender gap in access to assets has wide-ranging consequences. For example, adaptation to climate change also appears to be happening more slowly among female farmers. A study in the Rakai District of Uganda found that

Women's access to the same rights and resources as men is critical to improving agricultural productivity along with food and nutrition security.

farmers have begun to notice a range of climate effects, including declining soil quality, more frequent flooding, and new pests, but that rates of adaptation are noticeably gendered.[176] Some of this is attributable to male farmers' wealth advantage. However, it is also likely related to women's sometimes formal exclusion from land ownership—which would allow them to get loans for improvements and to be eligible for NGO and government initiatives aimed at landholding farmers—and to women's education and access to information. Studies in Bangladesh indicate that husbands in male-headed households tend to own and control more assets, especially in the form of land, but that extreme climatic events negatively affected these assets. Assets owned by wives or held jointly by husbands and wives in such households were not found to be affected in the same way.[177] Overall, assets controlled by women were found to benefit the well-being of other members of households, especially children, in terms of health, education, and nutrition.[178] This lends support for policies and programs aimed at protecting—and increasing—women's ownership and control of assets.

Land tenure reforms are a persistent theme in improving the economic prospects for women in LMICs. Control of land is, however, profoundly connected to control of water for rural populations. Even though women are responsible for a large share of smallholder agricultural productivity, their ability to gain legal control of the land they farm is not equivalent.[179] This has a negative impact on their ability to utilize support services (e.g., extension services, financing, and technology education) offered to landholders but disproportionately excluding women.[180]

While efforts to increase women's empowerment and resilience need to be tailored to specific local and institutional conditions, some generally effective approaches have emerged.[181] Improving women's access to financial training and services such as savings, insurance, credit, and emergency loans will help them adapt to changing water availability. This includes, in some cases, basic legal rights to own these assets. Additional investment in education and extension should be targeted to women to support their adoption of better technology and agricultural practice and to inform them about climate change, business management, and available financial tools. Gender relations need to be addressed all the way from the household to state- and national-level agricultural and water resource agencies.

Improvement in off-farm adaptive capacity is also essential. Assistance should be focused on helping women move into stable, well-paid livelihoods (e.g., fair wage employment, nonfarm entrepreneurship), ensuring safe working conditions, helping them overcome mobility constraints, and providing literacy and numeracy training. Reducing the water security gap and gendered exposure to water collection hazards have direct benefits for women's health and security. Moreover, many of the solutions to this problem for female smallholder farmers will make them more productive with a greater capacity to grow nutritious food, sell it profitably, and become resilient to climate change.

Pushkar Street Scene, India. Credit: istock/ferrantraite

CONCLUSION: THE PATH TO WATER SECURITY

A man waters a plant in Kenya. Credit: Katie G Nelson RTI International

Water is a vital resource that is becoming increasingly scarce and threatens to undermine the progress that has been made on global food and nutrition security. With the potential for severe economic, political, and humanitarian consequences across low- and high-income countries, water scarcity is a critical global issue that demands immediate action to improve water productivity and management.

Given that agriculture is by far the largest user of water, efforts to improve agricultural productivity and development for global food security in the coming decades must be combined with leadership and initiatives on effective water usage and management. Smallholder farmers, who represent the vast majority of farmers in LMICs, must be included in these efforts.

Agricultural diversification into higher-value crops such as fruits and vegetables is already seen as a successful strategy to help smallholder farmers increase their incomes and pull themselves and their communities out of poverty while helping meet growing demand for such foods. With the right policies, incentives, and support, smallholder farmers can play an important role in simultaneously increasing water productivity and moving the world toward greater water, food, and nutrition security.

With the potential for severe economic, political, and humanitarian consequences across low- and high-income countries, water scarcity is a critical global issue that demands immediate action to improve water productivity and management.

In addition to the strides that have been in agricultural productivity and diversification, there is an ongoing revolution in the processing, wholesale, and retail segments of the value chain that facilitates such diversification and has other far-reaching consequences.[182] This process has been moving quickly in LMICs during the past three decades and includes consolidation of value chain operations, rapid institutional and organizational change, and modernization of the procurement system. These changes have mainly been driven by the private sector through both domestic and foreign direct investment, but public-sector investment in infrastructure has been essential in providing the underlying conditions.

Both the public and private sectors as well as NGOs must be engaged to create the conditions for improved water productivity as part of these developments, which will be necessary to achieve water, food, and nutrition security. Policies and services needed for smallholder farmers in LMICs to successfully participate in this transformation are similar for water and crop productivity: access to inputs, credit, extension services, and technology.[183] General policy recommendations focused on water security specifically are summarized here. Effective implementation of these policies in countries will require understanding of specific institutional, agricultural, and economic contexts.

Improve water resource governance at basin, system, and subsystem levels

Improved water management in river basins can be achieved by strengthening the capacity of public institutions; coordinating across water, agriculture, and energy ministries; and improving tools for planning and monitoring. Devolution of important subbasin water management functions to community-based water user associations (WUAs), farmer groups, or other private-sector actors can also be beneficial. But institutional approaches need to be pragmatic in seeking solutions that are effective within the physical, social, and governance context of specific locations. Top-down implementation of integrated water resource management and WUAs has not generally worked well. Integrated management is often costly and politically difficult or impossible to implement, and second-best solutions that are less costly and take account of local conditions may be more effective. Similarly, WUAs are more likely to be effective when the design and implementation of the WUA involve prospective members and when the provision of improved water delivery services is emphasized, not just farmer obligations such as fee payments.

Implement more effective incentives for water management

An important reason for the slow uptake of management innovations and new technologies is the lack of incentives to conserve water and other inputs due to perverse subsidies and policies for water, energy, and fertilizer. Better incentives would improve the performance of water allocation and management. The establishment of secure water rights, recognizing and building upon existing customary rights, with a strong effort to ensure gender equity is an important first step in empowering farmers and providing a framework for more effective and efficient water management. When smallholder farmers have secure water rights, they know that they can retain their water even if the pattern of water use changes when they invest in farm improvement, new crop varieties, improved crop management, and appropriate levels of inputs.

Incentives for water management would be improved by rationalization of water, energy, and fertilizer subsidies, beginning with a reduction of costly generalized subsidies.

Innovative systems to introduce more effective incentives for efficient use of water should be developed and pilot tested (e.g., water brokering to WUAs; paying farmers for reduced water use; payment for environmental services from improved soil quality to integrated soil and water management or upper watershed management that improves downstream water quality). In regions with more advanced institutions, water markets can improve water allocation and the value of water use.

More focus needs to be put on water quality improvement, likely beginning with urban areas where pollution sources are easier to identify than in agriculture. Pollution charges and improved enforcement of existing water quality regulations would be productive.

Incentives for water management would be improved by rationalization of water, energy, and fertilizer subsidies, beginning with a reduction of costly generalized subsidies. The government budgetary funds saved from reducing general subsidies can be invested in increased agricultural R&D and infrastructure investment that will generate medium- and long-term benefits for farmers. In the short term, fiscal savings should also be used to provide nondistorting income support to smallholder farmers to compensate them for income losses due to reduction of subsidies. With the rapidly increasing access to ICTs, smart cards or phones can be used for efficient funds transfer to smallholder farmers. Carefully selected and implemented smart subsidies to achieve specific goals—such as adoption of solar irrigation pumps linked to the electric grid—have a role to play in initiating the adoption of new technology and the promotion of environmental services.

Boost crop and livestock productivity per unit of water and land through intensified investment in agricultural R&D, extension, and education

Expenditures on agricultural R&D, especially crop and livestock breeding, should be increased significantly. Additional funding should be targeted to more yield per unit of water and land, abiotic stresses such as heat and drought, and biotic stresses such as pest and diseases that will likely increase under climate change. Funding should be increased for R&D in both irrigated and rainfed conditions. Increased R&D funding should also be provided for management of water and waste in intensive livestock systems and for improved pasture varieties and management for grazing systems.

Support should also be increased for extension systems to increase gender-sensitive, farmer knowledge capacity, disseminate information, and improve adoption of new and existing technologies through radio, TV, social media, mobile phones, and other advanced ICTs. Increased participation by the private sector and NGOs in extension is important to

> *Funding should be targeted to more yield per unit of water and land, abiotic stresses such as heat and drought, and biotic stresses such as pest and diseases.*

better reach farmers. A movement to more decentralized, demand-driven, and participatory extension services would be more successful in many cases. Involving WUAs and producer organizations in extension activities helps to engage producers in programs that coincide with their own goals. However, decentralization across providers can also lead to a lack of prioritization, coordination, and coverage, so the public sector should continue to be a major player both in funding (or cofunding) public-private-NGO partnerships and in coordinating operations. Extension policies and strategies need to have an effective division of labor between public extension and other providers and identify overall objectives for public-sector involvement in extension.[184]

Significant investments in agricultural education and training are also needed, including special programs to target women and girls to reduce the gender gap in education. In addition to targeting farmers, education should focus on strengthening human resource capacity more broadly, especially within local government agencies, to make the delivery of rural services and other extension support more efficient. In addition, for agricultural extension programs to be effective and efficient, local government agencies should be involved in increasing the capacity of smallholder farmers through training.

Enhance the effectiveness of water use in existing systems through water and crop management reform and new technologies

Adoption of appropriate existing and new irrigation technologies through provision of credit, information services, and advanced ICT applications to improve the uptake and efficient use of these technologies by smallholder farmers could have significant benefits. These benefits include increased income from higher-value crops; more precise irrigation applications at critical crop growth periods, resulting in higher yields; farmer convenience and labor savings; and lower pumping costs. Major reductions in basin-wide consumptive water use due to new technologies should not be expected given the interconnectedness of water within the basin. However, physical controls on water usage based on consumption, which could include rationing or quotas through enforcement of water rights, can maintain or reduce basin-wide water use after the introduction of new technologies. In addition, it is important that when such interventions are introduced there be a commensurate investment in the governance and institutional systems to ensure that overall consumptive use does not increase, as has been the case in a number of locations.[185]

Irrigation system at a farm in Eikenhof, south of Johannesburg, South Africa. Credit: REUTERS/Siphiwe Sibeko

Existing irrigation technologies with potential for smallholder farmers include small-scale pumps, solar irrigation pumps, above-ground drip irrigation, and microsprinklers. Advanced technologies are emerging that are suitable for smallholder farmers. Satellite-based groundwater mapping, remote sensing of water productivity (consumptive use), on-the-ground measuring devices and sensors, integrated information processing and dissemination (including block chain and other relevant data storage and management tools) that facilitate real-time management and governance of water and cropping decisions can have major benefits in coming years, although more development of these technologies is required.

