Food and Agriculture Organization of the United Nations

WORLD WATER COUNCIL

TOWARDS A WATER AND FOOD SECURE FUTURE

Critical Perspectives for Policy-makers

WHITE PAPER

TOWARDS A WATER AND FOOD SECURE FUTURE

Critical Perspectives for Policy-makers

The outlook for 2050 is encouraging, globally, but much work is needed to achieve sustainable water use and ensure food security for all.

Revised reprint

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2015

WORLD WATER COUNCIL
Marseille, 2015

CONTENTS

FOREWORD iv

LIST OF TOPICAL BOXES v

KEY MESSAGES: EXECUTIVE SUMMARY vii

1. INTRODUCTION 1

2. FOOD SECURITY: AVAILABILITY, ACCESS, UTILIZATION, AND STABILITY 3

Availability 3

Access 3

Utilization 4

Stability 5

3. KEY MESSAGES: DISCUSSION 7

The Outlook for Water and Food in 2050 7

Critical Issues Determining the Outlook for 2050 9

Essential Policies and Investments 20

Water Governance, Institutions, and Incentives 34

4. REFERENCES 41

FOREWORD

The present White Paper has been prepared by the Food and Agriculture Organization of the United Nations (FAO) and the World Water Council (WWC), in support to the High Level Panel on Water for Food Security held at the Seventh World Water Forum in Daegu, South Korea, April 2015.

FAO and WWC wish to acknowledge the financial support of Deere & Company as contributing partner to the preparation and the conduct of the High Level Panel under which this publication has been Issued.

LIST OF TOPICAL BOXES

Box 1. Water, Food, and Agriculture in the Sustainable Development Goals 2

Box 2. Seeking Sustainable Food and Agriculture: FAO's SFA Approach 6

Box 3. The Changing Role and Status of Smallholders 11

Box 4. Investments in Irrigation Technology Do Not Always Save Water 12

Box 5. Water Accounting and Water Balance Analysis are Essential 14

Box 6. The Water, Energy, and Food Nexus 18

Box 7. Degrading Land and Water Quality Increases Pressure on Limited Water Resources 21

Box 8. Reducing Food Losses and Waste Could Reduce Pressure on Land and Water Resources 25

Box 9. Dryland Areas and Marginal Production Environments Are Already Severely Water Stressed 29

KEY MESSAGES: EXECUTIVE SUMMARY

The Outlook for Water and Food Security in 2050

1. The prospect for global food supply between now and 2050 is encouraging, although many of the poor will remain food insecure.

Food production will be sufficient to support a global population of 9 to 10 billion in 2050, although food and nutritional insecurity will persist in many regions. Substantial public and private-sector investments and policy interventions are needed between now and 2050, particularly in agriculture, to reduce poverty, increase incomes, and ensure food security for many of the world's rural and urban residents.

2. While there will be sufficient water to satisfy the demand for food at the global level, an increasing number of regions will face growing water scarcity, which will impact rural and urban livelihoods, food security and economic activities.

Globally, water resources will be sufficient to produce the food required in 2050, but many regions will face substantial water scarcity. Water shortages will result in increasing competition, which will constrain agricultural production and affect the incomes and livelihood opportunities of many residents in rural and urban areas. Innovative and more effective governance mechanisms, together with investments in water technologies and infrastructure will be needed to mitigate the impacts of growing water shortages to ensure water is allocated in such a way as to secure its efficient use, protection of the natural resource base, and to ensure access to water for household use and agricultural production. Countries in water-scarce regions will increasingly need to devise food security strategies that explicitly consider structural food supply deficit and trade arrangements that will provide protection from food price volatility.

Critical Issues Determining the Outlook for 2050

3. Much of the net growth in the global population up to 2050 will occur in the cities of developing countries, thus increasing urban demands for water and food.

The net growth in the global population between now and 2050 will occur in the cities of lower income countries. Increasing urbanization will impact the volume and quality of water available for agriculture, particularly in peri-urban areas. Agriculture can support larger numbers of urban residents, but farmers must be able to retain access to sufficient water to support crop and livestock production. The interaction between cities and the countryside will become increasingly intertwined and, if well managed, will offer new opportunities for mutual benefit, including recycling and reuse of water and nutrients held in municipal waste products.

4. At the same time, in 2050 a substantial share of the global population, and many of the poor, will continue to earn their living from agriculture.
Even with increasing urbanization, in 2050 much of the global population, and most of the poor, will continue to earn their living in agriculture. Thus, investments in agriculture in lower income countries will be critical in raising incomes of the poor and enabling them to achieve household food and nutritional security.

5. In 2050, agriculture will continue to be the largest user of water globally, accounting for more than half of withdrawals from rivers, lakes and aquifers, and will need to become increasingly efficient.
Agriculture will continue to be the largest user of developed water resources in most countries, often accounting for 70 percent or more of water withdrawals from rivers, lakes and aquifers. Increasing demand for water in cities and from industries, and for environmental flows, will reduce the volume of water available for agriculture in many areas. Yet, globally, the volume of water transpired in crop and livestock production must increase between now and 2050 to keep up with increasing demand. In many regions, farmers will need to adapt to less water being available for irrigation, while facing increasing demands for their products. Innovative technologies and investments are required for education and training in the management of water for both irrigated and rainfed settings so as to achieve more productive use of water in agriculture.

6. Climate change will increasingly necessitate investment in measures to enhance adaptation in agriculture that are mostly related to water management.
Climate change will bring greater variation in weather events, more frequent weather extremes, and new challenges requiring adaptation, particularly with regard to water and agriculture. More investments will be needed for measures that will enhance adaptation at the regional, watershed and household levels, such as water storage structures, conjunctive use of groundwater and surface water, wastewater capture and reuse, agroforestry, and research that generates more resilient production systems for smallholders. More effort is required to protect and sustain upland areas and mountainous regions where much of the world's water supply originates.

7. The excessive use and degradation of water resources in key production regions are threatening the sustainability of livelihoods that are dependent on water and agriculture.
In several key production regions, water resources are over-exploited or degraded in ways that are not sustainable. In large areas of South and East Asia, in the Near East, North Africa, North and Central America, groundwater withdrawals exceed the rates of natural recharge and aquifers are in decline.

In these regions, millions of households depend on water for production and over-exploitation cannot continue indefinitely. In other places, intensive agriculture, industrial development and growing cities pollute water bodies to the extent that domestic or agricultural is impossible. Urgent, policy interventions are needed to reduce water withdrawals and pollution in a planned and gradual manner, while assisting households to pursue alternative livelihood activities.

Essential Policies and Investments

8. Public investments and policies must help encourage private investments in technologies and management practices that enhance the sustainable production of crops, livestock, and fish by both smallholders and larger scale producers.

Continuous investment is essential in public agricultural research and extension and it should be refocused to emphasize sustainable intensification of smallholder crop, livestock and fish production. Improvements should be made in crop and livestock genetics, and in production techniques that will permit farmers to increase their output on the limited land and water available. These resources must be made available to smallholders, together with supporting investments in education, training and outreach. Private sector investments and public-private partnerships will increase the pace at which new technologies can be developed and implemented.

9. Investments are needed in programmes that enhance risk management in rainfed and irrigated settings.

Investments and programmes that enhance agricultural risk management, particularly for smallholders, will be critical in enabling farm households to adopt new technologies, diversify their activities, and sustain food security during periods of high input prices, low crop yields and major weather events. In addition to a more systematic use of climatic index-based insurance products, investments are needed in infrastructure that enhance the availability and transport of farm inputs, crop and livestock products, and reduce the transaction costs of marketing farm produce. Such investments will increase the value generated by farmers using limited water resources, while improving household food and nutritional security.

10. Access to water for domestic and other activities must be expanded. Further investments in water, sanitation, and health will be essential components of efforts to achieve household food and nutrition security, particularly in lower income countries.

Investments in drinking water supply, water quality, sanitation and health care that particularly focus on women and children are essential to ensure urban and rural residents can fully utilize available food and nutrition. Improved sanitation and health will ameliorate the effects of chronic diseases and other impediments to household welfare and education and increase productive opportunities. Successful use is essential for good health, as sufficient water is needed at the household level to secure growth and development for productivity, income-generation and food security. This virtuous cycle revolves around assured access to affordable clean water, sanitation and health facilities.

11. Policies and investments are needed to create viable, sustainable off-farm employment opportunities in rural areas.

Policies and investments are needed that will enhance off-farm employment opportunities in rural areas so as to increase incomes, reduce poverty, and improve food security, particularly where land and water resources are inadequate to support higher population densities. Higher incomes are essential to achieving food security, and in many rural areas, will need to be derived from new, off-farm employment.

12. Policies and investments are needed to enhance the role, equality and success of women in agriculture.

Women are responsible for much of the farming in Asia and Africa, and yet many of the institutional settings that influence agriculture do not support women's role in the sector. More appropriate institutions, supportive policies, and strategic investments are needed to enhance the role and success of women in agriculture, particularly in production, but also in research, education and outreach. Policies regarding the security of land tenure, secure access to water, credit, and representation in water user associations and farmer cooperatives are essential. So, too, are programmes that encourage women to enter careers in agricultural research, extension and teaching.

Water Governance, Institutions, and Incentives

13. Water institutions must communicate water scarcity conditions to users through instruments such as transparent allocation mechanisms, pricing, the assignment of water rights, entitlements and other incentive mechanisms, as appropriate in each setting, with proper measures prepared to protect the poor and the disadvantaged.

With increasing competition for water in agriculture and other sectors, national and provincial governments will need to effectively communicate water scarcity conditions, thus ensuring that water is allocated equitably and efficiently, and that all consumers are motivated to use water wisely. In the same way that security of land tenure is essential in encouraging efficient land use, secure water rights and allocations can motivate farmers to invest in their land and augment their returns from irrigated agriculture. Efforts towards continuous cooperation in international river basins will safeguard water and food security in countries that share surface or groundwater resources.

14. Innovations in water governance will be needed in many areas, partly because of the increasing competition for limited water supplies.

Given future increasing competition for water across sectors, innovative systems will be required for water rights, allocation and management. Original forms of water governance were once effective in allocating and managing water during relative abundance, or when most water was used for agriculture. New governance structures will provide broader groups of water users with enhanced involvement in water development, allocation and management decisions. Expected outcomes include wiser investment programmes that contribute to the achievement of sustainable water use, including appropriate concern for environmental amenities.

1. INTRODUCTION

The aim of this paper is to provide policy-makers with a helpful overview of the technical and economic aspects of water use in agriculture, with particular emphasis on crop and livestock production. Through 2050, in many countries, agriculture will remain an important determinant of economic growth, poverty reduction, and food security, even as, over time, the proportion of agricultural revenue in national gross income declines. Water use in agriculture will remain substantial, irrigated areas will expand and competition for water will increase in all sectors. Most likely, overall supplies of land and water will be sufficient to achieve global food production goals in 2050; although poverty and food insecurity will remain pressing challenges in several regions and countries. Thus, the focus of this report is on the regional and national aspects of food security.

Some of the future policies and investments needed to achieve food security in the most challenged regions and countries will relate directly to water, while others will pertain to agriculture more generally, and to other sectors in which water is used. Water interacts with other inputs in agriculture and is essential for providing and sustaining environmental amenities. The science and policy of water resources are complex, yet the fundamental challenge for policy-makers is straightforward.

Appropriate policies must be implemented, and the right investments must be made, at regional and national levels to ensure water volume, quality, and access are sufficient to support livelihoods and ensure food security in 2050 and beyond. Appropriate interventions will address water use in agriculture and other industries, municipal uses, environmental amenities and ecosystem services.

The mission of achieving sustainable use of water resources to support food security in 2050 and beyond is linked closely to several of the goals and preliminary objectives of the United Nations Sustainable Development Goals initiative [Box 1].

Box 1. Water, Food, and Agriculture in the Sustainable Development Goals

The Millennium Development Goals (MDGs), and their targets for 2015, motivated notable advances in poverty reduction, and in the health of women and children in many lower income countries (Cabero-Roura and Rushwan, 2014; Cohen *et al*., 2014; Lomazzi *et al*., 2014). The international community is now engaged in defining and agreeing upon a new set of global objectives that more broadly pertain to the concept of achieving sustainable economic development (Dora *et al*., 2015).

Two of the 17 proposed Sustainable Development Goals (SDGs) align closely with issues regarding water and food security (Maurice, 2013). In particular, SDG 2 calls for ending hunger, achieving food security and improving nutrition, while promoting sustainable agriculture. SDG 6 calls for ensuring the availability and sustainable management of water and sanitation for all (United Nations, 2014).

The objectives listed under SDG 2 describe both the demand and supply aspects of food security. In addition to calling for universal access to safe, nutritious and sufficient food, the objectives call for doubling the agricultural productivity and incomes of small-scale food producers, with a particular focus on women, indigenous peoples, family farmers, pastoralists and fishers. They note the importance of ensuring secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment (United Nations, 2014). It is essential that smallholders, and their households, have access to the resources and inputs needed to engage in livelihoods that will enable them to purchase food, particularly at times of short supplies and high prices.

Also embedded within SDG 2 is the call for ensuring sustainable food production systems and implementing resilient agricultural practices that increase productivity and production, while maintaining ecosystems, and mitigating the potential impacts of climate change (United Nations, 2014). To this end, it is essential that the international research community continue to generate global public goods, such as state-of-the-art research and outreach regarding climate-resilient agriculture, new varieties of cultivated plants, and improvements in livestock health and performance.

Several of the objectives within SDG 6 pertain to water supply, sanitation and wastewater recovery, yet several reflect issues involving agriculture more directly. For example, some of the objectives within SDG 6 describe the need to increase water-use efficiency in all sectors, achieve sustainable withdrawals of freshwater resources, implement integrated water resources management, protect the quality of lakes, rivers, wetlands and aquifers, and substantially reduce the number of people impacted by water scarcity (United Nations, 2014). Although not stated explicitly, the need to ensure access to water for use in food production and in support of other livelihood activities is implied within these objectives, as noted by the call for achieving sustainable freshwater withdrawals, protecting water sources and alleviating the impacts of water scarcity.

2. FOOD SECURITY: AVAILABILITY, ACCESS, UTILIZATION, AND STABILITY

The Declaration of the World Summit on Food Security, published in 2009, defines food security as the condition in which "all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food, which meets their dietary needs and food preferences for an active and healthy life" (FAO, 2009). Within this definition, four dimensions of food security are identified:

1. Food availability;
2. Economic and physical access to food;
3. Food utilization; and
4. Stability, which involves exposure to vulnerability and shocks, over time.

These dimensions can be evaluated at each of the relevant levels or scales by examining indicators pertaining to global, national and household food security.

Availability

Globally, food availability has increased substantially in recent decades, as the growth in agricultural output has exceeded the rate of population growth (Ray *et al*., 2012, 2013). Over this time, production per person has increased in all regions except sub-Saharan Africa. Diet quality has improved in all regions except Africa and South Asia (FAO, IFAD and WFP, 2013). Food availability is enhanced by improvements in agriculture; capture fisheries, aquaculture and the harvesting of forest products (FAO, IFAD and WFP, 2013).

Food production has been increasing faster than the rate of population growth for many years, in all regions except sub-Saharan Africa (Jayne *et al*., 2010). Probably this pattern will continue for some time, such that the global average production of food per person will continue to increase. Yet, global food demands can be satisfied while hundreds of millions of poor households remain food insecure. The leading cause of household food insecurity is the lack of sufficient income to purchase food in local markets, particularly during seasons and years when food is scarce and expensive (Barrett, 2010; Organisation for Economic Co-operation and Development (OECD) 2013; Harris and Orr, 2014; Nawrotzki *et al*., 2014). Availability is a necessary condition for household and national food security, but so too is affordable access to the available food.

Access

Access to food has both physical and economic dimensions. Infrastructure such as ports, roads, and railways are essential for moving food from areas of production to market centres. The same facilities are needed to carry farm inputs such as seeds, fertilizer, and chemicals to rural areas at the right times and in the amounts required to support agricultural production. The economic dimension of food access pertains to the affordability of food at the household level. Even in areas with adequate infrastructure, households must earn the income required to purchase food in local markets. Many poor households are food insecure because they lack the money to purchase food and nutrition.

Food security at national and household levels can be notably impaired by price spikes that occur in response to regional crop shortages, and the consequent hoarding by producers and consumers in exporting countries (Timmer, 2008, 2010; Briones, 2011). The disruption in food trade, caused by the hoarding of commodities for domestic consumption, can elevate a regional crop shortage into a global food crisis, with substantial welfare losses in food importing countries. Largely, the rapid increases in grain prices in 2007 and 2008 were started by the decision of India to cease exports of non-Basmati rice, and market interventions in Viet Nam, Thailand and the Philippines to protect domestic rice supplies (Timmer, 2010).

Such interventions degrade public faith in international markets, causing producers and consumers to call for protective trade policies that will limit helpful market responses to regional crop shortages (Timmer, 2012). Further price spikes could be mitigated by cooperation in the design of an international programme that would respond to crop shortages by coordinating the storage and release of key food grains, while enhancing both national and global food security (Belesky, 2014; Gilbert, 2012). Also, national efforts to improve economic growth, institutions and stabilize food prices would be helpful (Cummings, 2012; Dawe and Timmer, 2012; Timmer, 2012; Galtier, 2013).

Policies and interventions, designed to achieve food security, must address the issues that constrain household access to affordable food and nutrition. Investing only to increase global food supply will not ensure household food security or reduce the poverty that limits the capacity of many households to purchase food. It is essential that competing demands be considered for land and water in other sectors as well as the environmental implications of investing in agriculture. Many smallholders depend on ecosystem services that can be notably impacted by investments intended to assist increase their productive capacity. The optimal investment programme will vary with location and the nature of resource interactions and pressures in each production setting.

Utilization

Food utilization reflects the importance of good health, as both an input to achieving food security and as an indicator of successful outcomes. For example, children suffering from inadequate nutrition or diarrhoea cannot digest all the nutrients in their food (FAO *et al*., 2013). Thus, improvements are essential in health and sanitation, and strengthening children's access to adequate nutrition in efforts to enhance food security. On their own merit, providing safe water and sanitation to all residents in lower income countries are important objectives, and success in expanding services more broadly to urban and rural residents will improve food and nutritional security (Misselhorn *et al*., 2012).

There are evident gender and age dimensions to the utilization component of food security. Provision of adequate nutrition during the first 1 000 days, from conception to age two, greatly improves a child's opportunity for successful growth and development (Bhutta, 2013; Black and Hurley, 2014). Ensuring adequate nutrition for pregnant and lactating women provides substantial health benefits for both mothers and children (Black *et al*., 2013; Fanzo, 2014). Policies and interventions, intended to improve national or household food security, should include components that explicitly improve the food and nutrition available to women and children. Substantial progress has been achieved in recent years in reducing child mortality; yet additional interventions are required to extend the reach of current programmes (Bryce *et al*., 2013).

In 2013, women comprised an estimated 43 percent of the global, paid agricultural labour force. This proportion, which varies with crops and production activities, ranges from just over 20 percent in Southern and Central America to almost 50 percent in East Asia and Africa (FAO, 2015a). Thus, in many regions, the nutritional status of women is both a critical input and an important outcome of successful agricultural production. Agricultural and social policies that enhance women's status regarding property rights, land tenure, access to credit, and technical assistance will permit women farmers to increase crop production for sale and subsistence, while enhancing the nutritional status of women and children, and improving the health and welfare of farm households (Kevane, 2012; Ezezika *et al*., 2013; Nabarro, 2013; Ruel and Alderman, 2013; Du *et al*., 2015).

Stability

Stability involves risk and uncertainty at the global, national and household levels. Globally, over time, the output of major food crops can vary with changes in rainfall patterns, and because of floods, droughts, or pest infestations in key production areas. Such events can impact national food security, which depends on international trade, currency exchange rates and political considerations.

Households and smallholder farmers are particularly vulnerable to unexpected changes in market conditions, as, generally, they are unable to pay higher prices for food when there is a regional scarcity, or are unable to change production options quickly in response to market changes. The sharp increases in food prices observed in 2007-2008 caused the number of undernourished people around the world to increase from an estimated 850 million in 2007 to about 1 023 million in 2009 (High Level Panel of Experts on Food Security and Nutrition [HLPE], 2011).

Briefly, successful efforts to achieve food security at the national level and in households will require that a broad range of issues are examined involving agriculture, natural resources and livelihoods. Also, policies, institutions, and incentives should be considered that would encourage producers and consumers to make choices consistent with the notion of achieving sustainable food and agriculture. [Box 2].

Box 2. Seeking Sustainable Food and Agriculture: FAO's SFA Approach

The Food and Agriculture Organization of the United Nations (FAO) has been promoting the concept of Sustainable Food and Agriculture for many years. The premise for the programme is somewhat self-evident, as the notion of sustainability is embedded within the definition of food security. A household or country cannot be food secure if the agricultural sector within the country, or in the countries from which food is imported, is unsustainable. Thus, efforts to ensure food security must ensure the sustainability of agriculture.

Given this premise, FAO has identified five principles that comprise its approach to Sustainable Food and Agriculture:

- Improving efficiency in the use of resources is crucial to sustainable agriculture.
- Sustainability requires direct action to conserve, protect and enhance natural resources.
- Agriculture that fails to protect and improve rural livelihoods, equity and social well-being is unsustainable.
- Enhanced resilience of people, communities and ecosystems is key to sustainable agriculture.
- Sustainable food and agriculture requires responsible and effective governance mechanisms.

These principles reflect the importance of maintaining and enhancing the resource base that supports agriculture, and the importance of improving the livelihoods of the households and communities that engage directly in the sector. Truly sustainable agriculture allocates equal status to people, natural resources, and ecosystem services with the goals of increasing crop yields and generating sufficient crop and livestock products. This approach to agriculture can carry the global population successfully to 2050 and beyond, while helping to lift millions of smallholder households out of poverty, permitting them to enjoy more productive livelihoods, in which their food and nutritional security is assured.

3. KEY MESSAGES: DISCUSSION

THE OUTLOOK FOR WATER AND FOOD IN 2050

Key Message 1

The prospect for global food supply between now and 2050 is encouraging, although many of the poor will remain food insecure.

Food production will be sufficient to support a global population of 9 to 10 billion in 2050, but food and nutritional insecurity will persist in many regions. Substantial public and private-sector investments and policy interventions are needed between now and 2050, particularly in agriculture, to reduce poverty, increase incomes, and ensure food security for many of the world's rural and urban residents.

The outlook for global food production in 2050, as compared with global food demand, is positive. It is expected that sufficient food will be available in 2050, although food insecurity will continue to be a serious issue in regions and countries with inadequate per capita food consumption (Alexandratos and Bruinsma, 2012). Global incomes are expected to rise substantially by 2050, yet areas of observable poverty will persist in some countries, particularly in sub-Saharan Africa. The per capita annual income in 2050 may remain below US$1 000 in 15 of the 98 lower income countries examined by Alexandratos and Bruinsma (2012). Average food consumption could remain below 2 700 Kcal per person in 16 of the 98 countries; the 16 countries will become home to a population of 800 million. As a comparison, an estimated 4.7 billion people, 52 percent of the global population, will live in countries where the national average is more than 3 000 Kcal per person per day, up from 1.9 billion or 28 percent in 2011 (Alexandratos and Bruinsma, 2012).

Globally, the estimated increase in food production required to ensure food security in 2050 ranges from 60 to 100 percent above production in 2005 (Bruinsma, 2009). These proportions are notably higher than the rate of increase in population up to 2050, largely because of increasing demands and changing food preferences that come with higher incomes. Household and per capita food consumption will increase in many countries, and many residents will consume more meat and vegetables. Generally, these commodities, particularly beef, require more water and other inputs other than grains, per calorie of food consumed (Eshel *et al*., 2014). In some regions, the increasing demand for meat will place additional pressure on limited water resources. The projected increases in food demand, when realized, will reflect a significant improvement in food and nutritional security in households where there is sufficient income to buy adequate food.

Much of the persistent food and nutritional insecurity in 2050, as for today, will be found in poor households in countries with lower gross incomes, and in areas where depleted or degraded natural resources no longer support viable livelihood activities for smallholders. The primary cause of food insecurity will be persistent poverty, which prevents households from gaining access to sufficient food and nutrition, particularly during periods of notable scarcity or high prices. Thus, the policies and investments that will most likely enhance food security will be those that promote economic growth and increase incomes, particularly in rural areas, where many of the world's poor are engaged in agriculture.

Key Message 2

While water will be sufficient to satisfy the demand for food globally, an increasing number of regions will face growing water scarcity, which will impact rural and urban livelihoods, food security and economic activities.

Globally, water resources will be sufficient to produce the food required in 2050, although many regions will face substantial water scarcity. Water shortages will result in increasing competition, which will constrain agricultural production and affect the incomes and livelihood opportunities of many residents in rural and urban areas. Innovative and more effective governance mechanisms, together with investments in water technologies and infrastructure will be required to mitigate the impacts of growing water shortages and to ensure water is allocated in a way that ensures efficient use, while protecting the natural resources base, and safeguarding access to water for household use and agricultural production. Countries in water-scarce regions will increasingly need to devise food security strategies that explicitly consider structural food supply deficit and trade arrangements to protect them from food price volatility.

The volume of water withdrawn for irrigation, globally, will increase from 2.6 thousand km^3 in 2005–2007 to an estimated 2.9 thousand km^3 in 2050, with most of the net increase occurring in lower income countries (Bruinsma, 2011; FAO, 2011b, p.57). The irrigation requirement, which is the portion of consumptive use from irrigation withdrawals, is estimated to increase from 1.27 thousand km^3 to 1.34 thousand km^3. Generally, freshwater resources are sufficient to support this modest increase, although substantial water scarcity will persist in the Near East and North Africa, South Asia and elsewhere. Water scarcity will intensify in areas where current rates of surface and groundwater withdrawals are not sustainable, such as the North China Plain and portions of Central and South Asia.

Many analysts have suggested that there will be sufficient water in 2050 to produce the food needed to support a global population of 9 to 10 billion, provided water resources are allocated and managed wisely, and gains in agricultural productivity are achieved (de Fraiture *et al*., 2010; de Fraiture and Wichelns, 2010; Springer and Duchin, 2014). Wise allocation and use involves understanding the role of water in crop and livestock production, and its use in municipal, commercial, industrial sectors and in the provision of ecosystem services. The demand for water will continue to increase at pace with the global population, rising incomes, and successful efforts to extend water supply and sanitation to all residents of urban and rural areas, particularly in lower income countries.

Meeting these increasing demands will require that policy-makers and water purveyors provide effective leadership in communicating water scarcity conditions, appropriately allocating developed water supplies, encouraging wise use in all sectors, and accurately conveying the prospects of enhancing the broad spectrum of benefits obtained from water in productive and environmental uses. In countries, where there are many smallholder farmers, policy-makers should ensure access to land and water for agricultural households, because their livelihoods and food security are closely linked to the small areas of land and quantities of water used to produce crops and raise livestock.

Water scarcity will constrain agricultural production and livelihood activities in many additional areas in 2050, as the demands for water in agriculture and other sectors continue to increase. Land and water allocation between sectors will become an increasingly challenging political decision, with notable social and economic implications, as cities expand into agricultural areas, and as commerce and industry require additional water supplies. Smallholder farmers in peri-urban areas will be at risk of losing access to land and water to support their agricultural livelihoods.

Critical Issues Determining the Outlook for 2050

Key Message 3

Much of the net growth in global population up to 2050 will occur in the cities of developing countries, thus increasing urban demands for water and food.

The net growth in global population between now and 2050 will occur in the cities of lower income countries. Increasing urbanization will impact the volume and quality of water available for agriculture, particularly in peri-urban areas. Agriculture can support larger numbers of urban residents, but farmers must be able to retain access to sufficient water to support crop and livestock production. The interaction between cities and the countryside will become increasingly intertwined and, if well managed, will offer new opportunities for mutual benefit, including recycling and reuse of water and nutrients held within municipal waste products.

The global population rate is slowing, however, in both rural and urban areas the population will continue to increase for many years. Projections suggest that the global population will reach 9 to 10 billion, before stabilizing and eventually declining. Most of the net increase in global population between 2015 and 2050 will occur in the urban areas of lower income countries. In many regions, increasing urbanization, and the potential impacts of climate change on crop and livestock production, add urgency to the question of whether or not food demands will be met sustainably. It is essential therefore; that food produced in 2050 is accessible and affordable to everyone, in the interest of achieving national and household food security in all countries.

Population growth will continue to decline in many regions from today through 2050, yet many will be added to the global population each year. Most of the net growth will occur in lower income countries, and much will take place in urban areas. The declining rate of growth, overall, may reduce the demand pressures on land and water resources (Alexandratos and Bruinsma, 2012). Yet, local and regional resource issues could remain important and require critical attention, particularly in countries where population growth remains strong and where food insecurity persists.

Increasing urbanization will impact the volume and quality of water available for agriculture, particularly in peri-urban areas (Qadir *et al*., 2010). Substantial public and private investments in wastewater capture, treatment, and reuse will be required to protect public health in urban areas and to utilize both the water and nutrients in effluent streams. As cities expand, and urban populations increase, it will become increasingly important to capture the nitrogen, phosphorus, and other plant nutrients in wastewater, for use in agriculture. Efforts will be needed to ensure that farmers in peri-urban areas retain access to water for irrigation, particularly when there is collection and treatment of wastewater.

Technological advances for capturing and treating wastewater in the rural areas of lower income countries will improve water quality in rural villages and enhance the safety and effectiveness of wastewater irrigation, particularly for smallholder farms (Kim *et al*., 2014). Research on business models for the generation of income through the collection, treatment and sale of wastewater products will encourage private companies to provide wastewater service in areas that are not included in public collection and treatment programmes (Murray *et al*., 2011; Wichelns and Drechsel, 2011; Scott and Raschid-Sally, 2012; Otoo *et al*., 2015).

Key Message 4

At the same time, a substantial share of the global population, and many of the poor, will continue to earn their living in agriculture in 2050.

Even with increasing urbanization, much of the global population, and most of the poor, will continue to earn their living in agriculture in 2050. Thus, investments in agriculture in lower income countries will be critical in raising the income level of the poor and assisting them to achieve household food and nutritional security.

Smallholder agriculture will continue to be the dominant economic activity in much of rural Africa and Asia, although the nature of smallholder agriculture may change [Box 3]. In Africa, as a result of increasing population, the average farm size may continue to decline. In portions of Asia, the average farm size could begin to increase, as population growth slows, and as rural residents move to cities in search of employment. In all areas, smallholders will link more closely with commercial traders and market chains, although the pace and degree of such interactions will vary notably across countries and regions. This will create both opportunities and challenges for smallholder farmers who may have limited experience interacting in formal markets.

Key Message 5

In 2050, agriculture will continue to be the largest user of water resources withdrawn for human use, accounting for more than half of withdrawals from rivers, lakes, and aquifers, but will need to become increasingly efficient.

Agriculture will continue to be the largest user of developed water resources globally, often accounting for 70 percent or more of water withdrawals from rivers, lakes, and aquifers. Increasing demands for water in cities and industries, and for environmental flows, will reduce the volume of water available for agriculture in many areas. Yet, globally, the volume of water transpired in crop and livestock production must increase between now and 2050 to keep up with increasing demand. Farmers in many regions will need to adapt to there being less water available for irrigation, while facing increasing demands for their products. Innovations in technology and investments in education and training with regard to managing water in both irrigated and rainfed settings are needed to achieve more productive use of water in agriculture.

Box 3. The Changing Role and Status of Smallholders

Smallholder crop and livestock production in lower income countries contributes directly to household, regional, and national food security by enhancing home consumption and providing a source of affordable food in local and regional markets (Tscharntke *et al*., 2012; HLPE, 2013). Smallholder production provides households with the income needed to purchase the crop and livestock products they do not produce. Income can be saved as cash, or in the form of durable assets, for purchasing food during years when crop production is impaired by inadequate rainfall or a pest infestation. Savings are needed also when local food prices rise sharply, as a result of disruptions to local or international markets. Income from crop production enables households to purchase meat and vegetables that enhance their nutrition. Policies and interventions that support smallholder agriculture will be essential to ensuring household, regional, and national food security in many lower income countries.

The impacts of climate change on smallholders could be particularly severe, given their limited opportunities for adaptation. Small households, with limited finance and little or no access to irrigation, may be forced to seek new livelihoods if the changes in temperature and rainfall preclude them from continuing to grow crops and raise livestock. Policy makers should evaluate the global and local implications of climate change, while considering the differing impacts on large farms and smallholders. This is because smallholder output contributes to both household and regional food consumption.

Smallholder agriculture is evolving along somewhat different trajectories in Africa and Asia, although the starting points are quite different. The average farm size in Africa is declining, and will continue to decline through 2050, as the rural population on the continent increases (Masters *et al*., 2013). Hazel (2013) projects that the average annual growth rate in the rural population of Africa will slow from the 2.8 percent rate observed during 1990 to 2010, to 1.35 percent from 2011 to 2030, and to just 0.63 percent from 2030 to 2050. This contrasts with the projected average annual growth rates for the rural population in Asia, which are minus 0.35 percent for 2011 to 2030 and minus 0.83 percent for 2030 to 2050. These represent a substantial decline from the rate of 0.32 percent observed from 1990 to 2010.

The rate of change for the rural population determines average farm size, as most rural residents engage in agriculture, and the amount of land available is essentially fixed (Masters *et al*., 2013). Thus, it is possible that the average farm size in Asia will begin increasing, while the average farm size in Africa will continue to decline. Currently, population density in much of rural Asia is higher than that in rural Africa, such that the average farm size is quite small in much of Asia. In both regions, the increasing demand for agricultural output, in both domestic and international markets, should provide the impetus for public and private sector efforts to increase the productivity of crop and livestock production. Substantial investments are needed, particularly in Africa, where the perpetually low rates of fertilizer application have resulted in nutrient mining of farm soils for many years (Bekunda *et al*., 2010).

Box 3. The Changing Role and Status of Smallholders (continued)

As the demand for land and water increases in future, there will be pressure on national governments to provide sufficient resources for producing essential amounts of the standard food and feed crops, such as rice, wheat and maize. Maintaining sufficient production to meet global demands is essential, but so too is the need to ensure that all households have affordable access to food and nutrition. To this end, it is essential that resources be made available to ensure that smallholder households can continue to engage in the diversified crop and livestock agriculture that supports their livelihoods. Many smallholders produce some amount of basic food and feed crops, but many also produce pulses, vegetables, or fish for home consumption or for sale in local markets. This diversification provides income support and serves as a source of nutrients and protein not found in the basic food crops. With increasing competition for land and water, many smallholders could lose access to the resources on which they currently depend for these activities. Policies and interventions that prevent such losses, and that assist smallholders in maximizing the value of their limited resources, will be essential in ensuring household food and nutritional security for all in 2050.

Several authors have suggested that, given the increasing demands for water in competing sectors, agriculture must in future "produce more food with less water" (Springer and Duchin, 2014). While compelling at first read, this phrase is not sufficiently precise. The phrase does not distinguish between the water diverted and applied to farm fields, and the water transpired in the process of generating crop yields. Much of the water applied in irrigation runs off the ends of farm fields or percolates into shallow groundwater, where it is available for further use in irrigation or for another purpose. Only the portion of water consumed by the crop during transpiration, and the water that evaporates from plant and soil surfaces, is 'lost' from the system at this point in the hydrologic cycle. Opportunities for saving water through investments in technology will be limited by the extent to which water is lost in each setting [Box 4].

Box 4. Investments in Irrigation Technology Do Not Always Save Water

Advances in irrigation technology, when used appropriately, can reduce surface runoff and deep percolation from farm fields, thus potentially reducing water losses to non-beneficial evaporation and saline aquifers. Often, drip and sprinkler irrigation systems are recommended as a replacement for surface irrigation in areas with increasing water scarcity or where farmers use groundwater in excess of annual rates of recharge, with the aim of saving water by reducing evaporation, surface runoff and deep percolation. Yet, in areas where surface runoff to rivers and deep percolation to groundwater are used beneficially by neighbouring farmers or during subsequent seasons, the water is not actually lost when using surface irrigation methods (Humphreys *et al*., 2010; Ahmad *et al*., 2014). In such settings, the only potential water saving, when switching to a drip or sprinkler system, to reduce non-beneficial evaporation.

It is possible that the introduction of irrigation methods using higher technology will motivate farmers to intensify or expand crop production, thus leading to an increase in the consumptive use of water that is transpired. Drip and sprinkler systems allow farmers to improve the timing and distribution uniformity of irrigation, which can enhance crop yields, such that transpiration per hectare increases. The prospect of

Box 4. Investments in Irrigation Technology Do Not Always Save Water (continued)

higher returns per hectare will encourage some farmers to expand planted area, if the land is available (Berbel and Mateos, 2014).

Smallholders in Andhra Pradesh, India, increased their plot sizes by an average factor of 2.5 times, in response to the higher yields obtained from rice, sugar cane, sweet orange, and vegetables after switching to drip irrigation (Raz, 2014). Such a response, while possibly generating notable increases in income and livelihood status, can increase the rate of water withdrawal from a declining aquifer or an over-exploited stream.

Policy efforts and investments designed to achieve sustainable water use must acknowledge the distinction between water that consumed by irrigated or rainfed crops; water evaporated from plant and soil surfaces; water taken up by non-beneficial vegetation; and water that runs off farm fields or percolates into an aquifer. In areas where crop production is supported by limited surface water sources or aquifers that recharge very slowly, reduced consumptive use could achieve sustainable water management. Reducing consumptive use could call for substantial changes in cropping patterns, possibly including reduced irrigated area (Balwinder-Singh *et al*., 2015). For example, it may be necessary to limit agricultural production to a single crop, from two or three crops per year, to bring consumptive use into balance with the available water supply. The implications of such an outcome on household and regional food security should be considered well in advance of policy implementation.

Policy-makers must consider the farm-level perspective and economic rationale regarding irrigation technology choices (Vico and Porporato, 2011; Finger and Lehmann, 2012; Heumesser *et al*., 2012). Many farmers invest in a drip or sprinkler system to achieve higher yields and increase production, rather than attempting to save water (Ørum *et al*., 2010; Benouniche *et al*., 2014). Switching to higher technology systems can require investment, operation, and maintenance costs in excess of those required when using traditional, surface irrigation methods. The higher investment costs could place some farmers at greater financial risk and limit their responsiveness to changes in the amount or timing of irrigation water supplies, as might occur with climate change or with increasing competition for water in agriculture and other sectors. For these reasons, often the expected farm-level adoption rates and aggregate outcomes of programmes that promote the use of higher technology irrigation systems are not realized (Van der Kooij *et al*., 2013; Burnham *et al*., 2014).

The distinction between water diverted and water transpired is important when considering water requirements for crop and food production. The relationship between crop yield or biomass and the amount of water transpired is largely linear for a given cultivar and production setting (Zwart and Bastiaanssen, 2004; Tolk and Howell, 2008; Steduto *et al*., 2009). Thus, in a given setting, lacking technological advances, higher yields can be generated only by transpiring more water.