However, enabling conditions need to be in place for effective adoption of both existing technologies and the advanced technologies that are coming. Initial costs of new technologies are often too expensive for smallholder farmers. A reorientation of general subsidies to limited subsidies targeted to encouraging the purchase and sustainable operation of new technologies would be helpful. Other enabling conditions that need improvement for smallholder farmers are the availability of credit, low-cost weather insurance, and market accessibility.

The importance of urban and periurban agriculture should be recognized, and access to credit and legislative and regulatory changes should be implemented to promote efficient water use and reuse while ensuring safe and healthy crop production in this environment.

Promote dietary shifts and agricultural diversification to reduce the demand for water

In high-income countries like the United States, the consumption of meat is significantly higher than other parts of the world. In 2018 it was projected that Americans would consume on average 10 ounces of meat per day—almost double the amount recommended

> *Collective action across government and business could have an important impact on dietary shifts.*

by US Department of Agriculture (USDA) nutritionists.[186] Evidence indicates that reduction in meat consumption would result in lower overall water consumption—primarily because it reduces the water demand for animal feed, including cereals, soybean, and pasture. However, variations in efficiencies across different geographies and meat production systems make it difficult to predict the overall magnitude of impacts on water, and it is important to consider the local context of these changes.

There are many ways in which dietary preferences are influenced, ranging from community and cultural attitudes to public health education and private-sector marketing campaigns. As the food and nutrition community looks for ways to support balanced diets that promote both health and sustainability, collective action across government and business could have an important impact on dietary shifts. Educational institutions can be a platform for early nutrition education, setting healthy-eating behaviors in school meals; private-sector actors can convey health messages and promote healthier products; civil society can work with communities to address barriers to healthier diets. Additionally, policy changes can support the modification of corporate practices that undermine nutrition. Although behavioral change is difficult to achieve, recent evidence has shown that health communications and mass media campaigns can positively affect diets and nutrition. A review of health communication campaigns shows that many have positive impacts. Nutrition campaigns for increased fruit and vegetable consumption, reduced fat intake, and breastfeeding have been slightly more successful on average than those for other health topics.

Recent evidence has shown that health communications and mass media campaigns can positively affect diets and nutrition.

Nutrition campaigns that pay attention to the specific behavioral goals of the intervention and carefully target populations, communication activities and channels, message content and presentation, and techniques for feedback and evaluation should be able to change nutrition behaviors.[187]

More controversially, the use of carbon taxes—which will have a greater effect on livestock production—can be considered. As noted above, such taxes would need to be carefully designed, including accounting for the impacts on consumers and producers.

Increase the supply of water and expand the irrigated area

Selective investment in expansion of irrigation areas remains viable in some regions, notably Sub-Saharan Africa. Irrigated area potential comes from existing rainfed areas and pasture and fallow areas. Some large-scale systems are viable, but given the uncertain future of hydrology due to climate change and the need for flexible adaptation, smaller-scale, farmer-focused systems, including movable pumps, have higher potential. Potential also exists to expand research on and use of cost-effective desalination (in specific coastal environments for urban consumption), water recycling, and wastewater treatment to produce reusable water.

Greater investment in drainage and water table management can improve soil quality, crop production, water quality, and effective water availability. In order to improve the sustainability of groundwater aquifers, the potential and cost effectiveness of expanded artificial and naturally assisted groundwater recharge, both small-scale and large-scale, should also be explored and expanded as appropriate.

Improve macro, trade, and sectoral policies

Infrastructure investments, including rural roads, cell phone towers, markets, cold chains, and processing facilities should be expanded in partnership with the private sector. These investments are needed, in conjunction with the technologies described above, to reduce postharvest losses of food and water and improve the efficiency of value chains so that smallholder farmers receive higher prices for their outputs and pay less for inputs. Private-sector investments in the value chain will be critical, and governments should explore loan guarantees and blended finance to reduce the investment risks and incentivize private investments.

It is important to maintain open and fair agricultural trade, reducing trade and macroeconomic distortions. Open trade will become even more important because climate change will increase the reliance of many developing countries on food imports. As water scarcity worsens, imports of virtual water may be crucial in water-scarce areas to ensure food security. Finally, the increased variability in production over time due to climate change can increase the benefits from removal of agricultural trade and macroeconomic distortions because open trade will facilitate short-term imports to address food shortages caused by weather-induced production shortfalls.

Overcoming challenges to reform

Many of the policy reforms described here, such as trade liberalization and reduction in subsidies, will be difficult to implement and take time, political commitment, and money. Prevailing policies have strong constituencies that can be resistant to change. Even policies that will have substantial benefits for water management, food security, nutrition, and income will often reduce the well-being of some people (at least in the short term). Some of those who lose in the short term may be smallholder farmers and the poor. To facilitate reform by achieving broad political buy-in and to protect those who lose in the short term, policy reform should be accompanied by policies to strengthen social protection for those negatively affected in the short term and to enhance the ability of smallholder farmers and poorer households to take advantage of the opportunities created by policy reform.[188]

Examples of complementary reform packages described in this report include provision of income transfers to farmers who initially lose benefits due to a reduction in subsidies,

Policy reform should be accompanied by policies to strengthen social protection for those negatively affected in the short term and to enhance the ability of smallholder farmers and poorer households to take advantage of the opportunities created by the reform.

upgrading of water delivery services as a condition for water pricing reform, or requiring water users to contribute more to operations and maintenance of systems.

Other broader policies for overcoming barriers to reform include innovations within and across bureaucratic silos that can prevent policy change and educating the public about water challenges. Effective policymaking needs to take account of the local context and human interactions in reform and pay attention to the targeting, packaging, and sequencing of policy change.[189]

The challenges are daunting and will only become more difficult if not addressed. The time to act on fundamental reform of water policies for food and nutrition security is now.

PART IV

A man washes carrots in a ranch near the historic city of Thula located in Amran governorate, 45 km northwest of Sanaa. REUTERS/Mohamed al-Sayaghi

RECOMMENDATIONS FOR US GOVERNMENT ACTION

Leadership by the United States is essential to catalyze the innovations necessary—as outlined in this report—to achieve global water, food, and nutrition security. Water challenges will only get worse if left unaddressed, and the incredible development gains of the past 50 years could be lost. As a global leader in both food security and water access efforts, the US has the expertise, knowledge, and capability to ramp up solutions.

Leading a response to global water challenges

At home, the United States has been at the forefront of addressing agricultural water management by empowering entrepreneurial farmers through technological advancements, research, and innovative implementation models. In recent decades, Congress has recognized the importance of access to clean water globally and taken action through legislation like the Senator Paul Simon Water for the Poor Act of 2005 and the Senator Paul Simon Water for the World Act of 2014. Bipartisan leaders like Congressman Earl Blumenauer, former Congressman Ted Poe, former Senator Bob Corker, and Senator Dick Durbin, among others, led the way on passage of this important legislation and should be commended. These bills created a framework for the administration to draw upon centuries of US expertise and develop a global water strategy to address the threat of water scarcity through water resource management, including creating opportunities for the next generation of sustainable farmers.

The most recent Global Water Strategy of 2017 continues to emphasize the economic, social, and national security implications of water scarcity. The Department of Defense addendum to the 2017 administration strategy on international water specifically states, "The Department views water security as an issue of national security."[190] In addition, the report states that some regions might see economic growth declines from 6 to 15 percent as a result of dwindling water supplies in the near future. This would have massive implications for global food security efforts and could negatively affect regional stability, the future of American exports to those areas, and farmers already struggling with resource constraints. This, in turn, would not just stifle economic growth, but it would have lasting consequences for political stability, conflict and migration, and the health of the global population.

While current efforts are commendable, there is more the United States can and must do to significantly improve water management within agriculture, particularly for small-scale farmers in LMICs. Critical to this goal is enhanced efforts by the US government to stimulate research on technological innovations. These advancements can often help drive better policy environments and governance by LMICs as they successfully solve previously entrenched issues.

Solutions to water scarcity and water access cannot be considered outside of the context of food production and the increasing food and nutritional needs of growing populations. Importantly, the 2017 administration strategy on international water states, "Water is an entry point to advance core democratic values around equality, transparency, accountability, women's empowerment, and community organization." It also succinctly addresses the importance of regional water cooperation to regional stability by stating that "countries that cooperate on water are less likely to go to war."[191] As a global leader in food security and water access efforts, the United States has the expertise, knowledge, and capability to ramp up solutions. It will take bold action and a commitment from all actors to work together toward the common goal of a water-secure and food-secure future.

The recommendations presented in this section build on the conclusions of this report and highlight opportunities for the United States to uniquely respond and contribute to issues of critical importance to water, food, and nutrition security. While not all-encompassing, they reflect an opportunity for US leadership in areas such as support for water governance policies, expanding the supply of managed water and irrigated area, investing in R&D to improve productivity and reduce water use, and supporting diversification of agriculture to support diverse diets.

Box 17 – The Global Food Security Act and the flagship food security program, Feed the Future

The Global Food Security Act (GFSA) was reauthorized by Congress with overwhelming bipartisan support and signed into law by President Donald Trump in October 2018. It built on previous versions of the bill, but extended the authorization of funding from two to five years through FY2023. The legislation secured support for the continuation of a "whole-of-government" approach to global food and nutrition security programs and the continued implementation of the Global Food Security Strategy, which was created under the 2016 GFSA.

The Global Food Security Strategy laid the groundwork for how the United States can draw on the strengths and know-how across the government and work in close partnership with the private sector, universities, and civil society. The strategy also established a framework for transparency and accountability through 2021. Additional reports on the progress of the five-year strategy must be submitted to Congress yearly. GFSA requires specific selection criteria for target countries and beneficiaries of assistance based on the level of need, country commitment to food security investment and policy reform, opportunity for partnership, the potential for agricultural growth, opportunity for regional integration, and US government resource availability. The US government selected 12 countries for targeted investments under the new strategy: Bangladesh, Ethiopia, Ghana, Guatemala, Honduras, Kenya, Mali, Nepal, Nigeria, Niger, Senegal, and Uganda.