Similarly, more water will be transpired in agriculture as planted areas are expanded in pursuit of higher overall production. Advances in crop production technology that include genetic enhancement can modify the yield-transpiration relationship, such that more output is produced per unit of water transpired. Yet, lacking major advances in technology, the amount of water transpired in agriculture will increase between now and 2050.

The water required to support additional transpiration in 2050 can come from several sources. These include new development of surface and groundwater resources for use in agriculture, and better attempts to use surface runoff and deep percolation directly in crop production. Farmers can reduce evaporation by irrigating more carefully, and they can minimize evaporation by non-beneficial plants, by removing vegetation from irrigation canals and minimizing weeds in crop fields. Water accounting and water balance analysis will be essential tools in evaluating opportunities for agricultural intensification and expansion [Box 5].

Box 5. Water Accounting and Water Balance Analysis are Essential

Consistent with the discussion of water diverted, applied, transpired, or returned to a river or aquifer, it is essential that water ministries and purveyors conduct water accounting and establish policies and procedures to ensure that regional or basin-level water balance is maintained over time. Water accounting involves estimating how much water is diverted, applied, and transpired, how much water is lost, and how much surface runoff and deep percolation are available for irrigation and other uses. Water accounting is essential for determining the potential gains from investments in water saving technology. If little water is lost to evaporation and saline aquifers, there is little potential to save water with a drip or sprinkler system. It might be possible and desirable to increase crop yields, but the increase may require an increase in transpiration.

Water balance involves equating the rates of consumptive use and water losses with the amount of water available within a season and over time. Continuous overdraft of an aquifer with a slow rate of recharge will eventually result in the cessation of pumping from the aquifer, as pumping costs rise with increasing depths to the groundwater, potentially impacting livelihoods and household food security. In areas where farmers utilize both surface water and groundwater, along a river system or across a river basin, water balance analysis is essential to understanding interactions involving users in upstream and downstream settings and in establishing basin management plans that reflect sustainable water use for crop and livestock production and for competing activities.

Competing demands in other sectors, and public demands for environmental amenities, will limit the amount of new development of surface and groundwater for agriculture in many regions. Many farmers, however, can improve water management in ways that reduce non-beneficial evaporation and increase the portion of applied water that is transpired beneficially by crops. Farmers can increase the amount of crop yield obtained per unit of water transpired by ensuring that other essential inputs are available in adequate supply. Crop yields per hectare, and per unit of water applied, are generally higher when there are sufficient plant nutrients, farm chemicals, and labour, which are applied at appropriate times during the season.

Key Message 6

Climate change will increasingly necessitate investment in measures that enhance adaptation in agriculture, mostly related to water management.

Climate change will bring greater variation with more frequent, extreme weather events. New challenges will require adaptation, particularly with regard to water and agriculture. More investments will be needed for measures that strengthen adaptation at the regional, watershed and household levels, such as water storage structures, the use of groundwater and surface water, wastewater capture and reuse, agroforestry, and research that generates more resilient production systems for smallholders. Increased effort is required to protect and sustain upland areas and mountainous regions, where much of the world's water supply originates.

Climate change brings new challenges for farmers, policy-makers and investors. Globally, it appears that some regions will become warmer and drier, while others will become cooler and wetter, and the frequency and intensity of major weather events will change. Yet, the potential impacts on specific regions are uncertain. Given this uncertainty, the most helpful policies and investments may be those that provide short-term support for agricultural growth, while allowing some degree of adjustment as the future unfolds. Investments in roads, markets, capacity-building, household health and welfare, advances in crop and livestock genetics, water storage, and the combined use of surface and groundwater would fit within this category. So, too, would programmes in crop insurance and improvements in access to affordable credit at the farm-level.

The potential impacts of climate change influence the future outlook of gains in agricultural productivity. Some production areas may become warmer and drier, while others could receive more annual rainfall, although the timing of the additional precipitation may not be optimal from the viewpoint of seasonal crop production (Roudier *et al*., 2011). Thus, some regions may experience reduced agricultural output, particularly in arid areas where water supplies are limited. Other areas may experience beneficial changes in cropping patterns and increases in crop yields, with warmer temperatures and longer growing seasons (Kang *et al*., 2009; Gerardeaux *et al*., 2012; Zhou and Turvey, 2014). Higher concentrations of CO2 will increase the yields of C3 crops for example wheat, rice, barley, sugar beet, and cotton in some areas, while higher ozone concentrations will negatively impact others (Jaggard *et al*., 2010). In large countries, such as China and India, the impacts of climate change, and the appropriate policy responses and investments, could vary significantly across production regions (Chauhan *et al*., 2014; Wei *et al*., 2014; Xiong *et al*., 2010; Zhou and Turvey, 2014).

In some regions, investments in agroforestry could allow for better adaptation to climate change than mono-cropping systems (Lasco *et al*., 2014; Mbow *et al*., 2014a). Many smallholders in sub-Saharan Africa already practice some form of agroforestry, as tree-based farming systems offer a degree of crop diversity, thus improving food security, while providing an alternative source of income, ecological benefits and soil enhancement (Mbow *et al*., 2014b). The initial adoption of agroforestry, however, brings new risks to the farm level, as the potential impacts of climate change on agroforestry are not yet fully understood (Luedeling *et al*., 2014). Further research is required on market development; cultivar selection; yield gaps and the gender aspects of agroforestry systems (Smith and Mbow, 2014).

Livestock systems are subject to the potentially extensive impacts of climate change, with marked consequences for food security and welfare, particularly in lower income countries (Thornton *et al*., 2009; Herrero and Thornton, 2013; Godber and

Wall, 2014; Headey *et al*., 2014). Sustained high temperatures can impair livestock health and productivity, directly, while water shortages and higher ozone levels in the atmosphere can reduce the yields of livestock feed (Nardone *et al*., 2010; Nielsen *et al*., 2013; Megersa *et al*., 2014; Morignat *et al*., 2014). The potential impacts of climate change could be considerable in the livestock sector, as grazing and mixed rainfed systems account for 70 percent of all ruminants, and two-thirds of the milk and meat they produce, worldwide (Nardone *et al*., 2010).

The net effects of climate change on crop and livestock production in some countries will influence the likelihood of achieving national food security in 2050. Poor residents of lower income countries are particularly vulnerable to climate-change induced impairment of their food security, given their limited ability to modify production and consumption activities (HLPE, 2012). Rainfed production, which accounts for 80 percent of global cropland and 60 percent of global food output, could be markedly affected by climate change, particularly in arid and semi-arid areas (Turral *et al*., 2011). Efforts to mitigate or adapt to climate change, however, should not preclude research and interventions that increase crop yields and improve farm income, independent of considerations regarding climate change. Successful efforts to increase fertilizer use in Africa, or to reduce dependence on groundwater overdraft on the Indo-Gangetic plain are needed urgently, yet they may increase variations in farm output under climate change (Lobell, 2014).

Climate change can impact the availability and quality of both surface and groundwater, and affect agricultural production and associated ecosystems. Increasing variability of rainfall can influence the flow of water in surface systems and the rates of recharge and discharge from aquifers (Kløve *et al*., 2014; Kurylyk *et al*., 2014). Currently, an estimated 38 percent of the global irrigated area depends on groundwater (Siebert *et al*., 2013). Further research is needed to describe more fully the potential effects of climate change on groundwater dependent ecosystems, although the impacts are thought to be greater in arid regions, on shallow aquifers, and on ecosystems already stressed in advance of climate change (Kløve *et al*., 2014; Menberg *et al*., 2014).

Further study of interactions involving groundwater withdrawals, irrigation, and climate change would provide insight for policy-makers considering adaptation strategies. Ferguson and Maxwell (2012) show that the impacts of irrigation on groundwater storage and stream discharge in a semi-arid basin in the southern United States are similar to the simulated impacts of a 2.5 °C rise in temperature. The implications of this research, as described by the authors, are twofold: 1) Many semi-arid basins in which groundwater supports irrigation may already be experiencing some of the potential impacts of climate change, and 2) The actual impacts of climate change could be exacerbated by the additional stress placed on aquifers supporting irrigation. Thus, policy-makers should have additional incentives for regulating groundwater pumping in semi-arid irrigated basins.

The increased frequency of major weather events, and unexpected changes in weather patterns brought about by climate change, could cause more frequent crop failures in key production regions, which would cause short-term reductions in food supplies resulting in price increases, as occurred in 2008 and 2011. Given this likelihood, some degree of coordination among countries in establishing regional grain reserves, which could be released in times of production shortfalls, would help limit the harmful effects of a spike in food prices on poor households during periods of regional crop failure. Importing and exporting countries could share the cost of maintaining such a reserve.

Key Message 7

The excessive use and degradation of water resources in key production regions are threatening the sustainability of livelihoods dependent on water and agriculture.

In several key production regions, water resources are over-exploited or degraded in ways that are unsustainable. In large areas of South and East Asia, in the Near East and North Africa and in North and Central America, groundwater withdrawals exceed the rates of natural recharge and aquifers are in decline. In such regions, millions of households depend on water for production and over-exploitation cannot continue indefinitely. In other places, intensive agriculture, industrial development and growing cities pollute water bodies to the extent that they are no longer available for domestic or agricultural use. Urgent policy interventions are needed, to reduce water withdrawals and pollution in a planned and gradual manner, while assisting households to pursue alternative livelihood activities.

Groundwater use in agriculture and other sectors has increased substantially since the middle of the twentieth century and, in many areas, annual groundwater withdrawals exceed the rate of natural recharge. Global groundwater withdrawals in humid to semi-arid areas have increased from an estimated 312 km^3 per year in 1960 to an estimated 734 km^3 per year in 2006. (Wada *et al*., 2010). Most of the increased withdrawals and resulting depletion can be attributed to the increasing use of groundwater for irrigation, in response to rising demands for agricultural output.

Technological advances during the 1950s through the 1980s, including high-capacity pumps and affordable, small-scale pumps and tubewells, facilitated the rapid increase in groundwater pumping across large areas of North America, South Asia, and northern China (Qureshi *et al*., 2008; Shah, 2009; Zhang *et al*., 2010; Green *et al*., 2011; Shi *et al*., 2011). Subsidized energy prices contributed to intensified groundwater pumping in South Asia (Shah *et al*., 2012). Groundwater pumping is one example of a policy challenge that requires the comprehensive consideration of water, energy and food production goals, together with interactions to maximize policy success, while the minimizing unintended impacts [Box 6].

Grogan *et al*. (2015) examine groundwater use across much of China, using a hydrological model and a process-based crop-growth model. It was found that groundwater mining accounts for 20 to 49 percent of gross irrigation water demand, assuming all demand is met. Given this estimate, the authors suggest that from 15 to 27 percent of China's current crop production is made possible by mining groundwater.

Box 6. The Water, Energy, and Food Nexus

Water and energy interact in several ways in the production of food and in other productive activities. Water and energy are both complements and substitutes in agriculture and, in some settings, each is an input in the generation of the other. In rainfed areas, usually higher rainfall will generate higher yields that could be associated with larger amounts of fertilizer and machinery operations. Both of these inputs require notable amounts of energy. In this sense, water and energy are complements in crop production. In irrigated areas, farmers can apply water via gravity flow in furrows or they can use sprinkler or drip systems that require energy to pressurize the water. Efforts to improve water management by switching from furrow irrigation to a sprinkler or drip system often generate greater energy expenditure at the farm level.

Water and energy – and land – also interact in decisions regarding the production of crops for biofuel. In areas where land and water are limited, the decision to produce maize, soybeans, or canola for delivery to a biofuel facility reduces the amounts of those crops available for producing food in the current season. The impacts of such decisions on local and distant households will depend on market prices for food and energy, and the returns earned in each activity. Yet, the perception of allocating scarce resources for energy, instead of food, can have political implications, particularly if consumer food prices rise, while crops produced locally are used to produce biofuel for sale in a distant market (Tirado *et al*., 2010; Van der Horst and Vermeylen, 2011).

The decline in energy prices in 2014 and 2015 will reduce the returns to biofuel production, even with current levels of public subsidies in place in some countries. Thus, the amounts of crops diverted from food to biofuel may decline in the near term. The long-term implications will depend on further movements in energy prices and any changes in public subsidy programmes. Public officials will need to evaluate the trade-offs involved in decisions to support biofuel production (Miyake *et al*., 2012; Ribeiro, 2013). In areas where local or national food security will remain pressing political and social issues, it may become difficult to justify support for biofuel production, particularly if energy prices remain lower for some time.

Water, energy, and food also interact in the context of hydropower development in agricultural river basins (FAO, 2014c; Rasul, 2014). Hydropower projects often provide water storage for the generation of electricity and for delivery to irrigation schemes downstream of a reservoir. Operating a hydropower facility to optimize electricity generation can impose constraints on the release of water for irrigation. In some settings, the demand for electricity might be greater in winter, while the demand for irrigation water is highest in summer (Bauer, 2004; Karimov *et al*., 2013). Constructing a hydropower project can impact food production when farmers are removed from land that will be flooded by the reservoir.

Interactions involving water, energy, and food are found also in the context of unsustainable groundwater pumping in some production regions. In the past, several governments have subsidized energy prices to encourage increases in crop production, while supporting smallholder households. Although originally implemented with good intentions, agricultural and energy price subsidies have contributed to the rapid decline of groundwater levels in India, Pakistan, Mexico and Syria (Shah *et al*., 2012; Kumar *et al*., 2013; Scott, 2013; Aw-Hassan *et al*., 2014). Farmers provided with very low or flat rate pricing for electricity have little incentive to minimize their use of groundwater. Efforts to achieve sustainable water use in such settings must address the price and availability of the energy used to pump groundwater. Subsidies that remain in place

Box 6. The Water, Energy, and Food Nexus (continued)

today should be re-evaluated, with due consideration for achieving sustainable use of groundwater resources (Shah, 2009; Shah *et al*., 2012).

Nexus interactions are found also in the large amounts of energy required for transporting irrigation and drinking water supplies in large-scale canal delivery systems, such as those in California (Scott *et al*., 2011), and the large energy requirements for desalination facilities in the Near East and North Africa (Siddiqi and Anadon, 2011). Interactions are pertinent in areas where the demands for energy, water, and land are increasing in agriculture and in other sectors, particularly where efforts to achieve and sustain national food security remain a high priority (Mukuve and Fenner, 2015).

Optimizing the combined use of surface water and groundwater will enhance the sustainability of irrigated agriculture in many regions, particularly where excessive withdrawals cause costly increases in groundwater pumping depths or the return flows from agriculture degrade water quality in receiving streams (Shaw, 2009, 2014; Singh, 2014). Siderius *et al*. (2015) demonstrate the economic viability of conjunctively managing groundwater and rainfall in a tank irrigation system in Andhra Pradesh, India. The higher yields obtained of rice, groundnuts, and sugar cane generate sufficient revenue to offset the cost of rehabilitating the tank system at the start of the six-year experiment, while providing substantial net income per hectare of irrigated land.

Shah (2008) provides an overview of India's Groundwater Recharge Master Plan, which is designed to raise groundwater levels in the post-monsoon season to 3 m below ground level. The programme will involve the annual 'managed artificial recharge' of 36.4 km^3 of water, using an estimated four-million spreading-type recharge structures. While commending the intent of this ambitious recharge programme, the author recommends focussing on the most depleted basins, while utilizing the 11 million private dug wells already constructed by Indian farmers. In addition, Shah (2008) recommends revising energy tariffs to encourage farm-level support for the groundwater recharge programme.

As in many areas of India, farmers in the Indus river basin of Pakistan practice a *de facto* form of conjunctive use, as many small wells are used for irrigation, combined with canal water deliveries (Kazmi *et al*., 2012). Farm-level benefits vary with location along each delivery canal, as farmers, who are located further from a turnout, rely more on groundwater than do those located more closely. Access to groundwater provides many farmers with a higher degree of security regarding their water supply and permits them to optimize the timing of irrigation events. Thus, generally, crop yields and cropping intensities are improved in groundwater zones. Some degree of coordination will be required however to prevent salinization (Kazmi *et al*., 2012), which can impair agricultural productivity, over time, and degrade water quality in rivers and shallow aquifers [Box 7].

Essential Policies and Investments

Key Message 8

Public investments and policies must help encourage private investments in technologies and management practices that enhance the sustainable production of crops, livestock, and fish by both smallholders and larger scale producers.

Continuous investment is essential for the public research of technologies that will improve smallholder crop, livestock and fish production. Improvements in crop and livestock genetics, and in production techniques that permit farmers to produce more output with limited land and water resources must be made available to smallholders, with supporting investments in education, training and outreach. Private sector investments and public-private partnerships will strengthen the pace at which new technologies are developed and implemented.

Public and private investments in infrastructure, training, capacity-building, and natural resource protection will be needed between now and 2050, to further stimulate agricultural development in poorer countries and to bring resource use within sustainable bounds. Agricultural development will continue to be the primary engine of poverty alleviation in rural areas of poorer countries, as much of the population depends either directly or indirectly on agriculture for their livelihoods. Smallholders, in particular, need to be assured of sustained access to land, water, and other productive inputs. They need technical assistance, access to credit, and training that will allow them to adjust successfully to changing production and marketing opportunities.

Much has been learned in the last 50 years about the role of technology in improving water management, increasing crop yields and enhancing farm incomes. Many farmers in arid and semi-arid regions have adopted drip and sprinkler irrigation systems, while many use laser to level their fields, and many deliver fertilizer via their on-farm irrigation systems in a process known as fertigation (Castellanos *et al*., 2013; Chai *et al*., 2014; Gheysari *et al*., 2015). Optimizing the use of water and nutrients in crop production, planting hybrid varieties of some crops, using higher quality seeds, and implementing new methods of pest control, have contributed to the large and sustained increase in crop yields observed in many countries since the 1960s and 1970s (Biazin *et al*., 2012; Wright, 2012; Stevenson *et al*., 2013; Alston and Pardey, 2014).

Genetic improvement of crop varieties has been proven to increase household incomes and enhance food security. There are numerous ways to improve crops genetically, from traditional crossing and selection to the most recent gene transfer techniques. But all of these depend on the ability of crop breeders to assemble genes for the desired traits within new varieties. Recognizing the importance of crop genetic improvement, most countries support some form of public and/or private plant breeding system (FAO, 2010).

Box 7. Degrading Land and Water Quality Increases Pressure on Limited Water Resources

Generally, water scarcity can be described as an imbalance between supply and demand. When the amount of water demanded exceeds the amount available, at the current price, or given current access conditions, water is essentially scarce. Thus, water scarcity can worsen when either demand increases or supply diminishes. When water quality is degraded by pollution, the concentrations of undesirable constituents can increase to levels that render the water unfit for human consumption or for use in irrigation or aquaculture. Both surface water sources and groundwater can be impaired by water pollution, with consequent impacts on the supply of water available at a given location or point in time. In this manner, water quality degradation can generate or exacerbate water scarcity.

Land quality degradation can increase the demand for water in some settings. For example, when farmland becomes saline as a result of the over-application of irrigation water in arid regions, in combination with inadequate drainage service, farmers wishing to produce salt-sensitive crops will need to deliver additional amounts of irrigation water to leach accumulated salts from the soil profile. The additional water, or leaching fraction, must be added to the crop–water requirement when determining irrigation demands (Letey *et al*., 2011).

In this manner, allowing soils to become saline through unwise irrigation practices can place additional demand pressure on limited water supplies. Salinization can degrade the quality of water in rivers and aquifers, when saline drainage water is discharged into receiving ditches and when deep percolation increases the salinity of shallow groundwater (Cañedo-Argüelles *et al*., 2014; Vengosh, 2014). Persistent pumping of deep groundwater can facilitate the movement of saline shallow groundwater into deeper aquifers, thus contaminating important sources of water for drinking and irrigation (Chaudhuri and Ale, 2014).