GFSA and the Global Food Security Strategy underpin the United States' flagship food security program, Feed the Future. Feed the Future is led by USAID but draws on the agricultural, investment, and policy expertise of 11 agencies—including the US Department of Agriculture, the Millennium Challenge Corporation, and the Department of State. This approach effectively leverages the best and brightest of the US government and helps coordinate activities on agricultural development and food security across multiple agencies.

USAID reorganization

In April 2018 the USAID administrator announced his intention to reorganize the structure of the agency. The plans call for the Bureau for Food Security, which previously led the execution of the Global Food Security Strategy and the majority of Feed the Future activities, to be renamed the Bureau for Resilience and Food Security (RFS). Activities on global water security, climate adaptation, and food assistance would be combined under the new RFS, including some functions from the Bureau of Economic Growth, Education, and Environment (E3). In addition, four "Centers of Excellence" would be established in the new bureau focusing on resilience, agriculture, water, and nutrition.

Source: Congress.gov; USAID 2018

RECOMMENDATIONS 1 & 2

A man waters beet plants in a garden in Gao, Mali. Credit: REUTERS/Joe Penney

Recommendation 1: Strengthen the environment for cooperation and communication between water development and food and nutrition security

Action 1A: Create a formal, integrated, and multilayered process for communication and collaboration between implementers of the Global Water Strategy and the Global Food Security Strategy to improve whole-of-government efforts to expand sustainable agricultural development and water resource management simultaneously.

In the United States and internationally there is often a division, intentional or accidental, between programs and policies aimed at water for agriculture—which is part of the Global Food Security Strategy—and access to water for drinking, sanitation, and health—which is part of the Global Water Strategy. This division can lead to program and policy incoherence and missed opportunities for solutions that support both sets of goals.

Collaboration across issue areas is critical to meeting rising global demand for water and nutritious food. The US government has great technical capacity and expertise across the agencies in both agriculture and water. Fully integrating the expertise of these independent federal agencies in the Global Food Security Strategy and Global Water Strategy can simultaneously enhance holistic approaches. Currently, eight of the agencies in the Global Food Security Strategy are also included in the Global Water Strategy.[192] However, these five-year strategies are created independently and can, therefore, miss the opportunity to better coordinate across all US development efforts. They do not include areas of coordination between the two aligned goals of water and food security, nor do they reflect any overlap in the priority countries of those goals.

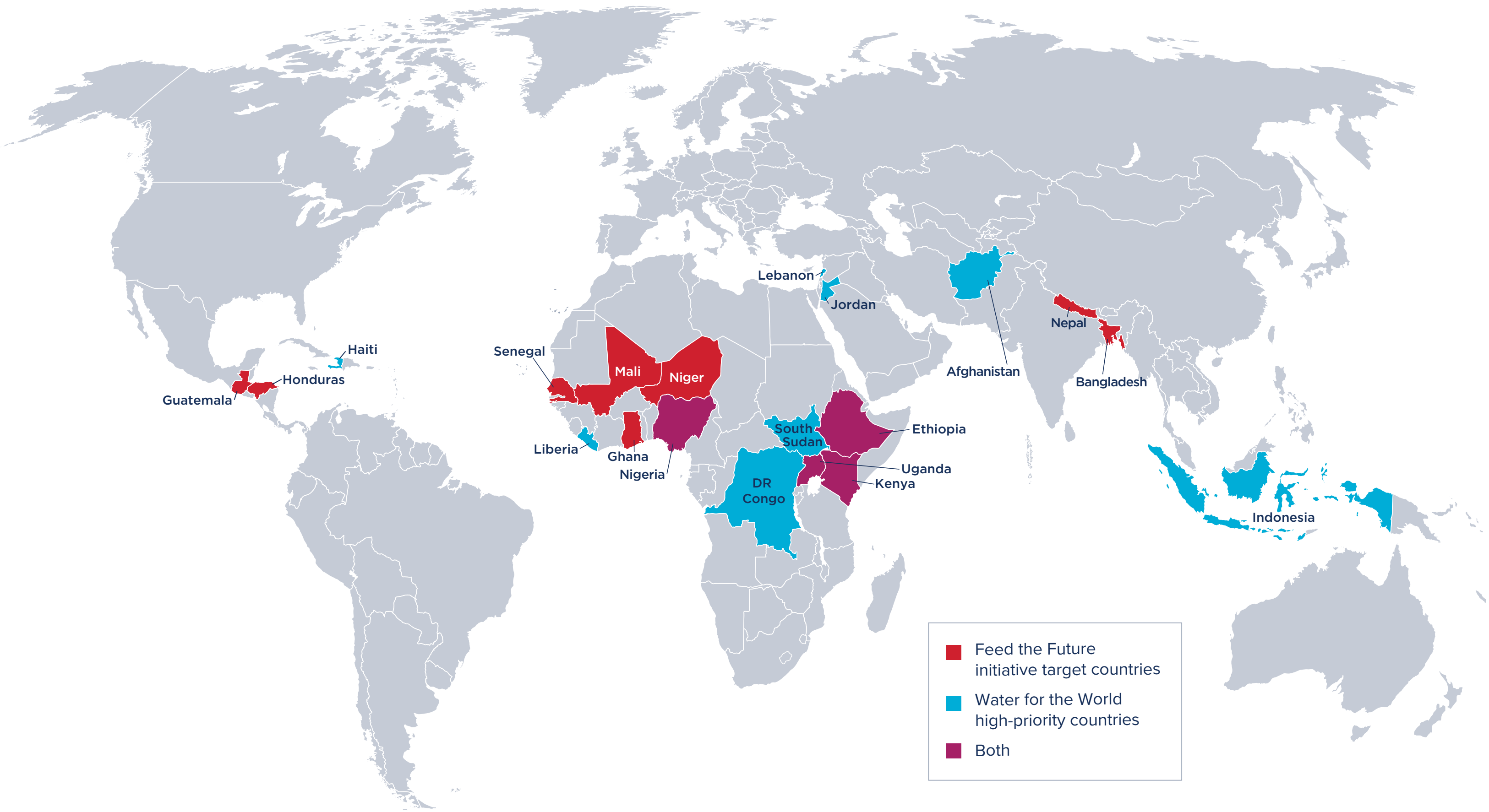
Congress should rectify this by legislatively strengthening coordination and communication between agriculture development policy and water policy both within Washington, DC, but also between Washington and our embassies and consulates globally. This is especially important in countries that have been designated jointly as "Feed the Future countries" and "priority water development countries" under the Global Water Strategy and the Global Food Security Act. Congress should consider specifically strengthening the coordination and communication between the USAID and water offices, including those at the Environmental Protection Agency, the Department of Agriculture, the State Department, and others.

Subaction: The Department of State and USAID should convene annually a joint working group made up of agencies mandated to work on both the Global Food Security Strategy and the Global Water Strategy in order to increase communication across and within agencies working on these two critical issues.

Action 1B: Congress should permanently authorize the Global Food Security Act, in alignment with the authorization for the Water for the World Act, to give projects, grants, and research adequate time to come to fruition.

On numerous occasions, the Chicago Council on Global Affairs has commended the bipartisan passage by Congress of the five-year authorization of the Global Food Security

Figure 9 – Feed the Future and Water for the World priority countries



Source: USAID 2018

Act. As a result, the Feed the Future program will continue into the next decade and will not need reauthorization until 2023. While a five-year authorization is a significant step to demonstrate leadership and commitment, a permanent authorization for global food and nutrition efforts remains the most important action the US government can take to move the United States and the world toward a more food-secure future. The 2014 Water for the World Act, the enabling legislation for the US response to water development, has already been permanently authorized. Congress should consider creating one unifying piece of legislation signifying the long-term priority and importance of water development and agricultural development in tandem with one another conceptually and structurally. At a minimum, Congress should request an evaluation of water management issues and efforts within the yearly global food security report and an evaluation of international agricultural development efforts within the yearly international water strategy. This permanent authorization should provide for significant oversight via reporting and metric evaluation.

Action 1C: Congress should request a comprehensive report from the administration on the impact of food and water insecurity on regional stability.

The national security implications of shocks to agriculture from water misuse, overuse, and scarcity in the coming decades are significant. The globe faces a fundamental risk to stability through the misuse of water in agriculture. Competition for increasingly scarce water resources have already triggered local conflicts and will magnify tensions in countries and regions of strategic importance to the United States in the future. As populations in these regions increase and resource availability becomes erratic, so too will pressure for agricultural productivity and competition for water resources.[193]

In 2015 the Office of the Director of National Intelligence said that food shortages due to drought and mass migrations will become more pervasive and will "almost certainly contribute to social disruptions and political instability."[194] The current US National Security Strategy recognizes the impact food insecurity has on regional stability. These reports in the future should contain a section that focuses on the nexus between US global water and food security efforts in an effort to counter extremism, instability, civil unrest, and migration in areas of strategic significance. For instance, it could take into account how current international engagement could, if leveraged correctly, decrease food and nutrition insecurity or inadvertently deepen already food-insecure regions if deployed without strategic forethought.

Action 1D: Bolster the new Bureau for Resiliency and Food Security by increasing interdisciplinary efforts and requiring increased accountability and engagement.

The administration has announced its intent to merge the Bureau for Global Food Security and the water office in the Bureau for Economic Growth, Education, and Environment within USAID into one overall Bureau for Resiliency and Food Security. While the goal of closer coordination between water, food security, and nutrition is laudable and praiseworthy, reorganization alone does not ensure success. Congress should use regular oversight and appropriations to ensure that both water development and food security remain fully supported equally and without drop off in either area.

It is vital that Congress and the administration endeavor to make sure that the missions of all three key global development strategies—nutrition, water, and food—remain intact and that no single area dominates the priorities of the bureau. It is essential that this reorganization take advantage of the synergies and enhance the response to all three of these crucial development areas rather than detract from any. Specifically, the water office at USAID should expand to include an emphasis on agricultural water management and land tenure for small-scale farming without sacrificing capacity or emphasis on WASH issues.

By combining the development priorities under one bureau, USAID will be able to foster innovative responses to complex problems. Inclusive, private-sector engagement should also be enabled and unleashed. For example, in order to develop public infrastructure that safely harnesses the wastewater outputs for agriculture such as vegetables in periurban settings, expertise will be needed on sanitary and phytosanitary standards, appropriate water quality standards, brown and gray water, urban infrastructure, farming techniques, and most importantly, private-sector collaboration to ensure the infrastructure is sustainable. USAID can facilitate these innovative responses in close collaboration with private-sector expertise.

Subaction: Congress should request an annual report on the status of the administration's efforts to incorporate water, food, and nutrition security—with an emphasis on water management within agriculture—into one strategic, outcome-driven effort. It will take time to determine the best areas of innovation and collaboration between food, nutrition, water, and resiliency efforts. For example, pairing water quality activities with activities that generate demand for fruits and vegetables—such as funding for a nutrition-focused agenda, efforts to support smallholder farmers, and land tenure issues—presents clear opportunities. Requesting an annual report on progress and priorities will ultimately promote the efficient use of resources and the achievement of shared outcomes as the work of the bureau progresses.

Subaction: The new bureau should continue to report directly to the USAID administrator.

Laborers collect rice saplings for planting in Karjat, India. Credit: REUTERS/Danish Siddiqui

Recommendation 2: Ease the challenges that hinder greater private-sector investment to expand sustainable water development for food and nutrition security

Action 2A: Assess the use of artificial intelligence and expansion of the National Agriculture Imagery Program (NAIP) at USDA for solving major development issues such as water resource scarcity.

The administration should commission a working group coordinating the Departments of Defense, State, and Agriculture; USAID; and the National Security Council to better understand the landscape of artificial intelligence and big data for water security and food security. The Department of Defense's Defense Advanced Research Projects Agency (DARPA) has already begun to explore the opportunities in this area. The United States should remain on the forefront of innovation and discovery, taking the lead now rather than reacting to private-sector pursuits. The commission could develop a protocol for incentivizing R&D to close innovation gaps, especially for data-poor countries and areas.

Action 2B: As a part of the restructuring of the bureau, USAID should establish an interagency policy working group to formalize and coordinate a holistic approach that will make development finance tools available to local private-sector investors, from small businesses and farmers to multinational corporations.

The reorganization should also provide a "single window" in the US government to assist agribusiness with smart investment opportunities and unleash market forces in coordination with agricultural and water development. The effort could be similar to that under the National Export Initiative of the last administration and would eliminate redundancy, cutting red tape. The effort should have the ability to work with US trade, development, foreign policy, and export promotion organizations to seize opportunities and find shared interests. USAID would be able to provide guidance to the private sector to encourage them to be inclusive to local businesses and smallholder farmers while emphasizing business predictability and demand-driven markets.

Action 2C: Congress should ensure the new US International Development Finance Corporation includes opportunities for short- and long-term investment in agriculture and water.

The passage of the BUILD Act of 2018 and the creation of the new US International Development Finance Corporation is a great step forward. This corporation is an opportunity for the United States to diversify and innovate the way it fosters development financing. Congress should support financing mechanisms that blend short- and long-term investments. It should also ensure that the new mechanisms fund both large-scale infrastructure and create financing tools for small-scale farmers to build local and regional irrigation infrastructure in coordination with the private sector. The corporation must also identify opportunities to create and enhance existing markets. This new entity should provide both key goals and evaluation of those goals with appropriate metrics. If the goals are met, a significant scaling up should be considered.

Subaction: Innovative financing tools should be used to improve affordability and access to small-scale irrigation.

Often, agricultural water technology is not adopted by farmers because the high initial costs of doing so are not returned quickly enough in farm profits.[195] Where appropriate, technology can be subsidized, but only if it will actually generate a sustained economic return for the farmer and be sustainable over time in practice. It may be better to fund a larger portion of the technology value chain than just the technology purchase itself, for example simultaneously setting up training and replacement supply sources for maintenance technicians. The highest water efficiency gains for smallholder farmers lie in obtaining higher value from existing consumption rates, not in marginal reductions in inefficiency by individual users.[196] Effort should be put into technology that produces high-value outputs (more nutritious food, livestock, and better economic returns for farmers) rather than into getting the same lower-value outputs (in terms of nutrition and yield) with less water.

Action 2D: The administration should support the development of an enabling environment for business through a standardization of regulations and support for rule of law.

The private sector, including international companies as well as small- and medium-sized enterprises (SMEs) within developing countries, must play a role in supporting the development of water management infrastructure, innovation, and modeling. However, there are often significant barriers for larger multinational companies and SMEs to entering markets in emerging economies. The Department of Commerce's foreign commercial service officers are charged with paving the way for US business to enter into new markets. Their policy expertise, working in conjunction with the agricultural know-how of USDA's Foreign Agriculture Service, should coordinate support for emerging economies that need guidance on best practices. This includes a focus on opening new markets for US businesses and SMEs working on water scarcity, water management, and global food security to spur market-based solutions from the private sector. The Department of Commerce could ensure US businesses are inclusive of smallholder farmers and any agreements are mutually beneficial.

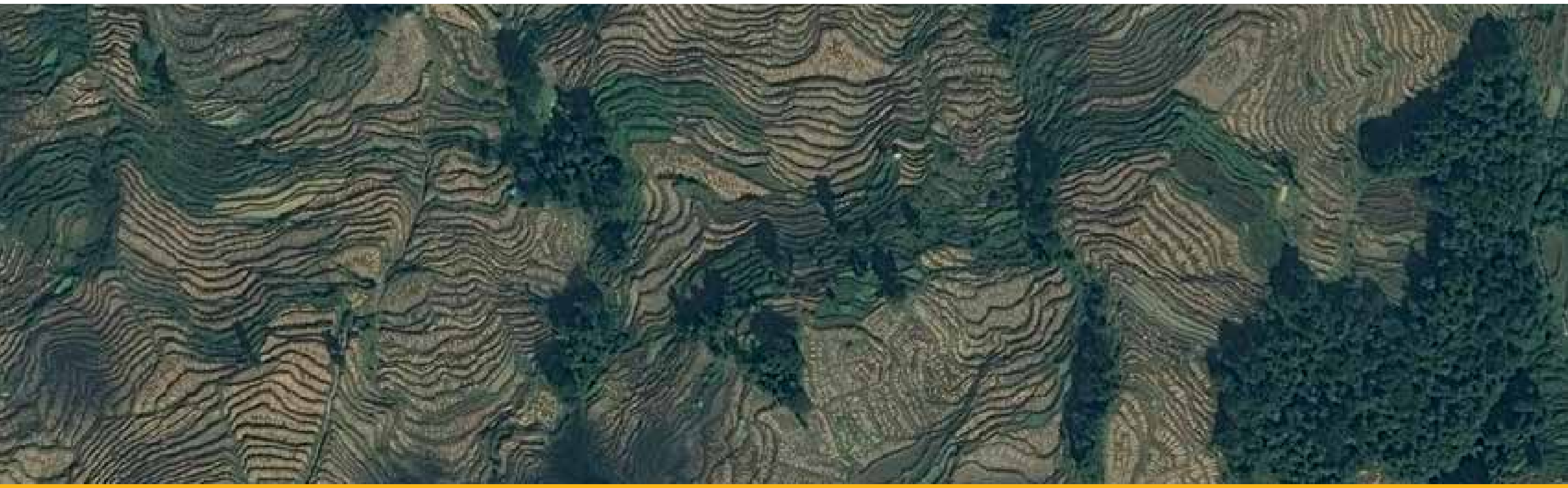
Action 2E: The administration should pilot collaborations with the private sector and civil society to design programs or innovations that build demand for nutritious diets.

As incomes rise, diets tend to diversify. However, the quality of new foods is not always high. Greater consumption of pulses, fruits and vegetables can improve nutrition and health status, and they can also lead to a reduction of water given the water requirements of major staple grains. But accessibility does not automatically translate to greater consumption. Alongside these healthy foods, availability of high-calorie, sugary, highly processed foods are also increasing, which can contribute to increases in obesity. Embedding nutrition messages in traditional agricultural extension or public health programs is important. However, actions must incorporate the private sector's capabilities and acknowledge incentives to advance nutritious, healthy diets. The administration should scan existing investments and pilot innovative partnerships across government, civil society, and the private sector to make progress in this area. Innovation among like-minded collaborators is needed to ensure knowledge of healthy diets is met with access to affordable, nutritious foods, including convenience foods.

Action 2F: NOAA should continue to maintain current investments in digital mapping of water resources, and incentives should be introduced to increase sharing of critical data by commercial entities on this common platform.

It is commendable that the US National Oceanic and Atmospheric Administration (NOAA) has continued to deregulate access to VHR short-wave infrared (SWIR) imagery, which is incredibly useful for water mapping. SWIR can even measure the level of soil moisture. Initially, regulations only allowed SWIR to be disseminated at 7.5m resolution, but now its native resolution of 3.75m can be disseminated.[197] NOAA is currently using high-resolution satellite data to track and measure water resources around the globe. Satellite imagery, in particular, is often the only option agencies have to gather data on remote, sometimes insecure areas that are persistently experiencing food and water insecurity. This resource offers a dependable, ongoing source of data globally so decision makers can understand changes over time and assess the efficacy of policy decisions and interventions.

This monitoring and evaluation is critical for domestic and international researchers to gain access to freely available and accurate data on the current state of global water resources. NOAA, in coordination with NASA and USAID's SERVIR, should facilitate the development of viable water accounting systems and practices in order to consolidate and confirm international policies on water management. SERVIR currently provides state-of-the-art, satellite-based Earth monitoring, imaging and mapping data, geospatial information, predictive models, and science applications to help improve environmental decision making among developing nations in eastern and southern Africa, the Hindu-Kush region of the Himalayas, and the lower Mekong River Basin in Southeast Asia. The administration can incentivize commercial providers to host their data in a central hub or push for sponsored open data, particularly in areas prone to food insecurity, flooding, and natural disasters.