Examples of the impact of degraded water quality on available water supplies are found in many settings. In China, cumulative water pollution is viewed as a major contributor to the emerging gap between water supplies and demands. Between 1992 and 2007, an estimated 225 million tonnes of chemical oxygen demand (COD) accumulated in Chinese water bodies, thus substantially reducing the supply of fresh water available in the country's lakes, rivers and aquifers (Guan *et al*., 2014). In 2011, the Chinese Government devoted its primary policy document to the discussion of water conservation and water quality objectives (Liu and Yang, 2012; Grumbine and Xu, 2013). China implemented an aggressive water management programme in 2014, to improve and protect water quality, with the objective of sustaining the notable rates of economic growth achieved in recent years. The programme will include new policies, investments in infrastructure and technology development (Guan *et al*., 2014).

In Sri Lanka, micro-propagation using tissue culture of an improved banana variety has enabled smallholder rice farmers to diversify their cropping pattern and earn additional income (Lagoda, 2013). Kabunga *et al*. (2014) observed similar results in a survey of 385 diversified smallholder farming households in the Central and Eastern Provinces of Kenya. Farmers adopting tissue culture technology for the vegetative propagation of bananas have increased their farm and household incomes by 116 and 86 percent, respectively, largely because of higher net yields and beneficial adjustments in the mix of inputs. Food security improved as a result of higher incomes and the larger amounts of bananas available for home consumption.

Agriculture can benefit from advances in technology that do not involve genetic enhancement. Advances in biotechnology can improve the detection and control of plant diseases, while biofertilizers and biopesticides can enhance plant nutrition and pest control (Ruane and Sonnino, 2011). Similar advances are available for use in livestock production and in aquaculture. For example, molecular-based serological techniques have notably improved animal health in lower income countries, while molecular-based pathogen detection systems are used to detect viruses in all countries producing commercial shrimp (Ruane and Sonnino, 2011).

Investing in rainfed and irrigated crop production

The remarkable increases in agricultural productivity that have been achieved since the 1960s have helped farmers in many countries produce sufficient food to support the world's population, which has increased from about 3 billion in 1960 to more than 7 billion in 2015. Much of the gain in aggregate output has been achieved through the expansion of planted area, while much has come from notably higher yields. Given the high costs, and environmental impacts of continuing to expand agricultural areas, in future much of the additional food production required by 2050 must come from increased yield from crops and livestock. Thus, the key question at this juncture is whether crop and livestock yields will continue to increase at sufficient pace to feed a global population of 9 to 10 billion in 2050.

Irrigated agriculture accounts for about 20 percent of the cultivated area worldwide, while generating an estimated 40 percent of crop production (Turral *et al*., 2010; FAO 2015a, 2015b). Yields are markedly higher with irrigation, partly because farmers apply larger amounts of fertilizer and farm chemicals when they can control the timing and amount of soil moisture in their fields (Monjardino *et al*., 2013). Much of the world's food supply in 2050 will come from irrigated farms, yet much will also come from farms that fully rely on rainfall and those that supplement rainfall with partial irrigation. In many countries, achieving national food security in 2050 will call for investments and interventions in both irrigated and rainfed areas.

Substantial research has been conducted in recent years on methods that will improve water management in rainfed areas, such as rainwater harvesting, plant nutrient strategies, cropping systems, mulching, tillage and other soil and water conservation practices (Karpouzoglou and Barron, 2014; Kurothe *et al*., 2014). Efforts to extend improved methods of farming under rainfed conditions will contribute to improving incomes and enhancing livelihoods in areas where poverty is correlated with low crop yields and inadequate use of fertilizer and modern seeds (Affholder *et al*., 2013; Dzanku *et al*., 2015).

Assessing the volumes and qualities of water supplies and demands, and determining the possible incidence of food and nutrition insecurity, will require on-going research in support of policy analysis. Advances in agricultural technology, including genetic enhancements, will permit many farmers to produce increased output with limited land and water supplies in both rainfed and irrigated settings.

Technology alone, however, will not be sufficient to completely offset increasing resource limitations pertaining to land, water and other natural resources.

It is likely that more water needs to be transpired in agriculture to achieve global food demands in 2050, even with notable advances in crop and livestock technology. It is also likely that greater amounts need to be applied of nitrogen, phosphorus and other plant nutrients. Opportunities for truly saving water in agriculture will be limited to situations in which water is currently lost. Accurate water accounting and water balance studies will be needed in many areas to identify the most appropriate interventions for increasing agricultural productivity with limited water supplies.

Closing the yield gaps

Continuous public investments are needed in the development of new technology and in technical assistance to support smallholder crop, livestock and aquaculture production. Many rural households will remain engaged in agriculture in 2050; their production will contribute to local and regional food supplies, while enhancing household incomes.

Smallholders in Latin America and the Caribbean currently produce from 27 to 67 percent of locally consumed food. Closing the large gaps that exist between smallholder yields and those obtained by experiment stations will serve to increase food supply and boost effective demand for food at household and community levels. New crop varieties, better methods of producing current varieties, and better outreach by crop and livestock extension specialists are needed.

Evidence in the literature is mixed concerning the challenge of closing yield gaps. The annual rate of increase in crop yields is slowing in key production areas, causing concern that future gains may not keep pace with the rate of increase in global food demand (Grassini *et al*., 2013; Jat *et al*., 2014). Some authors suggest that improvements in soil and water management, facilitated in part by affordable access to farm inputs in lower income countries, will help close existing yield gaps across a large portion of the world's agricultural landscape (Spiertz, 2012). Possible potential yield gaps are larger in rainfed settings than in irrigated areas, yet the challenges of increasing yields in rainfed areas are significant (Lobell *et al*., 2009; Kassie *et al*., 2014). In either setting, the desired increases in yield will take time, and progress will be uneven, as outcomes will vary with soil and water conditions and with access to fertilizer (Bryan *et al*., 2014; Conner and Minguez, 2012). Li *et al*. (2014) report that wheat yields on the North China Plain have increased by about 115 kg per ha per year, since 1981, thus substantially closing the farm-level yield gap. They report however that the wheat yield in some areas is no longer increasing.

Other authors suggest that advances in plant genetics, agronomy, biotechnology, and animal science will provide the improvements needed in crop and livestock technology to achieve further increases in yields (Powell *et al*., 2012; Blum, 2011, 2013; Cabello *et al*., 2014; Dolferus, 2014; Rothschild and Plastow, 2014; Vadez *et al*., 2014; Langridge and Reynolds, 2015). However, some authors question whether the needed advances can be developed, tested, and implemented broadly between now and 2050 (Hall and Richards, 2013). Substantial public investments in crop and livestock science are required to move research programmes forward, particularly those that will benefit smallholders (Anthony and Ferroni, 2012). Even with adequate financial support, ample time will be required to produce new cultivars with traits that meet both global and farm-level objectives (Spiertz, 2014).

Livestock production and marketing are essential livelihood components for more than one billion poor people in Asia and Africa (McDermott *et al*., 2010). Many are smallholders, for whom livestock represent a source of food and income, while serving as a means to accumulate wealth. The increasing global demand for livestock products will create opportunities for smallholders to generate higher incomes, provided they have access to output markets and to the inputs and capital needed to expand their operations sustainably, while maintaining an acceptable level of risk (Herrero *et al*., 2009; Tiwari *et al*., 2014).

Capturing and reusing plant nutrients in waste materials

The large yields from grains and other crops, achieved in many countries, are made possible, in part, by the application each season of large amounts of nitrogen and other plant nutrients. Plants utilize much of the applied nutrients in the process of carbon assimilation, yet some portion of the nutrients enters the atmosphere, runs off into streams, or seeps into groundwater. The portion taken up by plants is conveyed to processing plants and to the food we eat, and eventually to the wastewater stream leaving households, villages and cities. As urbanization intensifies in many areas, and as the direct and indirect costs of nutrient use in agriculture increase, over time, the need to recycle the water and plant nutrients in municipal wastewater will become more evident and more urgent.

The cost of producing nitrogen fertilizer largely depends on the price of energy, as the process is energy intensive. Although energy prices have declined sharply in recent months, energy prices could resume their long-term upward trend in the not-too-distant future. Phosphorus is an essential plant nutrient that is produced by mining phosphate rock (Johnston *et al*., 2014), limited supply remains in just a few countries (Ryan *et al*., 2012). Thus, there is some uncertainty regarding the future security of newly mined supplies of phosphorus. Recycling the phosphorus in wastewater will extend the useful life of existing phosphate rock reserves, by reducing the demand for that source of phosphorus. There are mixed views in the literature, as to if or when the world might exhaust its supply of phosphate rock (Ziadi *et al*., 2013). Globally, an enhanced programme of wastewater recycling, in which phosphorus, nitrogen and other elements are obtained and reused, could be a wise hedging strategy.

There is a sense of circularity or ecosystem closure with the concept of returning plant nutrients to farmland in the countryside, after food has been consumed in the city. The recovered nutrients can be used again to produce more food, and the cycle can be repeated in perpetuity. In addition, efforts to extend and intensify the capture and reuse of wastewater will reduce the negative impact on the environment of unregulated wastewater discharge into rivers and streams.

In areas where the economics of wastewater recovery and reuse are such that private firms can engage in the activity for profit, wastewater management will become a widely-acknowledged business enterprise that generates sustainable benefits for households, communities and farmers (Otoo *et al*., 2015). The health risks to farmers, households, and consumers can be managed through appropriate policy interventions (Hanjra *et al*., 2012; Keraita *et al*., 2015.)

In addition, substantial amounts of land, water, energy, and plant nutrients are used to produce the food that is lost or wasted along the supply chain from farms to households. In some settings, efforts to reduce these losses can contribute to improving resource use and enhancing food security [Box 8].

Box 8. Reducing Food Losses and Waste Could Reduce Pressure on Land and Water Resources

FAO defines food loss as "the decrease in quantity or quality of food and the agricultural or fisheries products intended for human consumption, that are ultimately not eaten by people or have incurred a reduction in quality reflected in their nutritional value, economic value or food safety" (FAO, 2014d). Food waste in comparison is defined as the discarding or alternative use of food that was once fit for human consumption. The discarding may occur by choice, or after the food has been left to spoil or expire as a result of negligence. Given these definitions, food losses tend to occur in the early stages of the food supply chain, particularly during harvest, post-harvest handling and processing. Food waste tends to occur in later stages of the supply chain, particularly in retail or wholesale shops and in consumer homes (FAO, 2014e). Both food loss and food waste might be viewed as the wasting of inputs, including the land, water and energy used to produce the crop and livestock products (Gustavsson *et al*., 2011).

Gustavsson *et al*. (2011), in a study conducted for FAO, suggest that one-third of the food produced for human consumption is lost or wasted at some point along the supply chain, resulting in a loss of about 1.3 billion tonnes of food per year. Losses and waste occur at all stages of the supply chain, from production on the farm, to household consumption. In lower income countries, much of the loss occurs during the early and middle stages of the supply chain, while in higher-income countries, much of the waste occurs at the consumer level (Gustavsson *et al*., 2011). Parfitt *et al*. (2010) report that food waste increases as the proportion of income spent on food declines. Thus, food waste generally is higher in homes with larger incomes, all else being equal. Consistent with these observations, Gustavsson *et al*. (2011) report that consumers in Europe and North America waste from 95 to 115 kg of food per year, while consumers in sub-Saharan Africa and South and Southeast Asia waste only 6 to 11 kg per year.

Buzby and Hyman (2012), using aggregate survey data for 2008, estimate the total value of food waste at the retail and consumer levels in the United States at US$165.6 billion, based on retail prices. The top three food groups, in terms of the value, were meat, poultry, and fish (41 %); vegetables (17 %); and dairy products (14 %). The losses in all groups equalled about 124 kg of food per capita. The estimates provided by Buzby and Hyman (2012) are timely and informative, yet Koester (2013) raises important questions regarding the methods used to estimate food losses, with possible implications for policy-makers. Better efforts to collect and report data describing food losses and waste at all levels of the food supply chain, and economic analysis of efforts to reduce food waste, would be helpful in assessing the global extent of the problem and identifying efficient corrective strategies (Parfitt *et al*., 2010, Koester, 2013; HLPE, 2014b).

Enhancing the sustainability of aquaculture

Fisheries and aquaculture are major sources of protein for much of the world's population. An estimated 3 billion people obtain about 20 percent of their animal protein intake from the output of a capture fishery or an aquaculture operation (HLPE, 2014a). An additional 1.3 billion people obtain 15 percent of their protein from fish. These proportions represent averages across many countries. The share can be much higher for individual countries, for example in Gambia, Sierra Leone and Ghana, the share of dietary protein from fish is higher than 60 percent (HLPE, 2014a). The share ranges from 50 to 60 percent in Cambodia, Bangladesh, Indonesia and Sri Lanka, where capture fisheries have long been important and where, since the 1990s, aquaculture has developed rapidly (HLPE, 2014a).

Aquaculture currently generates more than 50 percent of the fish and shellfish products consumed worldwide (Naylor *et al*., 2009; FAO, 2014a). More than 60 percent of global aquaculture production comes from China, while an additional 26 percent comes from other countries in Southern and Eastern Asia (FAO, 2014a). The Americas and Europe each account for about 4 percent of global aquaculture production, while Africa accounts for about 2 percent of the global amount. Although currently, production in Africa is a small portion of global output, in recent years the rate of growth of African production has been quite high. African production has increased from about 81 000 tonnes in 1990 to 1.4 million tonnes in 2012, thus increasing by a factor of 18 within 22 years (FAO, 2014a). China's production in 2012 (41 million tonnes), in comparison, is about six times higher than its production in 1990 (6.7 million tonnes).

Across Africa, aquaculture employs about 920 000 people and accounts for 0.15 percent of gross domestic product (de Graaf and Garibaldi, 2014). These are small portions of the employment and income generated by both fisheries and aquaculture in Africa. The full sector employs about 12 million and generates an annual income of about US$24 billion, or 1.26 percent of African gross domestic income (de Graaf and Garibaldi, 2014). Yet, for those involved in small-scale aquaculture, often combined with small-scale farming, the additional production and income enhance household food and nutritional security (Beveridge *et al*., 2013). The increasing demand for fish and fish products in Africa presents a substantial opportunity for further expansion of small-scale, commercial aquaculture.

Fish products from inland and ocean fisheries, and from aquaculture, contribute substantially to household food and nutritional requirements, particularly in Asia and Africa. Aquaculture has increased rapidly in recent years, with notable growth in China, which now produces more than half of global output from aquaculture. Fisheries and aquaculture provide livelihoods for many smallholders, often together with other activities, such as rice production, in which farmers use land and water for both fish and crops. In some areas, aquaculture competes with agriculture for water supply, and agriculture is impacted by degrading land and water quality. These and other environmental issues, including the use of fishmeal and fish oil as feed materials, and the off-site impacts of effluent from aquaculture operations will require policy interventions to ensure that aquaculture can continue to contribute to global food and nutrition demands sustainably.

Addressing environmental issues

The rapid increase in aquaculture production has noticeably improved household food and nutritional security in several countries. In some areas, efforts are needed to reduce the environmental impacts of aquaculture. The most common include pollution of aquatic and benthic ecosystems; impairment of coastal habitats and ecosystems; enhanced disease and parasite transmission between farmed and wild fish populations; the introduction and spread of invasive species; increased stress on freshwater resources; depletion of wild fish populations for stocking aquaculture operations; and overfishing of wild fish populations used as ingredients in aquaculture feed (Diana *et al*., 2013; Hixson, 2014; Troell *et al*., 2014). In addition, the use of fishmeal and fish oil from wild fisheries, as inputs in aquaculture, can threaten the food security of low-income households that rely on low-trophic level fish as a key source of food and protein, particularly in Africa, Asia and Latin America (Klinger and Naylor, 2012; Beveridge *et al*., 2013; Tacon and Metian, 2013; Troell *et al*., 2014; Cao *et al*., 2015).

The potential of aquaculture to increase the resilience of the global food system will not be realized unless policy-makers provide appropriate incentives and regulations (Troell *et al*., 2014). If commercial aquaculture becomes more dependent on fish-based or crop-based feeds, competition for fish and crops may increase, giving rise to allocation issues, particularly across income groups. The industry must be encouraged to find the right combination of feed inputs and to minimize negative externalities, including greenhouse gas emissions and the discharge of effluent from aquaculture operations. Operators could also consider the use of nutrient-rich effluent from fishponds as a source of supplemental irrigation on field crops or orchards, although water quality issues could be restrictive.

Marschke and Wilkings (2014) consider a programme of production standards for small-scale aquaculture producers in Viet Nam, which is the world's largest producer of farmed catfish, and the fourth largest producer of farmed shrimp. Mostly, small-scale operators are engaged in shrimp production on less than 2 ha of pond area (Marschke and Wilkings, 2014). The authors suggest that efforts to establish sustainability standards for small-scale aquaculture should acknowledge the special characteristics of smallholder production and minimize the transaction costs of participating in such a programme. Public officials developing sustainability standards could consider some of the suggestions regarding the construction and operation of fishponds, as described by Bosma and Verdegem (2011).

Key Message 9

Investments are needed in programmes that enhance risk management in rainfed and irrigated settings.

Investments and programmes that enhance agricultural risk management, particularly for smallholders, will be critical in enabling farm households to adopt new technologies, diversify their activities, and sustain food security during periods of high input prices, low crop yields and major weather events. In addition to a more systematic use of climatic index-based insurance products, investments are needed in infrastructure to improve the availability and transport of farm inputs, crop and livestock products and to reduce the transaction costs of marketing farm produce. Such investments will increase the value that farmers generate with limited water resources, while improving household food and nutritional security.

Investments in agriculture and water, and policies designed to encourage the wise use of resources, must recognize the inherent risk and uncertainty of farming, particularly in smallholder settings, in addition to the potential impacts of climate change. Often, smallholders are prevented from adopting new technologies, or utilizing the appropriate amounts of farm inputs, because they cannot risk losing their investment in expensive seeds or irrigation water if a dry spell or pest infestation destroys their crop. Crop insurance programmes and access to affordable credit can assist in such situations, but they do not fully eliminate risk at the farm level.

Crop yields are determined in large part by the amount of seeds or plants applied to each hectare, and the amount of water, fertilizer and chemicals used each season. Yet, weather, pests, and the timing of the application of inputs also influence yields. To some degree, farmers can manage the effects of weather and pests, and can choose the timing by which they apply key inputs, yet much of the resulting influence on crop yields is uncertain. The yield obtained in one season by applying 20 kg of seed, 100 kg of nitrogen, and 600 mm of irrigation water on a hectare of grain can be quite different from the yield achieved with the same inputs in a subsequent season, because of influences beyond the farmers' control.

The nature of risk and uncertainty, and the degree of farm-level risk aversion vary across farms, with differences in farmer perspectives, household savings, access to crop insurance, crop choices, weather patterns and market conditions. Perhaps the greatest distinction exists between farmers in developed countries, who have substantial savings accounts and crop insurance, and smallholder farmers in lower income countries with limited savings and no access to insurance. Often, the latter farmers will limit their use of costly inputs, such as high-quality seeds and plant nutrients, as inadequate rainfall or a serious pest infestation can cause them to lose their entire expenditure. Smallholders can manage risk to some degree by diversifying their crop choices, but opportunities are limited in areas having too much or too little rainfall (Kandulu *et al*., 2012). In such settings, interventions that assist farmers in accommodating risk can be helpful in improving household income and welfare.

Many smallholders operate in severely water-stressed dryland areas and have limited agricultural productivity. Interventions to assist these smallholders are needed, in the interest of enhancing their food security [Box 9].