Satellite imagery: rice paddy fields in China. Credit: © DigitalGlobe 2019

RECOMMENDATIONS 3 & 4

A girl carries a basket with mangoes in Al-Giza, on the outskirts of Cairo, Egypt. Credit: REUTERS/Mohamed Abd El Ghany

Recommendation 3: Leverage US expertise and influence to improve water resource governance and sustainability

As other global powers continue to scale up their development efforts in Africa and Asia in particular, it is critical that the United States continues to make smart, strategic investments while providing greater clarity in cooperation and competition of donor countries. Countries like China have engaged in large-scale water projects across the continent, which are important for development and can appear attractive as a short-term solution for host governments. However, those projects generally do not incorporate a focus on long-term sustainability, resiliency, and the path to self-sufficiency promoted by the United States and other traditional bilateral donors.[198]

Action 3A: In the face of rising investment from countries like China, the administration should employ all foreign policy tools available, with emphasis on technical assistance for water sustainability, to maintain US global leadership in strategically important regions.

Given the competition for leadership globally as well as the need for more cooperation on development financing from donor countries, Congress should continue to promote deeper leadership with partners abroad, especially when it enhances trade ties and economic opportunities for US farmers, agribusiness, and water management experts in new markets. This would maximize impact, mitigate redundancy, and increase efficient use of US tax dollars. The administration's "Prosper Africa" and USAID's Journey to Self-Reliance initiatives might be an opportunity to leverage US expertise, environmental standards, and technical skills to support sustainable development. Specifically, agricultural development and mitigating food insecurity supports the three main tenets of the Prosper Africa strategy: economic development, countering terror threats and violent conflict, and efficient use of US aid funding.

Subaction: Where support is desired, the United States should use expertise to build capacity and strengthen institutions to support cross-border water treaty development, with land grant universities playing a critical role. The United States has successfully negotiated cross-border water-sharing treaties and could continue to take the lead on encouraging more national agreements on shared water resources and capacity building for those agreements, including both groundwater and subsurface water resources. On the state level, the United States has a comprehensive and diverse set of best practices for managing local conflicts over water resources. These best practices could be useful to local and regional governments abroad. These include alternative regulatory regimens for groundwater extraction, water accounting practices, community water rights negotiations, and the best use of agricultural extension workers for water sustainability.

The United States is uniquely positioned to assist in ensuring that responsible natural resource management is incorporated into agreements and policy development processes at the national and subnational level. Additionally, the United States has a strong ability to fully assess the consequences of any agreement on smallholder farmers and communities upstream and downstream from the water resource.

Action 3B: The administration should include education on water resource management at the state and national level as part of fellowships and academic exchanges.

Fellowships and exchanges have been a foundational aspect of US foreign policy, especially for those engaged in agricultural development. The Cochran and Borlaug Fellowships have allowed countless international agriculture specialists to be trained and encouraged at US land-grant universities. A significant number of agricultural ministers around the globe have been educated in the United States. This has garnered the US unmeasurable goodwill and influence. However, there has not been a focus on teaching visiting fellows about the successful and innovative models of water management that exist in places like Nebraska, Texas, and Arizona, among others. The United States should include water development experts and practitioners, including those specializing in wastewater, into more international exchange programs like the Cochran and Borlaug Fellowships. In addition, just as with those who come to the United States, the same must be true for US citizens who work in LMICs.

Subaction: The Peace Corps Response and other relevant programs such as USDA's Farmer-to-Farmer program should better leverage experts on hydrology, irrigation, and water management in its programming. Peace Corps Response sends experienced professionals to undertake short-term, high-impact service assignments in communities around the world and would be an excellent resource for small-scale farmers. The Farmer-to-Farmer program could provide practical expertise by targeting volunteers from producer networks and land-grant universities with expertise on water and natural resource management.

Subaction: USDA should expand the Food Safety Network (FSN) program of the Foreign Agricultural Service, which recently examined the sanitary and phytosanitary capacity-building needs of five Feed the Future countries. The resulting action plans should be supported, in collaboration with industry partners, and assessments should be extended to all Feed the Future countries.

Subaction: The Commodity Future Trading Commission (CFTC) should expand technical exchanges to improve knowledge of commodity-hedging mechanisms as food price volatility increases in the face of changing rainfall patterns. A changing climate will create changing rainfall that could contribute to price shocks as global crop production becomes more unpredictable and demand for food continues to rise significantly. In 2007 and 2008 the world saw how these shocks can contribute to the instability of entire regions.[199] The CFTC can support greater technical knowledge transfer in the area of commodity price hedging for relevant government agencies and private-sector actors that may benefit from greater knowledge of US systems.

Action 3C: The administration should support active engagement with traditional multinational development institutions engaged in water management and development.

The relevant committees in Congress should give policy direction to the administration to exercise their influence with the multinational development institutions to support water development capacity for agricultural water management, including the prioritization of existing water security agreements. These institutions include the International Fund for Agricultural Development, the World Bank, Inter-American Development Bank, African Development Bank, Asian Development Bank, and other appropriate entities. The United States can exert influence on these entities to better coordinate between agricultural water, WASH, and nutrition groups, which can improve policy and programmatic coherence. In addition, these groups act as an important and distinctive counterbalance to other infrastructure development approaches like those promoted bilaterally by China or via the Asian Infrastructure Investment Bank. These multigovernmental entities play an important role in holding up environmental standards and examining social consequences around infrastructure development, which have not always been a core tenet of Chinese activities.[200]

Subaction: The US government should increase support for capacity building of national and subnational policymakers and implementers in LMICs to create and maintain land rights for smallholder farmers. This work should also support the security of water rights. Secure access to water is critical to helping farmers have the power to reallocate, transfer, and sell water. This is necessary to establish a dynamic, full cost recovery of service and valuing of water that supports sustainable water usage by creating water markets and incentivizing water management services.

A Chinese farmer works in a rice field. Credit: istock/Nikada

Recommendation 4: Strengthen support for agricultural R&D and interdisciplinary research at the nexus of water, food, and nutrition.

Changes in temperature and rainfall are projected to increase global food prices by as much as 84 percent by 2050.[201] Fisheries are anticipated to see a decline of 3 million metric tons per degree of global warming.[202] Given the most recent Intergovernmental Panel on Climate Change report on the impact of climate change on agricultural productivity and water scarcity in the very near future, now is the time for the United States to call upon and harness its unparalleled R&D capacity to address significant technological hurdles to bolster resiliency to water scarcity in the global food system.[203]

This would require significant US leadership and investment in R&D and extension in a number of areas. The renewal of the Foundation for Food and Agriculture Research, with the goal of unlocking US$200 million in private-sector research, is a positive step. Support for Water for Agriculture Challenge Area within the Agriculture Food Research Initiative (AFRI) is another good example of research that can support innovation for ensuring a water-secure future.[204] But there needs to be a specific emphasis on water management for agriculture that incorporates interdisciplinary approaches. For example, there is innovative work on using artificial intelligence to better model the consequences of water and food insecurity at research organizations like the Department of Defense's Advanced Research Projects Agency (DARPA). The administration should facilitate collaboration between research agencies working on water and food security. DARPA should better coordinate and share findings with critical agricultural research agencies like the Agricultural Research Service, Animal and Plant Health Inspection Service, National Institute of Food and Agriculture, and others.

Action 4A: The administration should coordinate and Congress should fund a significant challenge fund for water scarcity issues that encourages private-sector innovation.

Alongside an increased emphasis on water- and agriculture-related research topics in traditional agriculture research agencies, there is also a need for a dedicated fund to look into water scarcity issues for smallholder farmers and already food-insecure populations. The challenge fund should be coordinated with agencies involved in both the Global Food Security Strategy and the Global Water Strategy as well as the new US International Development Finance Corporation. It should be commenced to bolster technology and resiliency in agriculture. Such a challenge fund could build off or expand the 2012 program Securing Water for Food, which has generated important lessons in this area. It could also model a collaboration between the US government and Google's AI for Social Good program. In order to help improve awareness of impending floods, Google is using artificial intelligence to create better forecasting models that predict when and where floods will occur and incorporating that information into Google Public Alerts. A variety of elements—from historical events, to river level readings, to the terrain and elevation of a specific area—feed into their models. If coordinated with USG data and distribution, this could be a powerful partnership.[205] Priority areas for collaboration are mentioned in the conclusion of this report and span innovations in water-harvesting technologies in smallholder dominated regions to the transferability of precision agriculture practices to low-income settings to weather and water-monitoring technology that can ensure water is applied at the right time and not overused.

Action 4B: Support the creation of a USAID innovation lab at a land-grant university or expand existing innovation lab efforts to advance uptake and improvement of wastewater management and reuse for agriculture.

Innovations in wastewater reuse for agriculture is a critical need, especially in LMICs.[206] The creation of an innovation lab for small-scale irrigation is making critical contributions. However, an innovation lab exploring the large- and small-scale innovations that manage, treat, and use brown and gray water could make important progress. This will be ever more urgent as periurban areas and agricultural cultivation continue to surge with the growth of cities.

Action 4C: Advance innovative agricultural approaches to combat the impacts of a changing climate through targeted research.

USDA, in coordination with the Foundation for Food and Agriculture Research, should pledge research funding to drive forward innovative and cost-effective advancements in the field of desalination technology. Congress should ensure progress and exercise oversight through relevant committees in order to ensure effective use of funding.

Action 4D: The administration should affirm and support greater R&D opportunities that are interdisciplinary and target the nexus of food, water, and nutrition.

Illustrative examples of the range of R&D that can support nutritious, sustainable food systems that ensure our water resources are enough can be found in the Appendix.

A vegetable farmer works in Kenya. Credit: istock/boezie

Appendix

Research opportunities in the food-water-nutrition nexus

Opportunity	Rationale	Contribution
Crop agriculture		
Crop breeding for water efficiency, with increasing emphasis on a wider range of crops	As food system approaches begin to look at regional crop mixes for optimal agroecology, including water availability and healthy diets, new crops can take hold, but only with seed varieties that are climate resilient.	In order to support demand-generation activities for nutritious food and respond to demand in cities, farmers will need access to seed for a wider range of crops.
Animal agriculture		
Animal genetics improvement, particularly for dairy cows	Improvement of animal genetics can improve low productivity, increasing milk production while reducing water and feed use. Smallholder cows produce as little as three liters per day in East Africa in contrast to cows in high-income countries that produce 20 to 30 liters per day.[207]	As demand for diverse foods grows, dairy can provide an affordable source of essential micronutrients and support the nutrition of smallholder families, particularly young children.
Address core drivers of animal mortality for animals important for smallholder incomes and nutrition	Diseases like Newcastle can kill up to 90 percent of a chicken flock, wasting the resources invested. Diseases that particularly affect dairy cows, like brucellosis or contagious bovine pleuropneumonia, could particularly improve efficiency of natural resources and micronutrient availability.	Increasing availability and affordability of eggs will improve incomes and micronutrient intake for the most vulnerable.
Innovations for limiting animal waste impacts on human health	Nutrient-dense animal diets and confined production spaces have led to an increase in the scale and density of manure output from poultry, pigs, and livestock. While manure can be recycled as fertilizer, imbalances in its nutrient composition can also lead to harmful run-offs into local water tables and the possible contamination of important sources of drinking water.	Reducing the quantity and environmental footprint of animal waste has important implications not just for human health but for GHG emissions in agriculture and the quality of local water tables. A more balanced supply and use of animal manure will improve the quality and consistency of local water tables in the face of climate change.[208]

Opportunity	Rationale	Contribution
Crop-animal systems innovation		
Soil fertility for water management and nutrition	Soil fertility depends on complex interactions between physical, chemical, and biological factors. Modernizing agricultural systems have tended toward the overapplication of inorganic fertilizers as a short-term measure to increase soil fertility, with adverse effects on water tables and soil quality in the long term.[209]	Reducing fertilizer use in lieu of better management practices and planting patterns will significantly reduce GHG emissions from their production, transport, and application while improving the resilience of soil systems toward the effects of climate change.
Rainwater harvesting	Rainfed agricultural systems comprise 95% of cultivated land in Sub-Saharan Africa, 75% in the Near East and North Africa, and 60% to 65% in Asia.[210] Much of this farmland exists in semiarid regions that will face increasing rainfall variability in the coming years.	Rainwater harvesting plays a dual role in conserving water for later use and preventing erosion and runoff during periods of heavy rain. These effects may increase the potential for rainfed farmers to benefit from the expansion of new irrigation technologies.[211]
Improvement of aquaculture integration	Aquaculture now accounts for over 55% of global fish consumption, and this share is growing steadily by a rate of 4.5% annually.[212] A large share of aquaculture production and consumption occurs across densely inhabited parts of East and Southeast Asia, where the scarce availability of land makes integrated agri- and aquacultural systems economically viable.[213]	Pond aquaculture and irrigated farming practices share important complementarities, as by-products from one system can serve as direct inputs into the other. The viability of aquaculture schemes at both small and large scales also mean that they serve as an important source of nutritional self-sufficiency for smallholder farmers.
Improving appropriate irrigation technology	The global demand for irrigation water has tripled over the past 50 years, and irrigation now accounts for 70% of total water withdrawals. Competition from other sectors, increasing water table variability, and increasing demands for production improvements through irrigation necessitate more efficient and resilient irrigation systems.[214]	Efficiency improvements in irrigation lessen the environmental burden of agriculture and strengthen the economic viability of water-intensive crop varieties for smallholder farmers. The rollout of new irrigation technologies in semiarid areas could allow farmers to leapfrog more expensive and environmentally risky methods of improving their production.

Opportunity	Rationale	Contribution
Increasing water quality and availability		
Desalination innovations	Agriculture currently accounts for 70% of total freshwater withdrawals, and increasing rainfall variability threatens the stability of agricultural production in many semiarid coastal regions throughout the world.[215]	Newer, cost-effective desalination plants also contribute to water supplies for urban and industrial use. In this way, the expansion of desalination plants could lessen the pressure and competition that traditional sources of agricultural water now face from expanding urban and industrial areas.
Atmospheric water harvesting	The global importance of rainfed agricultural production, a global increase in rainfall variability, and the imperfect capture of rainwater through drainage and storage systems highlights the need for a more consistent source of irrigation water. In arid areas, up to 90% of rainfall evaporates back into the atmosphere.[216]	Pilot programs for atmospheric water harvesting in mountainous areas have shown that while this technology is in its infancy, it can be economically viable in the right settings. When successfully implemented, it could raise smallholder self-sufficiency, reduce the labor burden of water collection, and hedge smallholder farms against climatic shocks.[217]
Wastewater treatment and reuse innovation for agriculture, especially in periurban areas	Rising urban and industrial demands for water are placing additional stresses on traditional, agricultural water supplies. Simultaneously, global demands for high-value, water-intensive crops and livestock are coinciding with the relatively heavy application of fertilizers in modernizing farming systems, with significant environmental consequences in runoff.	Recycling urban and industrial water for agricultural use lessens the burden that groundwater sources face from agricultural water withdrawals.[218] Recycling agricultural water in periurban areas with proximity to oceans may be critical to reducing nutrient runoff into oceans, which ultimately threatens ocean health and fish health.

Opportunity	Rationale	Contribution
Improve data science and water monitoring capabilities for water, food, and nutrition sustainability	Increasingly, advances in artificial intelligence are allowing multiple models, with dozens of variables, to be integrated for better predictive analytics. These could be increasingly useful for modeling changing diets and changes in rainfall patterns and soil quality in response to climate change.	The World Modelers program, funded by DARPA, integrates multiple climate and food security models into one to allow for better workflow and quicker assessment. Programs like this will ultimately improve policy and investment outcomes.
Understand the threat and solutions for nutrient trapping in oceans and the impact on fish protein	Nutrient trapping is a phenomenon whereby phosphorus and nitrogen become trapped in deep ocean waters rather than circulating to the surface to feed phytoplankton. Warming ocean waters are increasing this risk and appear to present a significant threat to fish stocks and ocean health by midcentury.[219]	Interdisciplinary research collaborations are increasingly needed to reveal the complex interactions between biological changes and likely consequences on humanity. Recent nutrient-trapping research was conducted across five research institutions and multiple disciplines.

About the Chicago Council on Global Affairs

The Chicago Council on Global Affairs is an independent, nonpartisan membership organization that provides insight—and influences the public discourse—on critical global issues. We convene leading global voices, conduct independent research, and engage the public to explore ideas that will shape our global future. The Council is committed to bringing clarity and offering solutions to issues that transcend borders and transform how people, business, and government engage the world. Learn more at thechicagocouncil.org and follow @ChicagoCouncil.

For nearly 10 years the Chicago Council on Global Affairs has highlighted opportunities for US leadership and global bodies like the G7 and G20 to advance food and nutrition security and the alleviation of poverty through agricultural development. Its 2009 report provided a blueprint for the Obama administration's USAID global food security initiative, Feed the Future. Since then the Council has convened business, policy, scientific, and civil society leaders for task forces to examine the factors contributing to food and nutrition insecurity in the 20th century. The task forces have looked at urbanization and growing youth populations as forces changing the demands on the food system, the impact of climate change on food production, the opportunity to improve nutrition and health through food, and the links between food security and global peace and security. The resulting reports have influenced policy on global food security and have consistently provided guidance for how stakeholders from the public, private, and NGO sectors can work together to implement innovative solutions to global food security challenges. For further information, please visit thechicagocouncil.org/globalagdevelopment.

Author biography

Mark W. Rosegrant

Research Fellow Emeritus, International Food Policy Research Institute (IFPRI)

Mark W. Rosegrant is research fellow emeritus in the Director General's Office (DGO) of the International Food Policy Research Institute (IFPRI). Prior to joining the DGO, he was director of IFPRI's Environment and Production Technology Division. With a PhD in public policy from the University of Michigan, he has extensive experience in research and policy analysis in agriculture and economic development and the future of world food security, with an emphasis on water resources and other critical natural resource and agricultural policy issues as they impact food security, rural livelihoods, and environmental sustainability. He is the author or editor of 12 books and over 100 refereed papers in agricultural economics, water resources, and food policy analysis. Rosegrant has won numerous awards and is a fellow of the American Association for the Advancement of Science and of the Agricultural and Applied Economics Association.

Task force member biographies

Cochairs

Ertharin Cousin

Distinguished Fellow of Global Food and Agriculture, Chicago Council on Global Affairs; Payne Distinguished Lecturer, Freeman Spogli Institute for International Studies, Stanford University; Former Executive Director of the World Food Programme

Ertharin Cousin is a distinguished fellow of global food and agriculture at the Chicago Council on Global Affairs. She previously served as executive director of the World Food Programme (2012–2017). In 2009 Cousin was nominated by the president and confirmed by the Senate as the US ambassador to the UN Agencies for Food and Agriculture in Rome. In this role she served as the US representative for all food, agriculture, and nutrition-related issues. Cousin helped identify and catalyze US government investment in food security and nutrition activities supported by the USAID Feed the Future program. A Chicago native, Cousin is a graduate of the University of Illinois at Chicago, the University of Georgia Law School, and the University of Chicago Executive Management Finance for Nonfinancial Executives program. Cousin has received honorary doctorate degrees from universities around the globe. She has been listed numerous times on the *Forbes* "100 Most Powerful Women" list, as the *Fortune* "Most Powerful Woman in Food and Drink," on *TIME*'s "100 Most Influential People" list, and as one of the "500 Most Powerful People on the Planet" by *Foreign Policy*.

A.G. Kawamura

Panel of Advisors Member, Global Food and Agriculture Program, Chicago Council on Global Affairs; Founding Cochair, Solutions from the Land; Former Secretary of the California Department of Food and Agriculture

A.G. Kawamura is a third-generation grower and shipper from Orange County, California. He is the former secretary of the California Department of Food and Agriculture (2003–2010). He serves on several boards and committees, including founding chair of Solutions from the Land; Global Food and Agriculture Program Panel of Advisors, Chicago Council for Global Affairs; American Farmland Trust board member; Farm Foundation board member; and Western Growers Association board member and former chair. For over 30 years Kawamura has worked locally, nationally, and internationally to look for agricultural solutions to the toughest challenges of our time via the nexus of water, energy, food, technology, and trade. He remains active in policy discussions on food security and agricultural resilience. As a progressive urban farmer, he has a lifetime of experience working within the shrinking rural and urban boundaries of southern California. Through his company, Orange County Produce, LLC, he is building a collaborative and interactive 21st-century, 70-acre agricultural showcase at the Orange County Great Park in Irvine, California. Kawamura graduated with a bachelor's from UC Berkeley.