Key Message 10

Access to water for domestic and other activities must be generalized. Further investments in water, sanitation, and health will be essential components of efforts to achieve household food and nutrition security, particularly in lower income countries.

Investments in drinking water supply and quality, sanitation and health care, which particularly focus on women and children, are essential for ensuring residents of urban and rural areas can fully utilize available food and nutrition, while preventing chronic diseases and other impediments to household welfare and educational and productive opportunities. The successful use of sufficient water is essential for good health at the household level and to ensure successful growth and development for productivity, income-generation and food security. This virtuous cycle revolves around assured access to affordable clean water, sanitation and health facilities.

Box 9. Dryland Areas and Marginal Production Environments Are Already Severely Water Stressed

An estimated two billion people live in areas subject to perennial drought and persistent water scarcity. Known as the world's drylands, these areas represent about 41 percent of the Earth's land surface (D'Odorico and Bhattachan, 2012; Solh and Van Ginkel, 2014). Livelihoods in the drylands are precarious already, as rainfall is sparse and highly variable, droughts are frequent, and the productivity of cropland and rangeland is limited. It is probable that climate change will reduce precipitation in many of the world's drylands, and possibly increase rainfall variability (D'Odorico and Bhattachan, 2012), thus further challenging the region's agro-pastoralists.

Stroosnijder *et al*. (2012) recommend interventions to improve water-use efficiency in the drylands, such as increasing infiltration and using surfactants to enhance the water-holding capacity of dryland soils. Conservation tillage and mulching can reduce water loss from soil evaporation, and rainwater harvesting could permit farmers to optimize the values obtained with the limited annual rainfall (Totin *et al*., 2013; Nyakudya and Stroosnijder, 2015). Such interventions are helpful in current conditions, but they may not be sufficient to sustain production and support agricultural livelihoods in the drylands, if the impacts of climate change on the amount and variability of rainfall are significant.

Marginal production environments are those in which rainfall is insufficient to support crop and livestock production, or the soils or climate are unsuitable for producing viable yields of most crops. In such regions, many households are perpetually food insecure. In a household survey of 12 sites in Kenya, Uganda and Tanzania, Rufino *et al*. (2013) found substantial food insecurity in areas with annual rainfall of less than 800 mm. In areas with less than 700 mm of rainfall, many households relied on food aid. Many households in the region are poor and food insecure, and they subsist on inadequate diets (Rufino *et al*., 2013). Further degradation in their production environments, perhaps as a result of climate change, could move many households beyond the point of being able to sustain their livelihoods.

The numbers of households involved in marginal production environments is small, relative to the large numbers of poor people living in the rural areas of lower income countries in Asia and Africa (Rufino *et al*., 2013). Yet, the challenges faced by households in marginal environments are substantial, as is the downside risk from further degradation resulting from climate change. Rufino *et al*. (2013) propose policies that provide safety nets for poor households, insurance programmes, investments in roads, water and in crop and livestock input services. In areas with more than 800 mm of annual rainfall, households could benefit from training in risk management, crop diversification and livestock intensification.

Many poor households have inadequate access to clean water and sanitation. As a result, many women and children spend substantial time and effort fetching water for household use, and family members often suffer from ill health, caused by unclean or unsanitary living conditions. Such illness, and the time spent fetching and preparing water for use, reduce educational opportunities and limit labour productivity. Securing access to an affordable, safe water source can greatly enhance a household's likelihood of escaping poverty, as family members are able to devote more time and effort to educational and productive activities.

Many rural households lack secure title to the land and water they use to produce crops and raise livestock, as part of their essential livelihood activities. Many smallholders operate in rainfed settings, in which the crop water supply is inherently uncertain. Small reservoirs are helpful in capturing and storing rainwater for use in households or on crops, as needed, but not all farm households can afford such an investment, partly because of the cost of installation and partly because of the opportunity cost of withdrawing land from crop production.

Efforts to assist farmers in constructing small reservoirs and training farmers to optimize rainwater-harvesting strategies would be helpful in many areas. Where water is available from an irrigation scheme, or a wastewater treatment facility, many smallholders could benefit from assistance that would help them secure a permanent or long-term right to receive some portion of the available water in perpetuity. Over time, as funds allow, long-term land and water security will motivate smallholders to invest in improving their crop, livestock and aquaculture operations.

In many low-income countries, investment in water can be viewed as an investment in poverty reduction. The need for investments in water supply and treatment, irrigation, drainage, flood control and rainwater harvesting is quite high in many countries. Investors in the water sector can substantially improve livelihoods and greatly enhance the welfare of households and communities across much of Africa and Asia.

Investments must be carefully planned, and should account for many of the interactions and externalities inherent in water development projects. In many settings, the development of an irrigation scheme, or construction of a rainwater harvesting structure in one location, will improve water supply for one set of users, while impairing the water supply for others. The constraint might be direct, in terms of the volume or flow of water available in an aquifer or stream or indirect, in the form of reduced flows to an estuary that supports an indigenous fishery, or provides plant materials that are harvested each season by residents who produce crafts for sale in local markets. The best investments in water resources, from the viewpoint of poverty reduction, will be those that increase the volume and quality of water available for household use and production, while minimizing and mitigating impacts on other water users and the environment.

Key Message 11

Policies and investments are needed to create viable, sustainable off-farm employment opportunities in rural areas.

Policies and investments that enhance opportunities for off-farm employment in rural areas are needed to increase incomes, reduce poverty and enhance food security, particularly where land and water resources are inadequate to support higher population densities. Higher incomes are essential for achieving food security, and in many rural areas, higher incomes will need to come from new opportunities in off-farm employment.

Many residents of rural areas earn much of their income from non-farm activities. This is particularly true of landless households and women. Rural households with little or no land earn from 30 to 90 percent of their income from non-farm employment, while women in lower income countries account for one-quarter of the workforce in the rural non-farm economy (Haggblade *et al*., 2010). Households, having farmland that is insufficient to raise them above the poverty line, account for about half of rural families (Mellor, 2014). Most rural, non-farm households in lower income countries are poor, and in high-density rural areas, most of the poor are landless, or have too little land to support them in agriculture (Mellor, 2014). For these households, non-farm employment and viable opportunities are essential for producing and selling non-tradable good and services.

Many farm households rely on income from non-farm employment to supplement farm income, and as a source to finance farm inputs (Haggblade *et al*., 2010). An estimated 65 percent of smallholder farmers in Latin America and the Caribbean rely substantially and increasingly on non-farm income sources to sustain their livelihoods (Berdegué and Fuentealba, 2011). The non-farm economy also serves as a source of employment for family members who may not be required full-time in smallholder farming operations.

As the rural population density increases, so too does the importance of non-farm employment in providing livelihood opportunities for households with surplus labour, either seasonally or year-round. Quantifying the impact of non-farm employment on poverty reduction is challenging, because appropriate data is lacking and it is difficult to identify causality in environments where many macro-economic variables change with time. Yet, in some countries, it appears that non-farm employment has accounted for substantial poverty reduction (Haggblade *et al*., 2010).

Further work is needed to accurately determine the impacts of non-farm employment on poverty reduction in rural areas, and the impacts of agricultural growth on the non-farm economy. It is likely, however, that the success of commercially-oriented smallholder farmers will lead to greater expenditures on non-tradable goods and services in the rural non-farm sector, thus enhancing economic activity and providing new employment opportunities. This will reduce poverty and improve food security in rural areas (Mellor, 2014).

Several authors in recent years have provided empirical evidence of the impacts of non-farm employment on household income and food security. In a survey of 220 farm households in Nigeria, Babatunde and Qaim (2010) found that off-farm employment contributes to higher incomes, thus enabling greater consumption of calories and micronutrients. Opportunities to earn off-farm income significantly improved child height-for-age statistics in the villages in which the authors conducted their survey.

Kumanayake *et al*. (2014) show that as rural households in Sri Lanka have shifted from farm to non-farm sources of income, between 1990 and 2006, they have gained income and become less poor. Education has played a notable role in the ability of farm households to gain employment in the non-farm sector in Sri Lanka. Thus, investments in education in rural areas could lead to greater participation in the non-farm economy, with consequent improvement in household welfare.

Wossen and Berger (2015), combined large-scale survey data with information collected from 292 randomly selected households in northern Ghana, in a simulation of the potential impacts of access to off-farm employment opportunities and improved access to financial credit on poverty and food security. The authors determined that households with access to credit and off-farm employment could significantly increase their incomes and enhance their food security, particularly when subject to climate and price variability.

Imai *et al*. (2015), using aggregate data collected in national household surveys in India and Viet Nam, identified significant reductions in poverty and in vulnerability to shocks, for rural households engaged in non-farm employment. In addition, the authors report that employment in skilled jobs, such as in sales or professional activities, has a more notable impact on poverty and vulnerability than does employment in unskilled jobs, such as those involving manual labour. Thus, in India and Viet Nam, while employment in any form of non-farm employment is helpful in reducing household poverty and vulnerability, employment in skilled jobs is most desirable.

Key Message 12

Policies and investments are needed to enhance the role, equality and success of women in agriculture.

Women are responsible for much of the farming in Asia and Africa, and yet many of the institutional settings that influence agriculture are unsupportive of women's role in the sector. More appropriate institutions, supportive policies, and strategic investments are needed to enhance the role and success of women in agriculture, particularly in production, but also in research, education and outreach. Policies regarding the security of land tenure, secure access to water, access to credit, and representation in water user associations and farmer cooperatives are essential. So, too, are programmes that encourage women to enter careers in agricultural research, extension and teaching.

In Africa and in Asia, mostly women are engaged in farming (FAO, 2015a). Yet, often, women do not share the same status as men, regarding such issues as land tenure, water rights, access to credit, and representation in water user associations (Mohapatra, 2011). It is essential that the status of women be improved, so they may be accorded the same degree of access as men, to the tenure, credit, and other inputs needed to produce and market their crops successfully.

Efforts are needed to encourage and support the role of women in agricultural research, extension, and teaching, and as representatives in farmer groups and marketing cooperatives. As agriculture intensifies, and as new marketing opportunities arise for smallholders in lower income countries, interventions and investments must acknowledge the critical role of women in production and marketing activities. Policies and institutions must acknowledge the role of women in the allocation of household income, with the attendant implications for food and nutritional security, and educational opportunities for children (Mohapatra, 2011; McDermott *et al*., 2013). Engaging and empowering women in deliberative processes pertaining to climate change will enhance the resulting policies and interventions (Arora-Jonsson, 2011; Figueiredo and Perkins, 2013).

Several studies provide empirical evidence of the gender aspects of crop production and marketing. Ndiritu *et al*. (2014), in a survey involving 578 farm households in Kenya, find that women manage smaller plots than men, and are less likely to adopt sustainable intensification practices, such as manure application and minimum tillage. The authors find no gender differences in the adoption of other soil and water conservation practices, such as maize-legume intercropping, maize-legume rotations, improved seed varieties, and the use of chemical fertilizer. Such findings, while not fully explained, suggest that further work is needed to fully understand gender differences in the adoption of selected intensification practices.

The commercialization of smallholder agriculture provides farmers with opportunities to earn and retain higher revenues, as they gain access to a wider array of markets for their produce. One way in which smallholders can advance their participation in new markets is by forming cooperatives or farmer groups that interact in markets on behalf of the membership. Forming and joining farmer groups can modify crop choices, and the distribution of farm income within households, if the representation and status of men and women in such groups is different. Fischer and Qaim (2012) examine this issue, using data pertaining to banana production in the highlands of central Kenya.

Tissue culture propagation of bananas, in combination with a new mix of productive inputs, has enabled farmers in Kenya to achieve higher yields, thus providing the opportunity to expand sales of bananas in commercial markets. Many smallholders have joined farmer groups that interact with potential buyers, and sell large lots of bananas at collectively negotiated prices. Membership to these groups is open to individuals and both men and women may join, although generally the elected leadership is male dominated (Fischer and Qaim, 2012).

Using data from a survey of 444 member and non-member farm households, Fischer and Qaim (2012) test hypotheses regarding the impacts of farmer groups on crop production and revenue, women's control of farm revenues and household nutrition. The authors find that farmer groups tend to increase male control of banana production and revenues. This does not influence the number of calories consumed in the household, but there is a negative marginal impact on dietary quality, perhaps because of the differences in male and female spending preferences. Most notably, female membership in the groups can positively impact the share of income controlled by women.

There are also marked gender differences in the formation and productivity of rural non-farm enterprises. In a study of survey data collected by the World Bank in Bangladesh, Ethiopia, Indonesia, and Sri Lanka, Rijkers and Costa (2012) find that, except for Ethiopia, women are less likely than men to start a non-farm enterprise. Women's enterprises tend to be small and home based, and firms operated by women are less productive, as measured by sales per worker; with the exception of Indonesia.

Generally, male managers are better educated than female, yet the authors do not find evidence that differences in human capital account for gender differences in the performance of a firm. The authors also find there is no support for the hypothesis that gender productivity differences are related to differential gender impacts in the local investment climate (Rijkers and Costa, 2012). Further work is needed to fully understand the gender aspects of the rural non-farm economy in lower income countries.

Water Governance, Institutions, and Incentives

Key Message 13

Water institutions must communicate water scarcity conditions to users through instruments such as transparent allocation mechanisms, pricing, the assignment of water rights and other incentive mechanisms, as appropriate, in each setting.

With increasing competition for water in agriculture and other sectors, national and provincial governments will need to effectively communicate water scarcity conditions, and allocate water with the right mix of concern for equity and efficiency, and motivate all farmers, firms and consumers to use water wisely. Just as security of land tenure is essential for encouraging efficient use of land, secure water rights and allocations can motivate farmers to invest in their land and improve returns generated from irrigated agriculture. Continuous cooperation efforts in international river basins could enhance water and food security in regions where countries share surface water or groundwater resources.

Communicating scarcity conditions

The demands for agricultural land and water will increase in many countries, with increases in population and with continuing economic development. Given the limited supply of water in many regions, increasing demand will lead to greater scarcity and keener competition within and across all sectors of the economy. As the demand and competition for water increase, it is essential that all water users are made aware of scarcity conditions in ways that influence their water-use decisions. A highly visible and effective effort to communicate scarcity conditions should become an essential component of national water strategies.

Scarcity conditions can be communicated in the agricultural sector in a variety of ways, including farmer awareness campaigns, regulations, prices, fines, incentives and allocations. Farmer awareness campaigns regarding water scarcity are common in arid countries, where farmers are asked and reminded to use water wisely, in the interest of making the best use of a country's limited water resources. Many semi-arid countries and provinces also engage in farmer awareness campaigns during periods of extraordinary water shortages.

One advantage of farmer awareness campaigns is they can be implemented without legislation or a lengthy public review process pertaining to new rules or regulations. A disadvantage is that such campaigns generally attempt to persuade farmers to use water wisely, while not requiring changes in water use practices or imposing fines for excessive water use. The effectiveness of farmer awareness campaigns can fall short of expectations in areas where farmers retain access to plentiful water supplies at affordable prices, despite increasing aggregate water scarcity.

Water allocations, restrictions, and rationing

Regulations that limit water diversions, extractions, or consumption can modify water use behaviour, if they are implemented and monitored successfully. Water purveyors often implement water rationing during periods of water shortage, either by limiting water volumes delivered or the length of time during which water deliveries are made. Rationing often is viewed as a short-term response to temporary water shortage conditions. Thus, rationing often can be implemented without new legislation and without seeking public comment.

Many water agencies and purveyors maintain operating rules that include provisions for rationing during periods of water shortage. One challenge of implementing water rationing is to achieve the desired degree of equity and efficiency across water users and across competing sectors. An agricultural water agency may need to determine how to ration water for farmers producing grains, vegetables and perennial crops. For this reason, it is best to develop a water rationing policy in a collaborative process, well in advance of the need to implement water rationing.

Water pricing is an option, but is not always feasible

Economists often promote pricing as the best mechanism for communicating scarcity conditions. Low prices often indicate relative abundance, while higher prices reflect increasing scarcity. If water is scarce, but water users have access to abundant, affordable supplies, they will not be encouraged to manage their water use in accordance with the prevailing scarcity conditions. Farmers in an arid region, who receive water at minimal cost, will have little incentive to irrigate carefully. In many countries, when farmers retain access to abundant supplies at minimal cost, sustained efforts to motivate more careful management of irrigation water have largely been unsuccessful. Charging higher water prices to reflect scarcity conditions is one approach to encouraging farmers to manage their water deliveries with greater care.

Often, for political or cultural reasons, water pricing is difficult to implement, and once in place water tariffs can be difficult to modify (Ruijs *et al*., 2008; Dono *et al*., 2010; Cooper *et al*., 2014). For every successful implementation of appropriate water prices in agriculture, there are possibly several cases of unsuccessful attempts. Nonetheless, it is helpful to consider water pricing as a policy option, in conjunction with other potential options, such as water allocations, limiting withdrawal, pumping restrictions, rotational deliveries and restrictions pertaining to cropping patterns. Often, the outcomes of selected policy alternatives are not those foreseen when considering policy options. Analysing the likely impacts of proposed policies on farm-level economics and on the riskiness of farm-level production and investment choices can enhance the likelihood of achieving policy goals (Viaggi *et al*., 2010; Veettil *et al*., 2011; Nikouei and Ward, 2013; Giraldo *et al*., 2014; Lehmann and Finger, 2014; Shi *et al*., 2014; Vasileiou *et al*., 2014).

Two caveats are appropriate when discussing water prices: 1) Often, water prices alone are insufficient for ensuring efficient water use; 2) Water pricing is not the only method for effectively communicating water scarcity. Regarding the first caveat, public officials should consider the quality of water service provided and many other issues that influence a water user's response to higher water prices. In agriculture, many farmers are not averse to paying higher prices, if water delivery service is improved at the same time that prices are increased.

In the municipal and commercial sectors, water users could respond with greater enthusiasm to higher water prices if they are accompanied with improved water service, water quality, or water metering and billing procedures. An effective public awareness campaign that explains the need for water prices that reflect scarcity conditions may help promote a positive response to increased water prices.

In areas, where implementing higher water prices is not yet politically feasible, public officials might consider implementing water allocations. Such an approach can be just as effective in communicating scarcity conditions as a programme involving higher water prices. When the volume of water available in a river basin or irrigation district is limited, the aggregate volume can be divided among water users by assigning to each a pro-rated portion of that volume. When farmers know their water supply is limited, they have an incentive to optimize the values they obtain with the amount of water they receive.

A binding water constraint at the farm level can be as effective as water pricing in generating regional water use efficiency, if farmers are allowed to trade or sell portions of their water allocations. A water-trading programme permits farmers who can generate higher value to purchase water from farmers who generate lower value, thus increasing the value of output across a region or river basin. A water-trading programme also requires one that supports water rights, which are helpful in communicating water scarcity conditions and motivating water users to generate substantial value with the limited resources allocated. In addition, there must be strong public or private institutions to oversee compliance with market rules, a condition that is difficult to achieve in many countries and may entail high transaction costs. Often, the infrastructure needed to facilitate water trading is available within irrigation schemes, yet unavailable for moving water across a basin or between basins.

Incentive programmes can encourage water users to improve water management practices in both irrigated and rainfed settings. In agriculture, public support for investments in land levelling and the purchase of drip or sprinkler systems can be helpful, although such investments may not result in overall water savings. City residents can be encouraged to reduce water use with subsidies or rebates for purchasing water-efficient devices or installing drip irrigation in yards and kitchen gardens. Industries respond positively to subsidies for investments in water-saving processes and in wastewater capture and reuse. Such programmes are helpful when raising water prices. From the viewpoint of the water user, the higher prices modify the incremental price of water as desired, while the subsidies can limit the increase in the total cost of adjusting to higher water prices.

Regional and national monitoring programmes can assist in achieving efficient water allocation and use. The China Crop Watch System (CCWS) gathers high (30 m and above) and low-resolution (250 m to 1000 m) crop and water use information, via remote sensing, and evaluates several crop status indicators. The CCWS includes the following modules: crop growth monitoring; drought monitoring; grain production estimation; crop production prediction; crop planting structure inventory; cropping index monitoring; and grain supply-demand balance and early-warning (Wu *et al*., 2014). In addition to improving the understanding of land and water resource management in China, the programme provides information on droughts, cropping intensity, and the outlook for food supply and demand conditions.

Briefly, many measures are available to public officials wishing to communicate water scarcity conditions. Water pricing could work well in some areas and sectors, while a programme of increasing public awareness or water use restrictions may be needed in others. The key to achieving water-use efficiency on farms, in homes and factories, and across river basins, is to ensure that all water users are made aware of water scarcity conditions and are encouraged to adjust their water use accordingly.

Institutions and capacity-building

Institutions and capacity-building have played important roles in efforts to improve water management and increase farm yields. Advances in the definition and security of land tenure, the assignment of well-defined rights or allocations to land and water, improvements in market access, and crop insurance programmes have enabled and encouraged farmers to make better use of land and water resources (Kassie *et al*., 2013, 2015). Outreach efforts, such as farm advisory programmes, cooperative extension services, and farmer training programmes have enhanced the capacity of many farm households to implement advances in production technology and to strengthen their participation in input and output markets (Dethier and Effenberger, 2012).

Providing access to complementary inputs

Many governments endeavour to improve agricultural productivity, often with the aim of increasing domestic crop and livestock production, raising incomes in rural areas, and ensuring national food security. Such efforts are challenging, partly because agricultural programmes and subsidies are costly and can distort farm-level decisions regarding cropping patterns, resource use and long-term investments. Yet, in many lower income countries, smallholder farmers require assistance in gaining affordable access to essential farm inputs, such as irrigation water, high quality seeds, plant nutrients, farm chemicals, financial credit and technical assistance. Thus, many governments attempt to offset some of the financial burden of smallholder farmers by subsidizing selected inputs, including seeds, fertilizer and irrigation water (Ellis and Maliro, 2013; Jayne and Rashid, 2013). Some governments also support prices in agricultural markets, either through direct purchases or by imposing legislated minimum prices.

The annual cost of direct and indirect agricultural subsidies can be substantial, and yet the benefits are not always clear. Output price subsidies can promote expansion in planted area, but crop yields per hectare do not necessarily increase. Many smallholder farmers lack the technical expertise and experience to optimize the application of subsidized inputs in crop production. They also lack the financial resilience required to support production of higher valued crops that would enhance their earnings over time. When grain prices are subsidized, many farmers will produce grains, in part, because the downside risk is much smaller than for higher valued crops. This strategy, on the part of smallholders, is rational in the short-term, but limits the potential for long-term gains and the advancement of agriculture.

The challenge of subsidies is to design national programmes that achieve greater growth in the agricultural sector, while reducing annual government expenditures on farm inputs. A more appropriate approach would involve government investments in regional infrastructure, such as the modernization of irrigation and drainage systems, and investments in the services that would improve smallholder knowledge of farm practices and access to essential farm inputs. For example, national governments can invest in creating a more effective extension service that would conduct outreach and training programmes for farmers across the country. The extension programme could promote the development of production centres pertaining to higher valued crops, while providing support for those farmers continuing to produce grains and fodder, and those continuing to raise livestock for sale or home consumption.

The essence of the challenge is to switch from subsidy programmes, which involve annual expenditures to programmes entailing investments with longer-term returns, such as the rehabilitation of infrastructure, the enhancement of extension services, and the development of market mechanisms that assist smallholders to sell their produce in viable markets at reasonable prices, without suffering the negative impacts of collusive behaviour in restricted market settings. Such investments will contribute to the enhancement of both the supply and demand components of national efforts to ensure food security in 2050.

Key Message 14

Innovations in water governance will be needed in many areas, partly because of increasing competition for limited water supplies.

In future, innovations will be required to address systems of water rights, allocation, and management in many settings, given the increasing competition for water across sectors. Many of the original forms of water governance were effective in allocating and managing water during times of relative abundance, or when most available water was used for agriculture. New governance structures will provide broader groups of water users with greater involvement in water development, allocation and management decisions. The outcomes will include wiser investment programmes that contribute toward the goal of achieving sustainable water use, with appropriate concern for environmental amenities.

National policies that are designed to achieve sustainable use of land and water resources, with the goal of achieving or sustaining food security in 2050, must address the socio-economic and cultural dimensions of resource use in agriculture, while acknowledging the critical agronomic and hydrologic aspects of water supply and management in crop and livestock production (Bjornlund *et al*., 2014). Policies should reflect the increasing demand for water to sustain environmental flows in many river systems (Erfani *et al*., 2015).

As noted above, sufficient water and food will probably be available globally in 2050, provided that appropriate policies and programmes are implemented, and where such interventions are needed, wise investments in institutions and infrastructure are made. In addition, national policy-makers must endeavour to ensure that in 2050 the available water and food are accessible and affordable to all. Thus, policy-makers and investors must continue to support efforts to enhance and sustain smallholder access to the land and water needed to support their livelihoods.

The provision of an irrigation service usually involves some form of collective action and management, as irrigation systems require substantial investment and generally deliver water to more than one user. National and provincial governments have built and operated many irrigation schemes, worldwide, often with mixed results in terms of system performance and financial viability (Borgia *et al*., 2013; Al Zayed *et al*., 2015). Farmer-managed systems have gained popularity in recent decades, partly because of the efforts of national governments to off-load the financial responsibility for operating and maintaining irrigation schemes (Cakmak *et al*., 2010; Rap and Wester, 2013; Suhardiman, 2013; Zinzani, 2014; Senanayake *et al*., 2015). Farmer-managed systems, and those operated jointly with private sector contractors, have achieved mixed results (Wellens *et al*., 2013; Huang, 2014; Latif *et al*., 2015). Water user associations are popular in many countries, yet the financial performance, and quality of service provided to farmers, vary substantially with differences in institutional settings, rules pertaining to farmer representation and the agronomic and hydrologic settings (Bhatt, 2013; Yami, 2013; Zhang *et al*., 2013; Hu *et al*., 2014).

The degree to which farmer-managed systems achieve success is partly related to the institutional setting in which the scheme operates. Farmer-managed schemes have achieved moderate success in countries with well-defined institutions that support the assignment of property rights to land and water, and provide legal recourse for disputes regarding those rights (Hanemann, 2014). Efforts to establish successful farmer-managed irrigation schemes have been less successful in countries lacking these features (Meinzen-Dick, 2014). In future, innovations in water governance structures will be needed in both lower and higher income countries, to address successfully the water allocation and management challenges that arise with increasing water scarcity (Bjornlund *et al*., 2014; Young, 2014).

4. REFERENCES

Affholder, F., Poeydebat, C., Corbeels, M., Scopel, E., Tittonell, P. 2013. The yield gap of major food crops in family agriculture in the tropics: Assessment and analysis through field surveys and modelling. *Field Crops Research* 143, 106-118.

Ahmad, M.-U.-D., Masih, I., Giordano, M. 2014. Constraints and opportunities for water savings and increasing productivity through resource conservation technologies in Pakistan. *Agriculture, Ecosystems and Environment* 187, 106-115.

Ahmed, M., Sultan, M., Wahr, J., Yan, E. 2014. The use of GRACE data to monitor natural and anthropogenic induced variations in water availability across Africa. *Earth-Science Reviews* 136, 289-300.

Alexandratos, N., Bruinsma, J. 2012. World agriculture towards 2030/2050: the 2012 revision. ESA Working paper No. 12-03. Rome, FAO.

Alston, J.M., Pardey, P.G. 2014. Agriculture in the global economy. *Journal of Economic Perspectives* 28(1), 121-146.

Al Zayed, I.S., Elagib, N.A., Ribbe, L., Heinrich, J. 2015. Spatio-temporal performance of large-scale Gezira Irrigation Scheme, Sudan. *Agricultural Systems* 133, 131-142.

Anthony, V.M., Ferroni, M. 2012. Agricultural biotechnology and smallholder farmers in developing countries. *Current Opinion in Biotechnology* 23(2), 278-285

Arora-Jonsson, S. 2011. Virtue and vulnerability: Discourses on women, gender and climate change. *Global Environmental Change* 21, 744-751.

Aw-Hassan, A., Rida, F., Telleria, R., Bruggeman, A. 2014. The impact of food and agricultural policies on groundwater use in Syria. *Journal of Hydrology* 513, 204-215.

Babatunde, R.O., Qaim, M. 2010. Impact of off-farm income on food security and nutrition in Nigeria. *Food Policy* 35(4), 303-311.

Balwinder-Singh, Humphreys, E., Sudhir-Yadav, Gaydon, D.S. 2015. Options for increasing the productivity of the rice-wheat system of north-west India while reducing groundwater depletion. Part 1. Rice variety duration, sowing date and inclusion of mungbean. *Field Crops Research* 173, 68-80.

Barrett, C.B. 2010. Measuring food insecurity. *Science* 327(5967), 825-828.

Bauer, C.J. 2004. *Siren song: Chilean water law as a model for international reform.* RFF Press, Routledge. 182 pp.

Bekunda, M., Sanginga, N., Woomer, P.L. 2010. Restoring soil fertility in sub-Saharan Africa. *Advances in Agronomy* 108(C), 183-236.

Belesky, P. 2014. Regional governance, food security and rice reserves in East Asia. *Global Food Security* 3(3-4), 167-173.

Benouniche, M., Kuper, M., Hammani, A., Boesveld, H. 2014. Making the user visible: analysing irrigation practices and farmers' logic to explain actual drip irrigation performance. *Irrigation Science* 32(6), 405-420.

Berbel, J., Mateos, L. 2014. Does investment in irrigation technology necessarily generate rebound effects? A simulation analysis based on an agro-economic model. *Agricultural Systems* 128, 25-34.

Berdegué, J.A., Ricardo Fuentealba, R. 2011. Latin America: The state of smallholders in agriculture. Paper presented at the IFAD Conference on New Directions for Smallholder Agriculture, 24-25 January, 2011. 38 pp. Rome, IFAD.

Bergmann, J.C., Tupinambá, D.D., Costa, O.Y.A., Almeida, J.R.M., Barreto, C.C., Quirino, B.F. 2013. Biodiesel production in Brazil and alternative biomass feedstocks. *Renewable and Sustainable Energy Reviews* 21, 411-420.

Beveridge, M.C.M., Thilsted, S.H., Phillips, M.J., Metian, M., Troell, M., Hall, S.J. 2013. Meeting the food and nutrition needs of the poor: The role of fish and the opportunities and challenges emerging from the rise of aquaculture. *Journal of Fish Biology* 83(4), 1067-1084.

Bhatt, S. 2013. How does participatory irrigation management work? A study of selected water users' associations in Anand district of Gujarat, western India. *Water Policy* 15(2), 223-242.

Bhutta, Z.A. 2013. Early nutrition and adult outcomes: Pieces of the puzzle. *The Lancet* 382, 486-487.

Biazin, B., Sterk, G., Temesgen, M., Abdulkedir, A., Stroosnijder, L. 2012. Rainwater harvesting and management in rainfed agricultural systems in sub-Saharan Africa: A review. *Physics and Chemistry of the Earth* 47-48, 139-151.

Birdsall, N., Lustig, N., Meyer, C.J. 2014. The strugglers: The new poor in Latin America? *World Development* 60, 132-146.

Bjornlund, H., Xu, W., Wheeler, S. 2014. An overview of water sharing and participation issues for irrigators and their communities in Alberta: Implications for water policy. *Agricultural Water Management* 145, 171-180.

Black, M.M., Hurley, K.M. 2014. Investment in early childhood development. *The Lancet* 384, 1244-1245.

Black, R.E., Victora, C.G., Walker, S.P., Bhutta, Z.A., Christian, P., de Onis, M., Ezzati, M., Grantham-McGregor, S., Katz, J., Martorell, R., Uauy, R. 2013. Maternal and child undernutrition and overweight in low-income and middle-income countries. *The Lancet* 382 (9890), 427-451.

Blum, A. 2011. Drought resistance is it really a complex trait? *Functional Plant Biology* 38(10), 753-757.

Blum, A. 2013. Heterosis, stress, and the environment: A possible road map towards the general improvement of crop yield. *Journal of Experimental Botany* 64(16), 4829-4837.

Borgia, C., García-Bolaños, M., Li, T., Gómez-Macpherson, H., Comas, J., Connor, D., Mateos, L. 2013. Benchmarking for performance assessment of small and large irrigation schemes along the Senegal Valley in Mauritania. *Agricultural Water Management* 121, 19-26.

Bosma, R.H., Verdegem, M.C.J. 2011. Sustainable aquaculture in ponds: Principles, practices and limits. *Livestock Science* 139(1-2), 58-68.

Briones, R.M. 2011. Regional cooperation for food security: The case of emergency rice reserves in the ASEAN plus three. ADB Sustainable Development Working Paper Series, Number 18. Asian Development Bank, Manila.

Bruinsma, J. 2009. The resource outlook to 2050: by how much do land, water and crop yields need to increase by 2050? FAO expert meeting on how to feed the world in 2050. Rome, FAO.

Bruinsma, J. 2011. The resources outlook: by how much do land, water and crop yields need to increase by 2050? In: P. Conforti (Ed.) Looking Ahead in World Food and Agriculture: Perspectives to 2050. Rome, FAO.

Bryan, B.A., King, D., Zhao, G. 2014. Influence of management and environment on Australian wheat: Information for sustainable intensification and closing yield gaps. *Environmental Research Letters* 9(4), 044005.

Bryce, J., Black, R.E., Victora, C.G. 2013. Millennium development goals 4 and 5: Progress and challenges. *BMC Medicine* 11(1), 225-228.

Burney, J., Cesano, D., Russell, J., La Rovere, E.L., Corral, T., Coelho, N.S., Santos, L. 2014. Climate change adaptation strategies for smallholder farmers in the Brazilian Sertão. *Climatic Change* 126 (1-2), 45-59.

Burnham, M., Ma, Z., Zhu, D. 2014. The human dimensions of water saving irrigation: lessons learned from Chinese smallholder farmers. *Agriculture and Human Values*, in press.

Buzby, J.C., Hyman, J. 2012. Total and per capita value of food loss in the United States. *Food Policy* 37(5), 561-570.

Cabello, J.V., Lodeyro, A.F., Zurbriggen, M.D. 2014. Novel perspectives for the engineering of abiotic stress tolerance in plants. *Current Opinion in Biotechnology* 26, 62-70.

Cabero-Roura, L., Rushwan, H. 2014. An update on maternal mortality in low-resource countries. *International Journal of Gynecology and Obstetrics* 125, 175-180.

Cakmak, B., Kibaroglu, A., Kendirli, B., Gokalp, Z. 2010. Assessment of the irrigation performance of transferred schemes in Turkey: A case study analysis. *Irrigation and Drainage* 59(2), 138-149.

Cañedo-Argüelles, M., Kefford, B.J., Piscart, C., Prat, N., Schäfer, R.B., Schulz, C.-J. 2013. Salinisation of rivers: An urgent ecological issue. *Environmental Pollution* 173, 157-167.

Cao, L., Naylor, R., Henriksson, P., Leadbitter, D., Metian, M., Troell, M., Zhang, W. 2015. China's aquaculture and the world's wild fisheries: Curbing demand for wild fish in aquafeeds is critical. *Science* 347(6218), 133-135.

Castanheira, E.G., Grisoli, R, Freire, F., Pecora, V., Coelho, S.T. 2014. Environmental sustainability of biodiesel in Brazil. *Energy Policy* 65, 680-691.

Castellanos, M.T., Tarquis, A.M., Ribas, F., Cabello, M.J., Arce, A., Cartagena, M.C. 2013. Nitrogen fertigation: An integrated agronomic and environmental study. *Agricultural Water Management* 120, 46-55.

Castiblanco, C., Etter, A., Aide, T.M. 2013. Oil palm plantations in Colombia: a model of future expansion. *Environmental Science & Policy* 27, 172-183.

Castiblanco, C., Etter, A., Ramirez, A. 2015. Impacts of oil palm expansion in Colombia: What do socioeconomic indicators show? *Land Use Policy* 44, 31-43.

Castle, S.L., Thomas, B.F., Reager, J.T., Rodell, M., Swenson, S.C., Famiglietti, J.S. 2014. Groundwater depletion during drought threatens future water security of the Colorado River Basin. *Geophysical Research Letters* 41, in press.

Chai, Q., Gan, Y., Turner, N.C., Zhang, R.-Z., Yang, C., Niu, Y., Siddique, K.H.M. 2014. Water-saving innovations in Chinese agriculture. *Advances in Agronomy* 126, 149-201.

Chaudhuri, S., Ale, S. 2014. Long term (1960-2010) trends in groundwater contamination and salinization in the Ogallala aquifer in Texas. *Journal of Hydrology* 513, 376-390.

Chauhan, B.S., Prabhjyot K., Mahajan, G., Randhawa, R.K., Singh, H., Kang, M.S. 2014. Global warming and its possible impact on agriculture in India. *Advances in Agronomy* 123, 65-121.

Ceddia, M.G., Bardsley, N.O., Gomez-Y-Paloma, S., Sedlacek, S. 2014. Governance, agricultural intensification, and land sparing in tropical South America. *Proc. of the National Academy of Sciences of the United States of America* 111(20), 7242-7247.

Chen, J., Li, J., Zhang, Z., Ni, S. 2014. Long-term groundwater variations in Northwest India from satellite gravity measurements. *Global and Planetary Change* 116, 130-138.

Cohen, R.L., Alfonso, Y.N., Adam, T., Kuruvilla, S., Schweitzer J., Bishai, D. 2014. Country progress towards the Millennium Development Goals: Adjusting for socioeconomic factors reveals greater progress and new challenges. *Globalization and Health* 10(1), 1-19.

Collischonn, B., Lopes, A.V., Pante, A.R. 2014. Dealing with variability in water availability: The case of the Verde Grande River basin, Brazil. *IAHS-AISH Proceedings and Reports* 364, 176-181.

Connor, D.J., Mínguez, M.I. 2012. Evolution not revolution of farming systems will best feed and green the world. *Global Food Security* 1(2), 106-113.

Cooper, B., Crase, L., Pawsey, N. 2014. Best practice pricing principles and the politics of water pricing. *Agricultural Water Management* 145, 92-97.

Costa, A.O., Oliveira, L.B., Lins, M.P.E., Silva, A.C.M., Araujo, M.S.M., Pereira Jr., A.O., Rosa, L.P. 2013. Sustainability analysis of biodiesel production: A review on different resources in Brazil. *Renewable and Sustainable Energy Reviews* 27, 407-412.

Cummings Jr., R.W. 2012. Experience with managing foodgrains price volatility in Asia. *Global Food Security* 1(2), 150-156.

Dal Belo Leite, J.G., Justino, F.B., Silva, J.V., Florin, M.J., van Ittersum, M.K. 2015. Socioeconomic and environmental assessment of biodiesel crops on family farming systems in Brazil. *Agricultural Systems* 133, 22-34.