Members

Sanjeev Asthana

Nonresident Fellow, Global Food and Agriculture Program, Chicago Council on Global Affairs; Founder and Managing Partner, I-Farm Venture Advisors

Sanjeev Asthana is a recognized thought leader in food, agriculture, retail, nutrition and food security, livelihoods, etc. He has worked in some of the largest global corporations. He is the chairman of National Skills Foundation of India (NSFI); chairs the governing council at Agriculture Skill Council of India (ASCI); is director of the ActImpact Foundation, Canada; and serves on boards of leading public institutions and private-sector corporations. He has served as a task force member and been on several policy forming committees of government of India. He is on the national councils of leading industry and trade chambers, namely the Confederation of Indian Industry (CII) and the Federation of Indian Chambers of Commerce and Industry (FICCI). He has also chaired various committees at trade chambers and government. He was on an India task force on water of Earth Institute at Columbia University. Asthana has a distinguished corporate career at senior positions across countries. He was the president and chief executive at Reliance Retail and served on the boards of Reliance Group companies. He was director of Cargill India and Asia Pacific trading head in Singapore. He was country head of ITC Global Holdings based in Indonesia and East European head based at Romania. He works closely at the policy level with government and international institutions like GAIN, UNICEF, World Bank, IFC, ADB, and leading companies on agriculture, food security, nutrition, livelihoods, and sustainability. He is a regular speaker at international conferences and universities.

David Bennell

Manager, Food, Land, and Water, World Business Council for Sustainable Development

David Bennell is the North American manager of food, land, and water for the World Business Council for Sustainable Development, where he focuses on climate-smart agriculture and global food systems reform (FReSH). Previously, he was director of food and capital markets for the investor-led organization Ceres. Additionally, he has worked for Microsoft, REI, and L.L. Bean in leadership development, product development, and sourcing positions. His career has also included working as a funder with a focus on sustainable forestry, cocreating the for-profit social enterprise company CottonConnect, cocreating a US$10 million impact investing fund focused on food and agriculture investments, and leading the apparel industry NGO Textile Exchange with a focus on standards development for responsible sourcing.

Douglas Bereuter

Distinguished Fellow, Global Food and Agriculture Program, Chicago Council on Global Affairs; President Emeritus, Asia Foundation

Douglas Bereuter is president emeritus of the Asia Foundation, a nongovernmental development organization he led for more than six years following his 26-year service as a member of the US House of Representatives. During his congressional career, he was a leading member of the House International Relations Committee, where he served as vice chairman for six years, and chairman of the Asia-Pacific Subcommittee and later the

Europe Subcommittee. He also had long tenures on the subcommittees on Economic Policy and Trade and Human Rights and was president of the NATO Parliamentary Assembly. He also served on the House Financial Services Committee for 23 years and on the House Permanent Select Committee on Intelligence, retiring as its vice chairman. Bereuter graduated Phi Beta Kappa from the University of Nebraska and has master's degrees from Harvard University in both city planning and public administration. He served as an infantry and intelligence officer in the US Army, practiced and taught graduate courses in urban and regional planning, led various agencies and programs in the Nebraska state government, and served one four-year term as a Nebraska state senator. He is a member of the Council on Foreign Relations and the World Affairs Council of Northern California and served six years on the State Department's International Security Advisory Board.

Jessica Fanzo

Bloomberg Distinguished Professor of Global Food and Agriculture Policy and Ethics, Johns Hopkins University

Jessica Fanzo, PhD, is the Bloomberg distinguished associate professor of global food and agriculture policy and ethics at the Berman Institute of Bioethics, the Bloomberg School of Public Health, and the Nitze School of Advanced International Studies (SAIS) at Johns Hopkins University. She also serves as the director of the Global Food Ethics and Policy Program at Johns Hopkins. She is the cochair of the Global Nutrition Report and was the team leader for the UN High Level Panel of Experts report on food systems and nutrition. In 2018 she was on a one-year leave of absence to serve as the senior nutrition and food systems officer in the Nutrition and Food Systems division of the Food and Agriculture Organization of the United Nations. Prior to joining Johns Hopkins, Fanzo held positions at Columbia University in the College of Physicians and Surgeons and the Earth Institute, the World Food Programme, Bioversity International, and the Millennium Development Goal Centre at the World Agroforestry Center in Kenya. Her area of expertise is the linkages between agriculture, nutrition, health, and the environment in the context of sustainable and equitable diets and livelihoods. She was the first laureate of the Carasso Foundation's Sustainable Diets Prize in 2012 for her work on sustainable food and diets for long-term human health. Fanzo has a PhD in nutrition from University of Arizona.

Pierre Ferrari

President and CEO, Heifer International

Pierre Ferrari was born in the Belgian Congo (today the Democratic Republic of Congo). Ferrari received a master's degree in economics from the University of Cambridge and a master's of business administration from Harvard Business School. He joined Heifer International in 2010 with more than 40 years of business experience. Ferrari is leading Heifer to scale its programs and accelerate rural market growth to help 4 million families achieve living incomes by 2020. Heifer is using its proven community development approach and livestock expertise to help farmers create market demand to help lift them out of poverty. Ferrari worked for many years at Coca-Cola USA before deciding in 1995 to focus his energies and business acumen on social issues. He is using his skills and aptitude to invest in and partner with people living in poverty to help them achieve self-sufficiency, independence, and health—goals that directly align with Heifer's empowerment-oriented mission.

Ferrari is a current board member of the Small Enterprise Assistance Fund and is also a former chair and current board member of Ben and Jerry's Ice Cream.

Dan Glickman

Distinguished Fellow, Global Food and Agriculture Program, Chicago Council on Global Affairs; Vice President, The Aspen Institute; Executive Director, The Aspen Institute Congressional Program

Dan Glickman is vice president of the Aspen Institute and executive director of the Aspen Institute Congressional Program. Glickman serves as a senior fellow at the Bipartisan Policy Center, where he is cochair of its Democracy Project. He also serves as cochair of the US Global Leadership Coalition and is on the board of the World Food Program USA. He is a board member and founding chair of the Foundation for Food and Agriculture Research, created in the 2014 Farm Bill to fund new and innovative research projects in the areas of food and agriculture. Prior to joining the Aspen Institute, Glickman served as US Secretary of Agriculture in the Clinton administration. He also represented the fourth congressional district of Kansas for 18 years in the US House of Representatives, where he was very involved in federal farm policy on the House Agriculture Committee. He also served on the House Judiciary Committee as chairman of the House Permanent Select Committee on Intelligence. In addition, he is the former chairman of the Motion Picture Association of America, Inc. and former director of the Institute of Politics at Harvard University's John F. Kennedy School of Government. Glickman has served as president of the Wichita, Kansas, school board; was a partner in the law firm of Sargent, Klenda, and Glickman; and worked as a trial attorney at the US Securities and Exchange Commission. He received his bachelor's in history from the University of Michigan and his doctorate of law from the George Washington University. He is a member of the Kansas and District of Columbia bars.

Cedric Habiyaremye

PhD Candidate in Agronomy and Crop Science, Washington State University

Cedric Habiyaremye is a PhD candidate in agronomy and crop science at Washington State University. He is an accomplished agricultural consultant and researcher with a history of working in higher education and international agricultural development. Habiyaremye's areas of community development expertise include women and youth empowerment in agriculture, health, entrepreneurship and SME development, and career advisory and youth employment. In 2018 Habiyaremye won the World Hunger Leadership Award for his contributions in agricultural development and the fight against hunger. He was a 2018 Next Generation Delegate at the Chicago Council's Global Food Security Symposium; a 2017 World Food Prize Borlaug LEAP Delegate; a WSU Department of Crop and Soil Sciences Mug Awards recipient (2017 and 2018); and a WSU College of Agricultural Human and Natural Resource Sciences Interdisciplinary Research Team Award recipient. He served as a fellow for the US Borlaug Fellowship on Global Food Security, the Norman E. Borlaug Leadership Enhancement in Agriculture Program, and the Association for International Agriculture and Rural Development Future Leaders Forum. He holds an master's in crop science from Washington State University, a bachelor's in agricultural science with honors in irrigation and drainage, and an advanced diploma in soil and water management from University of Rwanda College of Agriculture and Veterinary Medicine.

Melissa D. Ho

Senior Vice President, Freshwater & Food, World Wildlife Fund-United States

As senior vice president for freshwater and food at WWF-US, Melissa D. Ho drives landscape and transformational initiatives that ensure sustainable agricultural production of protein systems and the conservation of water for the environment and ecosystem services. She also supports the integration of food and water issues in all of WWF's other workstreams. Ho has over 25 years of experience as a scientist, policy advisor, and development professional. Throughout her career, Ho has leveraged a keen focus on the intersection of water and agriculture and its connections to energy and health. She has worked at the landscape level, engaging in large-scale public irrigation systems, agricultural value chains, community-based water resource planning and management systems, and household water technology delivery through the private sector. Ho came to WWF from the Millennium Challenge Corporation, where she oversaw a US$1.5 billion portfolio of infrastructure investments in West Africa. She also served at USAID overseeing the technical team responsible for the strategy development and implementation of Feed the Future. Previously, she developed and implemented the agricultural water management strategy and grant portfolio at the Bill & Melinda Gates Foundation. She has also served in various capacities in the US Congress. She has a PhD in plant physiology from the Pennsylvania State University, a master's in soil science (plant-water relations) from the University of California, Davis, and a bachelor's in environmental systems from Cornell University.

Nnaemeka Ikegwuonu

Executive Director, the Smallholders Foundation

Nnaemeka Ikegwuonu is a farmer, innovator, and social entrepreneur; executive director of Smallholders Foundation Ltd./Gte.; and CEO of ColdHubs, Ltd. He founded the Smallholders Foundation, which uses radio programs and field practical demonstrations to inform, educate, and improve the livelihood of rural small farmers. Additionally, the foundation distributes planting materials to farmers and gives out microloans to female farmers. He recently launched the for-profit company ColdHubs, Ltd., which assembles and installs solar-powered walk-in cold rooms that provides 24/7 off-grid storage and preservation of perishable foods in off-grid markets and farms. Ikegwuonu is a social entrepreneur who has been recognized worldwide with more than 27 local and international awards for his innovations that improve the yields and incomes of smallholder farmers. He is a 2008 Ashoka Fellow, laureate of the Rolex Awards for Enterprise 2010, laureate of the WISE Awards 2010, Future Awards Nigeria's Young Person of the Year 2011, Fast Company USA 100 "Most Creative People in Business" 2012, laureate of the Niigata International Food Prize Japan 2012, and 2013 laureate of the Yara Prize for Green Revolution in Africa (now Africa Food Prize). He sits on the board of many organizations such as the Food, Agriculture, and Natural Resources Policy Research Network (FANRPAN) and Einstein Rising USA.

Prasanta Kalita

Professor and Presidential Fellow, University of Illinois at Urbana-Champaign

Prasanta Kalita is a professor of agricultural and biological engineering and the associate dean for academic programs in the College of Agricultural, Consumer, and Environmental Sciences (ACES) at the University of Illinois at Urbana-Champaign. A fellow of the American Society of Agricultural and Biological Engineers (ASABE) and Indian Society for Agricultural Engineering (ISAE), Kalita's areas of research include water resources management and environmental sustainability, food security, food loss and waste reduction, and water quality. He is widely recognized for his excellence in teaching, research, and international engagement. He has worked extensively in educational development and capacity building, water resources, food production, and food security issues around the world. He has published more than 150 articles in journals and conferences and served as editor-in-chief and associate editor for three international journals. Kalita has served on numerous university, national, and international committees, including serving as the director of the ADM Institute for the Prevention of Postharvest Losses at the University of Illinois for more than three years. As of August 2018 he is serving as the presidential fellow for the University of Illinois System. His career is marked by over 40 honors and awards recognizing educational excellence, research excellence, and outstanding service and leadership.

Peter G. McCornick

Executive Director, Daugherty Water for Food Global Institute, University of Nebraska

Peter G. McCornick is the executive director of the Daugherty Water for Food Global Institute (DWFI) at the University of Nebraska, where he leads the institute in delivering on its vision of a water- and food-secure world, building its partnerships and collaborations in Nebraska, nationally in the United States, and in other key food producing regions in the world. He is a tenured professor in the Department of Biosystems Engineering at the University of Nebraska-Lincoln and is the Robert B. Daugherty Chair of Water for Food. Prior to joining DWFI, McCornick was the deputy director general of research at the International Water Management Institute. With an international career focused on improving the sustainable management of water resources, he has led interdisciplinary research and development programs on water, agriculture, and the environment in Africa, Asia, the Middle East, Canada, and the United States He earned his bachelor's from the University of Newcastle, and his master's and doctorate from Colorado State University. He is a licensed professional civil engineer in the state of Colorado and a member of the American Academy of Water Resources Engineers. McCornick was recently elected to the board of governors of the World Water Council and is a member of the steering committee of the Water Scarcity in Agriculture (WASAG) initiative, a global partnership organized by the Food and Agricultural Organization of the UN (FAO).

Rhiannan Price

Director, Sustainable Development Practice, DigitalGlobe

Rhiannan Price is the director of the Sustainable Development Practice at DigitalGlobe and works with partners across the public and private sectors. She focuses on bridging the gap between what is technically feasible using remote sensing and what is needed to achieve the Sustainable Development Goals. Price also serves as an advisor on NASA's Applied

Sciences Committee, the International Criminal Court's Technology Advisory Board, and the USGS National Geospatial Advisory Committee. She has lived and worked in Uganda, Tanzania, and Dominica and speaks four languages. Price has a master's degree in international human rights from the Korbel School at the University of Denver, where she was a Boren Fellow, and is also a former Peace Corps volunteer.

Isha Ray

Associate Professor, Energy & Resources Group; Co-Director, Berkeley Water Center, University of California, Berkeley

Isha Ray's research interests are water and development; sanitation, gender, and development; and technology and society. Her research projects focus on access to water and sanitation for the rural and urban poor and on the role of technology in advancing sustainable development goals. She and her students have worked on access to and affordability of water in China, India, Mexico, Tanzania, Turkey, and California's Central Valley. She teaches courses on research methods in the social sciences, community-driven development, and water and development. Ray served on the editorial committee of the *Annual Review of Environment and Resources* from 2003 to 2013, serves as a reviewer for 14 peer-reviewed journals, has extensive experience in the international nonprofit sector on development and freshwater issues, and is a regular adviser to United Nations Women. She has a bachelor's in philosophy, politics, and economics from Oxford University, and a PhD in applied economics from Stanford University.

Lindiwe Majele Sibanda

Senior Research Fellow, Institute for the Advancement of Scholarship, University of Pretoria

A globally renowned agriculture and food systems policy advisor, Lindiwe Majele Sibanda is currently a senior research fellow at the Institute for the Advancement of Scholarship at the University of Pretoria. She is the former vice president for country support, policy, and delivery at the Alliance for a Green Revolution in Africa (AGRA). Prior to joining AGRA, Sibanda was the CEO and head of mission for the Food, Agriculture, and Natural Resources Policy Analysis Network (FANRPAN), a pan-African institution active in food and nutrition security policy development across the content, with presence in 17 African countries. She has over 25 years of transdisciplinary experience in agriculture and rural development and public- and private-sector reforms and management. She has served as an advisor and governor to numerous international organizations, including chairman of the board of the International Livestock Research Institute; steering committee member of the Consultative Group on International Agricultural Research (CGIAR) Water, Land, and Ecosystems Program, and member of the Independent Steering Committee of the CGIAR Research Program on Climate Change, Agriculture, and Food Security. She also served as a member of the EAT-Lancet Commission. Sibanda is a serving member of the World Vegetable Board and a cochair of the Global Alliance for Climate Smart Agriculture. Sibanda has received numerous awards for her contribution to agriculture and food security, including the Yara-Africa Prize in 2013. She holds a bachelor's from the University of Alexandria, Egypt, and a master's degree and PhD in agriculture from the University of Reading, United Kingdom.

Acronyms

AFRI: Agricultural Food Research Initiative

APHIS: Animal and Plant Health Inspection Service of the USDA

ARS: Agricultural Research Services of the USDA

BCC: behavior change communication

BUILD Act: Better Utilization of Investments Leading to Development Act

CGIAR: Consultative Group on International Agricultural Research

CFTC : Commodity Future Trading Commission

DARPA: Defense Advanced Research Projects Agency

DoD: US Department of Defense

DoS: US Department of State

EU: European Union

FBA: Farm Business Advisors

FSN: Food Safety Network

GCF: Green Climate Fund

GDP: gross domestic product

GHG: greenhouse gas

HWISE: Household Water Insecurity Experiences

ICT: information and communication technologies

iDE: International Development Enterprises

IFPRI: International Food Policy Research Institute

INM: integrated nutrient management

IWMI: International Water Management Institute

IWRM: integrated water resources management

IPCC: Intergovernmental Panel on Climate Change

LMICs: low- and middle-income countries

MBR: membrane bioreactors

MLD: minimal liquid discharge

NAIP: National Agriculture Imagery Program

NGO: nongovernment organization

NIFA: National Institute of Food and Agriculture of the USDA

NOAA: United States National Oceanic and Atmosphere Administration

NSC: US National Security Council

OECD: Organization for Economic Cooperation and Development

PES: payments for environmental services

R&D: research and development

SMEs: small- and medium-sized enterprises

SSA: Sub-Saharan Africa

SWIR: short-wave infrared

UNICEF: United Nations International Children's Emergency Fund

USAID: United States Agency for International Development

USDA: United States Department of Agriculture

USG: United States Government

WASH: water, sanitation, and hygiene

WUAs: water user associations

Key terms

Blue water: water sourced from surface water or groundwater.

Brown water: household wastewater contaminated with fecal and organic matter. Filtration and chemical treatment are required before it can be returned to the environment or reused. Also known as black water.

Carbon dioxide fertilization: the carbon dioxide fertilization effect is the phenomenon that increased carbon dioxide concentrations in the atmosphere "fertilize" plant growth by accelerating the rate of photosynthesis in plants.

Consumptive use: water removed from a water source for use and not returned to the environment.

Drip irrigation: the practice of dripping water slowly to the roots of plants, which dramatically minimizes water waste and evaporation during irrigation.

External catchment systems: a method of rainwater harvesting that collects runoff from a large catchment area (1,000 square meters to 200 hectares), often located on a hillside, and conveys that water to a cropped area. The main distinctions between micro- and external catchment are the runoff transfer distance and ratio catchment. Also known as macrocatchment or long-slope water harvesting.

Gray water: household wastewater generated from streams without fecal contamination. It has a lower pollution level than brown water and is easier to treat.

Green water: water from precipitation that is stored in soil and available for uptakes by plants.

Microcatchments: a method of rainwater harvesting that collects surface runoff from a small catchment area (less than 1,000 square meters) and stores it in the root zone of an adjacent infiltration basin irrigating trees and crops.

Minimal liquid discharge: a cost-effective water treatment process that relies on filtration technologies and can achieve up to 95 percent wastewater recycle.

Membrane bioreactors: water treatment processes that integrate a perm-selective membrane like microfiltration or ultrafiltration with a suspended growth bioreactor.

No–climate change scenario: a projection of future agricultural productions without effects of climate change. Often used as a reference case.

Private goods: private goods are excludable and rival. Consumption by one individual prevents others from consuming it.

Public goods: public goods are nonexcludable and nonrival. Individuals cannot be effectively excluded from using them, and one individual's consumption does not affect the good's availability to others. Examples include national security.

Reverse osmosis: a water filtration technology that uses a semipermeable, thin membrane that removes foreign contaminants, solid substances, large molecules, and minerals from drinking water.

Rooftop runoff collection: a domestic rainwater harvesting technique that collects, controls, and conveys precipitation runoff from a roof.

Turnouts: a point at which water leaves a central canal for a smaller canal or a field.

Water abstraction: water removal from the environment for human use, but it is typically used for groundwater specifically.

Water pricing: the process of assigning prices to clean water, which can differ greatly under different circumstances.

Water withdrawal: water removed from a surface water or groundwater source and returned some period of time later (may not be to the same place or in the same quality and quantity).

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