Dawe, D., Peter Timmer, C. 2012. Why stable food prices are a good thing: Lessons from stabilizing rice prices in Asia. *Global Food Security* 1(2), 127-133

de Fraiture, C., Molden, D., Wichelns, D. 2010. Investing in water for food, ecosystems, and livelihoods: An overview of the comprehensive assessment of water management in agriculture. *Agricultural Water Management* 97(4), 495-501.

de Fraiture, C., Wichelns, D. 2010. Satisfying future water demands for agriculture. *Agricultural Water Management* 97(4), 502-511.

de Graaf, G., Garibaldi, L. 2014. The value of African fisheries. FAO Fisheries and Aquaculture Circular. No. 1093. Rome, FAO. 76 pp.

Dethier, J.-J., Effenberger, A. 2012. Agriculture and development: A brief review of the literature. *Economic Systems* 36(2), 175-205.

Diana, J.S., Egna, H.S., Chopin, T., Peterson, M.S., Cao, L., Pomeroy, R., Verdegem, M., Slack, W.T., Bondad-Reantaso, M.G., Cabello, F. 2013. Responsible aquaculture in 2050: Valuing local conditions and human innovations will be key to success. *BioScience* 63(4), 255-262.

Díaz-Caravantes, R.E., Wilder, M. 2014. Water, cities and peri-urban communities: Geographies of power in the context of drought in Northwest Mexico. *Water Alternatives* 7(3), 499-417.

D'Odorico, P., Bhattachan, A. 2012. Hydrologic variability in dryland regions: Impacts on ecosystem dynamics and food security. Philosophical Transactions of the Royal Society B: Biological Sciences 367 (1606), 3145-3157.

Dolferus, R. 2014. To grow or not to grow: A stressful decision for plants. *Plant Science* 229, 247-261.

Dono, G., Giraldo, L., Severini, S. 2010. Pricing of irrigation water under alternative charging methods: Possible shortcomings of a volumetric approach. *Agricultural Water Management* 97(11), 1795-1805.

Dora, C., Haines, A., Balbus, J., Fletcher, E., Adair-Rohani, H., Alabaster, G., Hossain, R., de Onis, M., Branca, F., Neira, M. 2015. Indicators linking health and sustainability in the post-2015 development agenda. *The Lancet* 385(9965), 380-391.

Du, L., Pinga, V., Klein, A., Danton, H. 2015. Leveraging agriculture for nutrition impact through the feed the future initiative. *Advances in Food and Nutrition Research* 74, 1-46.

Dzanku, F.M., Jirström, M., Marstorp, H. 2015. Yield gap-based poverty gaps in rural sub-Saharan Africa. *World Development* 67, 336-362.

Ellis, F., Maliro, D. 2013. Fertiliser subsidies and social cash transfers as complementary or competing instruments for reducing vulnerability to hunger: The case of Malawi. *Development Policy Review* 31(5), 575-596.

Erfani, T., Binions, O., Harou, J.J. 2015. Protecting environmental flows through enhanced water licensing and water markets. *Hydrology and Earth System Sciences* 19(2), 675-689.

Eshel, G., Shepon, A., Makov, T., Milo, R. 2014. Land, irrigation water, greenhouse gas, and reactive nitrogen burdens of meat, eggs, and dairy production in the United States. *Proc. of the National Academy of Sciences of the United States of America* 111 (33), 11996-12001.

Ezezika, O.C., Deadman, J., Daar, A.S. 2013. She Came, She Saw, She Sowed: Re-negotiating Gender-Responsive Priorities for Effective Development of Agricultural Biotechnology in Sub-Saharan Africa. *Journal of Agricultural and Environmental Ethics* 26(2), 461-471.

Fahmi, A. 2011. Benefits of new tools in biotechnology to developing countries in South Asia: A perspective from UNESCO. *Journal of Biotechnology* 156, 364-369.

Famiglietti, J.S., Rodell, M. 2013. Water in the balance. *Science* 340 (6138), 1300-1301.

Fanzo, J. 2014. Strengthening the engagement of food and health systems to improve nutrition security: Synthesis and overview of approaches to address malnutrition. *Global Food Security* 3(3-4), 183-192.

FAO. 2009. Declaration of the World Summit on Food Security. Rome. (Seven pages also available at ftp://ftp.fao.org/docrep/ fao/Meeting/018/k6050e.pdf).

FAO, 2010. The Second Report on the State of the World's Plant Genetic Resources for Food and Agriculture. Rome, Chapter 4, 98 pp.
(Also available at http://www.fao.org/docrep/013/i1500e/i1500e.pdf)

FAO. 2011a. The State of Food and Agriculture 2010-11. Women in Agriculture: Closing the Gender Gap for Development. Rome, FAO.

FAO. 2011b. The State of the World's Land and Water Resources for Food and Agriculture (SOLAW) - Managing Systems at Risk. Rome and London, FAO and Earthscan.

FAO, 2011c. State of the World's Forests. Rome, Chapter 1, 27 pp.

FAO, 2013. Panorama of Food and Nutritional Security in Latin America and the Caribbean. Rome, 30 pp.

FAO. 2014a. The State of World Fisheries and Aquaculture 2014. Opportunities and Challenges. Rome.

FAO, 2014b. Food and Nutrition in Numbers. FAO, pp 249.

FAO. 2014c. The Water-Energy-Food Nexus: A new approach in support of food security and sustainable agriculture. Rome.

FAO. 2014d. Global Initiative on Food Loss and Waste Reduction. Rome. 8 pp.

FAO. 2014e. Save Food: Global Initiative on Food Loss and Waste Reduction, Definitional Framework of Food Loss. Rome. Working Paper, 18 pp.

FAO. 2015a. FAOSTAT. Rome.

FAO. 2015b. AQUASTAT, FAO's global water information system. Rome.

FAO, 2015c. General Summary Latin America and Caribbean: Water Resources, AQUASTAT, FAO, Rome. (Also available at. http://www.fao.org/nr/water/AQUASTAT/countries_regions/lac/index3.stm, accessed 26 February 2015).

FAO, IFAD & WFP, 2013. *The State of Food Insecurity in the World 2013. The Multiple Dimensions of Food Security*. Rome.

Fearnside, P.M. 2005. Deforestation in Brazilian Amazonia: History, rates, and consequences. *Conservation Biology* 19(3), 680-688.

Ferguson, I.M., Maxwell, R.M. 2012. Human impacts on terrestrial hydrology: Climate change versus pumping and irrigation. *Environmental Research Letters* 7(4), 044022.

Figueiredo, P., Perkins, P.E. 2013. Women and water management in times of climate change: participatory and inclusive processes. *Journal of Cleaner Production* 60(1), 188-194.

Finger, R., Lehmann, N. 2012. Policy reforms to promote efficient and sustainable water use in swiss agriculture. *Water Policy* 14(5), 887-901.

Fischer, E., Qaim, M. 2012. Gender, agricultural commercialization, and collective action in Kenya. *Food Security* 4(3), 441-453.

Flachsbarth, I., Willaarts, B., Xie, H., Pitois, G., Mueller, N.D., Ringler, C., Garrido, A. 2015. The role of Latin America's land and water resources for global food security: Environmental trade-offs of future food production pathway. *PLoS ONE* 10 (1), e0116733.

Frappart, F., Seoane, L., Ramillien, G. 2013. Validation of GRACE-derived terrestrial water storage from a regional approach over South America. *Remote Sensing of Environment* 137, 69-83.

Galtier, F. 2013. Managing food price instability: Critical assessment of the dominant doctrine. *Global Food Security* 2(2), 72-81.

Gerardeaux, E., Giner, M., Ramanantsoanirina, A., Dusserre, J. 2012. Positive effects of climate change on rice in Madagascar. *Agronomy for Sustainable Development* 32(3), 619-627.

Gheysari, M., Loescher, H.W., Sadeghi, S.H., Mirlatif, S.M., Zareian, M.J., Hoogenboom, G. 2015. Water-yield relations and water use efficiency of maize under nitrogen fertigation for semiarid environments: Experiment and synthesis. *Advances in Agronomy*, 55 pages. (In press).

Gilbert, C.L. 2012. International agreements to manage food price volatility. *Global Food Security* 1(2), 134-142.

Giraldo, L., Cortignani, R., Dono, G. 2014. Simulating volumetric pricing for irrigation water operational cost recovery under complete and perfect information. *Water (Switzerland)* 6 (5), 1204-1220.

Godber, O.F., Wall, R. 2014. Livestock and food security: Vulnerability to population growth and climate change. *Global Change Biology* 20 (10), 3092-3102.

Grassini, P., Eskridge, K.M., Cassman, K.G. 2013. Distinguishing between yield advances and yield plateaus in historical crop production trends. *Nature Communications* 4, 2918.

Grau, H.R., Aide, M. 2008. Globalization and land-use transitions in Latin America. *Ecology and Society* 13(2), 1-16.

Green, T.R., Taniguchi, M., Kooi, H., Gurdak, J.J., Allen, D.M., Hiscock, K.M., Treidel, H., Aureli, A. 2011. Beneath the surface of global change: Impacts of climate change on groundwater. *Journal of Hydrology* 405(3-4), 532-560.

Grogan, D.S., Zhang, F., Prusevich, A., Lammers, R.B., Wisser, D., Glidden, S., Li, C., Frolking, S. 2015. Quantifying the link between crop production and mined groundwater irrigation in China. *Science of the Total Environment* 511, 161-175.

Grumbine, R.E., Xu, J. 2013. Recalibrating China's environmental policy: The next 10 years. *Biological Conservation* 166, 287-292.

Guan, D., Hubacek, K., Tillotson, M., Zhao, H., Liu, Z., Liang, S. 2014. Lifting China's water spell. *Environmental Science and Technology* 48(19), 11048-11056.

Guedes, G.R., VanWey, L.K., Hull, J.R., Antigo, M., Barbieri, A.F. 2014. Poverty dynamics, ecological endowments, and land use among smallholders in the Brazilian Amazon. *Social Science Research* 43, 74-91.

Gustavsson, Jenny, Cederbert, C., Sonesson, U., van Otterdijk, R., Meybeck, A. 2011. Global food losses and food waste: Extent, causes, and prevention. Rome, FAO. 29 pp.

Haggblade, S., Hazell, P., Reardon, T. 2010. The rural non-farm economy: Prospects for growth and poverty reduction. *World Development* 38(10), 1429-1441.

Hall, A.J., Richards, R.A. 2013. Prognosis for genetic improvement of yield potential and water-limited yield of major grain crops. *Field Crops Research* 143, 18-33.

Hanemann, M. 2014. Property rights and sustainable irrigation-A developed world perspective. *Agricultural Water Management* 145, 5-22.

Hanjra, M.A., Blackwell, J., Carr, G., Zhang, F., Jackson, T.M. 2012. Wastewater irrigation and environmental health: Implications for water governance and public policy. *International Journal of Hygiene and Environmental Health* 215(3), 255-269.

Harris, D., Orr, A. 2014. Is rainfed agriculture really a pathway from poverty? *Agricultural Systems* 123, 84-96.

Hazell, P. 2013. Comparative study of trends in urbanization and changes in farm size in Africa and Asia: Implications for agricultural research. A foresight study of the Independent Science and Partnership Council. (Available at: http://ispc.cgiar.org/publications/search?combine=&field_publication_date_value_1[value][date]=2013, Accessed 3 February 2015)

Headey, D., Taffesse, A.S., You, L. 2014. Diversification and development in pastoralist Ethiopia. *World Development* 56, 200-213.

Herreras Martínez, S., Van Eijck, J., Pereira Da Cunha, M., Guilhoto, J.J.M, Walter, A., Faaij, A. 2013. Analysis of socio-economic impacts of sustainable sugarcane-ethanol production by means of inter-regional Input-Output analysis: Demonstrated for Northeast Brazil. *Renewable and Sustainable Energy Reviews* 28, 290-316.

Herrero, M., Thornton, P.K. 2013. Livestock and global change: Emerging issues for sustainable food systems. *Proc. of the National Academy of Sciences of the United States of America* 110(52), 20878-20881.

Herrero, M., Thornton, P.K., Gerber, P., Reid, R.S. 2009. Livestock, livelihoods and the environment: understanding the trade-offs. *Current Opinion in Environmental Sustainability* 1(2), 111-120.

Heumesser, C., Fuss, S., Szolgayová, J., Strauss, F., Schmid, E. 2012. Investment in irrigation systems under precipitation uncertainty. *Water Resources Management* 26(11), 3113-3137.

High Level Panel of Experts (HLPE) 2011. Price volatility and food security. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome.

High Level Panel of Experts (HLPE) 2012. Food security and climate change. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome.

High Level Panel of Experts (HLPE) 2013. Investing in smallholder agriculture for food security. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome.

High Level Panel of Experts (HLPE) 2014a. Sustainable fisheries and aquaculture for food security and nutrition. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome.

High Level Panel of Experts (HLPE) 2014b. Food losses and waste in the context of sustainable food systems. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome.

Hixson, S.M. 2014. Fish nutrition and current issues in aquaculture: The balance in providing safe and nutritious seafood, in an environmentally sustainable manner. *Journal of Aquaculture Research and Development* 5(3), 1-10.

Hu, X.-J., Xiong, Y.-C., Li, Y.-J., Wang, J.-X., Li, F.-M., Wang, H.-Y., Li, L.-L. 2014. Integrated water resources management and water users' associations in the arid region of northwest China: A case study of farmers' perceptions. *Journal of Environmental Management* 145, 162-169.

Huang, Q. 2014. Impact evaluation of the irrigation management reform in northern China. *Water Resources Research* 50(5), 4323-4330.

Huber-Sannwald, E., Palacios, M.R., Moreno, J.T.A., Braasch, M., Peña, R.M.M., Verduzco, J.G.A., Santos, K.M. 2012. Navigating challenges and opportunities of land degradation and sustainable livelihood development in dryland social-ecological systems: A case study from Mexico. *Philosophical Transactions of the Royal Society B: Biological Sciences* 367(1606), 3158-3177.

Humphreys, E., Kukal, S.S., Christen, E.W., Hira, G.S., Balwinder-Singh, Sudhir-Yadav, Sharma, R.K. 2010. Halting the groundwater decline in north-west India: Which crop technologies will be winners? *Advances in Agronomy* 109(C), 155-217.

Imai, K.S., Gaiha, R., Thapa, G. 2015. Does non-farm sector employment reduce rural poverty and vulnerability? Evidence from Viet Nam and India. *Journal of Asian Economics* 36, 47-61.

Iniguez-Montiel, A.J. 2014. Growth with equity for the development of Mexico: Poverty, inequality, and economic growth (1992-2008). *World Development* 59, 313-326.

Jaggard, K.W., Qi, A., Ober, S. 2010. Possible changes to arable crop yields by 2050. *Philosophical Transactions of the Royal Society B: Biological Sciences* 365(1554), 2835-2851.

Jat, M.L., Bijay-Singh, Gerard, B. 2014. Nutrient management and use efficiency in wheat systems of South Asia. *Advances in Agronomy* 125, 171-259.

Jayne, T.S., Mather, D., Mghenyi, E. 2010. Principal challenges confronting smallholder agriculture in sub-Saharan Africa. *World Development* 38(10), 1384-1398.

Jayne, T.S., Rashid, S. 2013. Input subsidy programmes in sub-Saharan Africa: A synthesis of recent evidence. *Agricultural Economics (United Kingdom)* 44(6), 547-562.

Jin, S., Feng, G. 2013. Large-scale variations of global groundwater from satellite gravimetry and hydrological models, 2002-2012. *Global and Planetary Change* 106, 20-30.

Johnston, A.E., Poulton, P.R., Fixen, P.E., Curtin, D. 2014. Phosphorus: Its efficient use in agriculture. *Advances in Agronomy* 123, 177-228.

Kabunga, N.S., Dubois, T., Qaim, M. 2014. Impact of tissue culture banana technology on farm household income and food security in Kenya. *Food Policy* 45, 25-34.

Kandulu, J.M., Bryan, B.A., King, D., Connor, J.D. 2012. Mitigating economic risk from climate variability in rain-fed agriculture through enterprise mix diversification. *Ecological Economics* 79, 105-112.

Kang, Y., Khan, S., Ma, X. 2009. Climate change impacts on crop yield, crop water productivity and food security - A review. *Progress in Natural Science* 19(12), 1665-1674.

Karimov, K.S., Akhmedov, K.M., Abid, M., Petrov, G.N. 2013. Effective management of combined renewable energy resources in Tajikistan. *Science of the Total Environment* 461-462, 835-838.

Karpouzoglou, T., Barron, J. 2014. A global and regional perspective of rainwater harvesting in sub-Saharan Africa's rainfed farming systems. *Physics and Chemistry of the Earth* 72, 43-53.

Kassie, B.T., Van Ittersum, M.K., Hengsdijk, H., Asseng, S., Wolf, J., Rötter, R.P. 2014. Climate-induced yield variability and yield gaps of maize (Zea mays L.) in the Central Rift Valley of Ethiopia. *Field Crops Research* 160, 41-53.

Kassie, M. Jaleta, M., Shiferaw, B., Mmbando, F., Mekuria, M. 2013. Adoption of interrelated sustainable agricultural practices in smallholder systems: Evidence from rural Tanzania. *Technological Forecasting & Social Change* 80, 525-540.

Kassie, M., Teklewold, H., Jaleta, M., Marenya, P., Erenstein, O. 2015. Understanding the adoption of a portfolio of sustainable intensification practices in eastern and southern Africa. *Land Use Policy* 42, 400-411.

Kazmi, S.I., Ertsen, M.W., Asi, M.R. 2012. The impact of conjunctive use of canal and tube well water in Lagar irrigated area, Pakistan. *Physics and Chemistry of the Earth* 47-48, 86-98.

Keraita, B., Medlicott, K., Drechsel, P., Mateo-Sagasta Dávila, J., 2015. Health risks and cost-effective health risk management in wastewater use systems. In: Drechsel, P., Qadir, M., Wichelns, D. (Eds.) Wastewater: Economic Asset in an Urbanizing World. Springer, Chapter 3, pp. 39-54.

Kevane, M. 2012. Gendered production and consumption in rural Africa. *Proc. of the National Academy of Sciences of the United States of America* 109(31), 12350-12355.

Klinger, D., Naylor, R. 2012. Searching for solutions in aquaculture: Charting a sustainable course. *Annual Review of Environment and Resources* 37, 247-276.

Kim, M., Lee, H., Kim, M., Kang, D., Kim, D., Kim, Y., Lee, S. 2014. Wastewater retreatment and reuse system for agricultural irrigation in rural villages. *Water Science and Technology* 70(12), 1961-1968.

Kløve, B., Ala-Aho, P., Bertrand, G., Gurdak, J.J., Kupfersberger, H., Kværner, J., Muotka, T., Mykrä, H., Preda, E., Rossi, P., Uvo, C.B., Velasco, E., Pulido-Velazquez, M. 2014. Climate change impacts on groundwater and dependent ecosystems. *Journal of Hydrology* 518 (PB), 250-266.

Koester, U. 2013. Total and per capita value of food loss in the United States: Comments. *Food Policy* 41, 63-64.

Kumanayake, N.S., Estudillo, J.P., Otsuka, K. 2014. Changing Sources of Household Income, Poverty, and Sectoral Inequality in Sri Lanka, 1990-2006. *The Developing Economies* 52(1), 26-51.

Kumar, M.D., Scott, C.A., Singh, O.P. 2013. Can India raise agricultural productivity while reducing groundwater and energy use? *International Journal of Water Resources Development* 29(4), 557-573.

Kurothe, R.S., Kumar, G., Singh, R., Tiwari, S.P., Vishwakarma, A.K., Sena, D.R., Pande, V.C. 2014. Effect of tillage and cropping systems on runoff, soil loss and crop yields under semiarid rainfed agriculture in India. *Soil and Tillage Research* 140, 126-134.

Kurylyk, B.L., MacQuarrie, K.T.B., McKenzie, J.M. 2014. Climate change impacts on groundwater and soil temperatures in cold and temperate regions: Implications, mathematical theory, and emerging simulation tools. *Earth-Science Reviews* 138, 313-334.

Lagoda, P.J.L. 2013. Use of tissue culture and mutation inductIon to improve banana productIon for smallholders in Sri Lanka. In: J. Ruane, J.D. Dargie, C. Mba, P. Boettcher, H.P.S. Makkar, D.M. Bartley and A. Sonnino (Eds.), Biotechnologies at Work for Smallholders: Case Studies from Developing Countries in Crops, Livestock and Fish. Rome, FAO.

Langridge, P., Reynolds, M.P. 2015. Genomic tools to assist breeding for drought tolerance. *Current Opinion in Biotechnology* 32, 130-135.

Lasco, R.D., Delfino, R.J.P., Catacutan, D.C., Simelton, E.S., Wilson, D.M. 2014. Climate risk adaptation by smallholder farmers: The roles of trees and agroforestry. *Current Opinion in Environmental Sustainability* 6(1), 83-88.

Latif, M., Haq, Z.-U., Nabi, G. 2015. Comparison of state-managed and farmer-managed irrigation systems in punjab, Pakistan. *Irrigation and Drainage* 63(5), 628-639.

Laurance, W.F., Sayer, J., Cassman, K.G. 2014. Agricultural expansion and its impacts on tropical nature. *Trends in Ecology and Evolution* 29(2), 107-116.

Lee, H., Chan, Z., Graylee, K., Kajenthira, A., Martínez, D., Roman, A. 2014. Challenge and response in the São Francisco River Basin. *Water Policy* 16(Suppl. 1), 153-200.

Lehmann, N., Finger, R. 2014. Economic and environmental assessment of irrigation water policies: A bioeconomic simulation study. *Environmental Modelling and Software* 51, 112-122.

Lenk, O. 2013. Satellite based estimates of terrestrial water storage variations in Turkey. *Journal of Geodynamics* 67, 106-110.

Letey, J., Hoffman, G.J., Hopmans, J.W., Grattan, S.R., Suarez, D., Corwin, D., Oster, J.D., Wu, L., Amrhein, C. 2011. Evaluation of soil salinity leaching requirement guidelines. *Agricultural Water Management* 98(4), 502-506.

Li, K., Yang, X., Liu, Z., Zhang, T., Lu, S., Liu, Y. 2014. Low yield gap of winter wheat in the North China Plain. *European Journal of Agronomy* 59, 1-12.

Liu, J., Yang, W. 2012. Water sustainability for China and beyond. *Science* 337(6095), 649-650.

Lobell, D.B. 2014. Climate change adaptation in crop production: Beware of illusions. *Global Food Security* 3(2), 72-76.

Lobell, D.B., Cassman, K.G., Field, C.B. 2009. Crop yield gaps: Their importance, magnitudes, and causes. *Annual Review of Environment and Resources* 34, 179-204.

Lomazzi, M., Borisch, B., Laaser, U. 2014. The Millennium Development Goals: Experiences, achievements, and what's next. *Global Health Action* 7(Suppl. 1), 1-7.

Luedeling, E., Kindt, R., Huth, N.I., Koenig, K. 2014. Agroforestry systems in a changing climate-challenges in projecting future performance. *Current Opinion in Environmental Sustainability* 6(1), 1-7.

Marschke, M., Wilkings, A. 2014. Is certification a viable option for small producer fish farmers in the global south? Insights from Vietnam. *Marine Policy* 50, 197-206.

Martinelli, L.A., Filoso, S. 2008. Expansion of sugarcane ethanol production in Brazil: Environmental and social challenges. *Ecological Applications* 18(4), 885-898.

Martinelli, L.A., Naylor, R., Vitousek, P.M., Moutinho, P. 2010. Agriculture in Brazil: Impacts, costs, and opportunities for a sustainable future. *Current Opinion in Environmental Sustainability* 2(5-6), 431-438.

Masters, W.A., Djurfeldt, A.A., De Haan, C., Hazell, P., Jayne, T., Jirström, M., Reardon, T. 2013. Urbanization and farm size in Asia and Africa: Implications for food security and agricultural research. *Global Food Security* 2(3), 156-165.

Maurice, J. 2013. New goals in sight to reduce poverty and hunger. *The Lancet* 382, 383-384.

Mbow, C., Smith, P., Skole, D., Duguma, L., Bustamante, M. 2014a. Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. *Current Opinion in Environmental Sustainability* 6(1), 8-14.

Mbow, C., Van Noordwijk, M., Luedeling, E., Neufeldt, H., Minang, P.A., Kowero, G. 2014b. Agroforestry solutions to address food security and climate change challenges in Africa. *Current Opinion in Environmental Sustainability* 6(1), 61-67.

McDermott, J., Aït-Aïssa, M., Morel, J., Rapando, N. 2013. Agriculture and household nutrition security-development practice and research needs. *Food Security* 5(5), 667-678.

Megersa, B., Markemann, A., Angassa, A., Ogutu, J.O., Piepho, H.-P., Valle Zaráte, A. 2014. Impacts of climate change and variability on cattle production in southern Ethiopia: Perceptions and empirical evidence. *Agricultural Systems* 130, 23-34.

Meinzen-Dick, R. 2014. Property rights and sustainable irrigation: A developing country perspective. *Agricultural Water Management* 145, 23-31.

Mellor, J.W. 2014. High rural population density Africa - What are the growth requirements and who participates? *Food Policy* 48, 66-75.

Menberg, K., Blum, P., Kurylyk, B.L., Bayer, P. 2014. Observed groundwater temperature response to recent climate change. *Hydrology and Earth System Sciences* 18(11), 4453-4466.

Misselhorn, A., Aggarwal, P., Ericksen, P., Gregory, P., Horn-Phathanothai, L., Ingram, J., Wiebe, K. 2012. A vision for attaining food security. *Current Opinion in Environmental Sustainability* 4(1), 7-17.

Miyake, S., Renouf, M., Peterson, A., McAlpine, C., Smith, C. 2012. Land-use and environmental pressures resulting from current and future bioenergy crop expansion: A review. *Journal of Rural Studies* 28(4), 650-658.

Mohapatra, S. 2011. The pillars of Africa's agriculture. *Rice Today* 10(2), 22-23.

Monjardino, M., McBeath, T.M., Brennan, L., Llewellyn, R.S. 2013. Are farmers in low-rainfall cropping regions under-fertilising with nitrogen? A risk analysis. *Agricultural Systems* 116, 37-51.

Morignat, E., Perrin, J.-B., Gay, E., Vinard, J., Calavas, D., Hénaux, V. 2014. Assessment of the impact of the 2003 and 2006 heat waves on cattle mortality in France. *PLoS ONE* 9(3), e93176.

Mukuve, F.M., Fenner, R.A. 2015. The influence of water, land, energy and soil-nutrient resource interactions on the food system in Uganda. *Food Policy* 51, 24-37.

Murray, A., Cofie, O., Drechsel, P. 2011. Efficiency indicators for waste-based business models: Fostering private-sector participation in wastewater and faecal-sludge management. *Water International* 36 (4), 505-521.

Nabarro, D. 2013. Global child and maternal nutrition - The SUN rises. *The Lancet* 382(9893), 666-667.

Nardone, A., Ronchi, B., Lacetera, N., Ranieri, M.S., Bernabucci, U. 2010. Effects of climate changes on animal production and sustainability of livestock systems. *Livestock Science* 130(1-3), 57-69.

Nawrotzki, R.J., Robson, K., Gutilla, M.J., Hunter, L.M., Twine, W., Norlund, P. 2014. Exploring the impact of the 2008 global food crisis on food security among vulnerable households in rural South Africa. *Food Security* 6(2), 283-297.

Naylor, R.L., Hardy, R.W., Bureau, D.P., Chiu, A., Elliott, M., Farrelle, A.P., Forstere, I., Gatlin, D.M., Goldburg, R.J., Hua, K., Nichols, P.D. 2009. Feeding aquaculture in an era of finite resources. *Proc. of the National Academy of Sciences of the United States of America* 106(36), 15103-15110.

Ndiritu, S.W., Kassie, M., Shiferaw, B. 2014. Are there systematic gender differences in the adoption of sustainable agricultural intensification practices? Evidence from Kenya. *Food Policy* 49(P1), 117-127.

Nielsen, A., Steinheim, G., Mysterud, A. 2013. Do different sheep breeds show equal responses to climate fluctuations? *Basic and Applied Ecology* 14(2), 137-145.

Nikouei, A., Ward, F.A. 2013. Pricing irrigation water for drought adaptation in Iran. *Journal of Hydrology* 503, 29-46.

Nyakudya, I.W., Stroosnijder, L. 2015. Conservation tillage of rainfed maize in semi-arid Zimbabwe: A review. *Soil and Tillage Research* 145, 184-197.

OECD. 2013. Global food security: Challenges for the food and agricultural systems. Paris, OECD Publishing.

Ørum, J.E., Boesen, M.V., Jovanovic, Z., Pedersen, S.M. 2010. Farmers' incentives to save water with new irrigation systems and water taxation: A case study of Serbian potato production. *Agricultural Water Management* 98(3), 465-471.

Otoo, M., Drechsel, P., Hanjra, M.A. 2015. Business models and economic approaches for nutrient recovery from wastewater and fecal sludge. In: Drechsel, P., Qadir, M., Wichelns, D. (Eds.) Wastewater: Economic Asset in an Urbanizing World. London, Springer, Chapter 13, pp. 247-270.

Padula, A.D., Santos, M.S., Ferreira, L., Borenstein, D. 2012. The emergence of the biodiesel industry in Brazil: Current figures and future prospects. *Energy Policy* 44, 395-405.

Parfitt, J., Barthel, M., MacNaughton, S. 2010. Food waste within food supply chains: Quantification and potential for change to 2050. *Philosophical Transactions of the Royal Society B: Biological Sciences* 365(1554), 3065-3081.

Powell, N., Ji, X., Ravash, R., Edlington, J., Dolferus, R. 2012. Yield stability for cereals in a changing climate. *Functional Plant Biology* 39(7), 539-552.

Qadir, M., Wichelns, D., Raschid-Sally, L., McCornick, P.G., Drechsel, P., Bahri, A., Minhas, P.S. 2010. The challenges of wastewater irrigation in developing countries. *Agricultural Water Management* 97(4), 561-568.

Qaim, M., Kouser, S. 2013. Genetically modified crops and food security. *PLoS ONE* 8 (6), 1-7.

Qureshi, A.S., McCornick, P.G., Qadir, M., Aslam, Z. 2008. Managing salinity and waterlogging in the Indus Basin of Pakistan. *Agricultural Water Management* 95(1), 1-10.

Rap, E., Wester, P. 2013. The practices and politics of making policy: Irrigation management transfer in Mexico. *Water Alternatives* 6(3), 506-531.

Rasul, G. 2014. Food, water, and energy security in South Asia: A nexus perspective from the Hindu Kush Himalayan region. *Environmental Science & Policy* 39, 35-48.

Ray, D.K., Mueller, N.D., West, P.C., Foley, J.A. 2013. Yield Trends Are Insufficient to Double Global Crop Production by 2050. *PLoS ONE* 8(6), e66428.

Ray, D.K., Ramankutty, N., Mueller, N.D., West, P.C., Foley, J.A. 2012. Recent patterns of crop yield growth and stagnation. *Nature Communications* 3, 2296.

Raz, A.E. 2014. Successful implementation of large-scale drip irrigation projects: An exploratory study of the socio-economic impact of the APMIP among smallholders in India. *Acta Horticulturae* 1015, 283-294.

Ribeiro, B.E. 2013. Beyond commonplace biofuels: Social aspects of ethanol. *Energy Policy* 57, 355-362.

Rijkers, B., Costa, R. 2012. Gender and Rural Non-Farm Entrepreneurship. *World Development* 40(12), 2411-2426.

Rothschild, M.F., Plastow, G.S. 2014. Applications of genomics to improve livestock in the developing world. *Livestock Science* 166(1), 76-83.

Roudier, P., Sultan, B., Quirion, P., Berg, A. 2011. The impact of future climate change on West African crop yields: What does the recent literature say? *Global Environmental Change* 21(3), 1073-1083.

Ruane, J., Sonnino, A. 2011. Agricultural biotechnologies in developing countries and their possible contribution to food security. *Journal of Biotechnology* 156, 356-363.

Ruel, M.T., Alderman, H. 2013. Nutrition-sensitive interventions and programmemes: How can they help to accelerate progress in improving maternal and child nutrition? *The Lancet* 382(9891), 536-551.

Rufino, M.C., Thornton, P.K., Ng'ang'a, S.K., Mutie, I., Jones, P.G., van Wijk, M.T., Herrero, M. 2013. Transitions in agro-pastoralist systems of East Africa: Impacts on food security and poverty. *Agriculture, Ecosystems and Environment* 179, 215-230.

Ruijs, A., Zimmermann, A., van den Berg, M. 2008. Demand and distributional effects of water pricing policies. *Ecological Economics* 66(2-3), 506-516.

Ryan, J., Ibrikci, H., Delgado, A., Torrent, J., Sommer, R., Rashid, A. 2012. Significance of phosphorus for agriculture and the environment in the West Asia and North Africa region. *Advances in Agronomy* 114, 91-153.

Scott, C.A. 2011. The water-energy-climate nexus: Resources and policy outlook for aquifers in Mexico. *Water Resources Research* 47(12), W00L04.

Scott, C.A., Pablos, N.P. 2011. innovating resource regimes: Water, wastewater, and the institutional dynamics of urban hydraulic reach in northwest Mexico. *Geoforum* 42(4), 439-450.

Scott, C.A. 2013. Electricity for groundwater use: Constraints and opportunities for adaptive response to climate change. *Environmental Research Letters* 8(3), 1-8.

Scott, C.A., Pierce, S.A., Pasqualetti, M.J., Jones, A.L., Montz, B.E., Hoover, J.H. 2011. Policy and institutional dimensions of the water–energy nexus. *Energy Policy* 39, 6622-6630.

Scott, C.A., Raschid-Sally, L. 2012. The global commodification of wastewater. *Water International* 37(2), 147-155.

Senanayake, N., Mukherji, A., Giordano, M. 2015. Re-visiting what we know about Irrigation Management Transfer: A review of the evidence. *Agricultural Water Management* 149, 175-186.

Shah, T. 2008. India's master plan for groundwater recharge: An assessment and some suggestions for revision. *Economic & Political Weekly* 43(51), 41-49.

Shah, T. 2009. Climate change and groundwater: India's opportunities for mitigation and adaptation. *Environmental Research Letters* 4(3), 1-13.

Shah, T. 2014. Towards a managed aquifer recharge strategy for Gujarat, India: An economist's dialogue with hydro-geologists. *Journal of Hydrology* 518, 94-107.

Shah, T., Giordano, M., Mukherji, A. 2012. Political economy of the energy-groundwater nexus in India: exploring issues and assessing policy options. *Hydrogeology Journal* 20(5), 995-1006.

Shi, J., Wang, Z., Zhang, Z., Fei, Y., Li, Y., Zhang, F., Chen, J., Qian, Y. 2011. Assessment of deep groundwater over-exploitation in the North China Plain. *Geoscience Frontiers* 2(4), 593-598.

Shi, M., Wang, X., Yang, H., Wang, T. 2014. Pricing or quota? A solution to water scarcity in oasis regions in China: A case study in the Heihe River Basin. *Sustainability (Switzerland)* 6(11), 7601-7620.

Siddiqi, A., Anadon, L.D. 2011. The water–energy nexus in Middle East and North Africa. *Energy Policy* 39, 4529-4540.

Siderius, C., Boonstra, H., Munaswamy, V., Ramana, C., Kabat, P., van Ierland, E., Hellegers, P. 2015. Climate-smart tank irrigation: A multi-year analysis of improved conjunctive water use under high rainfall variability. *Agricultural Water Management* 148, 52-62.

Siebert, S., Henrich, V., Frenken, K., and Burke, J. 2013. Update of the global map of irrigation areas to version 5. Rome, FAO. Available at: http://www.fao.org/nr/water/aquastat/catalogues/index.stm

Simões, A.F., Kligerman, D.C., Rovere, E.L.L., Maroun, M.R., Barata, M., Obermaier, M. 2010. Enhancing adaptive capacity to climate change: The case of smallholder farmers in the Brazilian semi-arid region. *Environmental Science and Policy* 13(8), 801-808.

Singh, A. 2014. Conjunctive use of water resources for sustainable irrigated agriculture. *Journal of Hydrology* 519, 1688-1697.

Smith, M.S., Mbow, C. 2014. Editorial overview: Sustainability challenges: Agroforestry from the past into the future. *Current Opinion in Environmental Sustainability* 6(1), 134-137.

Solh, M., Van Ginkel, M. 2014. Drought preparedness and drought mitigation in the developing world's drylands. *Weather and Climate Extremes* 3, 62-66.

Spiertz, H. 2012. Avenues to meet food security. The role of agronomy on solving complexity in food production and resource use. *European Journal of Agronomy* 43, 1-8.

Spiertz, H. 2014. Agricultural sciences in transition from 1800 to 2020: Exploring knowledge and creating impact. *European Journal of Agronomy* 59, 96-106.

Springer, N.P., Duchin, F. 2014. Feeding nine billion people sustainably: Conserving land and water through shifting diets and changes in technologies. *Environmental Science and Technology* 48(8), 4444-4451.

Steduto, P., Hsiao, T.C., Raes, D., Fereres, E. 2009. AquaCrop - The FAO crop model to simulate yield response to water: I. Concepts and underlying principles. *Agronomy Journal* 101(3): 426-437.

Stevenson, J.R., Villoria, N., Byerlee, D., Kelley, T., Maredia, M. 2013. Green Revolution research saved an estimated 18 to 27 million hectares from being brought into agricultural production. *Proc. of the National Academy of Sciences of the United States of America* 110(21), 8363-8368.

Stroosnijder, L., Moore, D., Alharbi, A., Argaman, E., Biazin, B., van den Elsen, E. 2012. Improving water use efficiency in drylands. *Current Opinion in Environmental Sustainability* 4(5), 497-506.

Suhardiman, D. 2013. The power to resist: Irrigation management transfer in Indonesia. *Water Alternatives* 6(1), 25-41.

Tacon, A.G.J., Metian, M. 2013. Fish matters: Importance of aquatic foods in human nutrition and global food supply. *Reviews in Fisheries Science* 21(1), 22-38.

Thornton, P.K., van de Steeg, J., Notenbaert, A., Herrero, M. 2009. The impacts of climate change on livestock and livestock systems in developing countries: A review of what we know and what we need to know. *Agricultural Systems* 101(3), 113-127.

Timmer, C.P. 2008. Causes of high food prices. ADB Economics Working Paper Series, Number 128. Manila, Asian Development Bank.

Timmer, C.P. 2010. Reflections on food crises past. *Food Policy* 35(1), 1-11.

Timmer, C.P. 2012. Behavioral dimensions of food security. *Proc. of the National Academy of Sciences of the United States of America* 109(31), 12315-12320.

Tirado, M.C., Cohen, M.J., Aberman, N., Meerman, J., Thompson, B. 2010. Addressing the challenges of climate change and biofuel production for food and nutrition security. *Food Research International* 43(7), 1729-1744.

Tiwari, R., Dileep Kumar, H., Dutt, T., Singh, B.P., Pachaiyappan, K., Dhama, K. 2014. Future challenges of food security and sustainable livestock production in India in the changing climatic scenario. *Asian Journal of Animal and Veterinary Advances* 9(7), 367-384.

Torres, M.D.O., Maneta, M., Howitt, R., Vosti, S.A., Wallender, W.W., Bassoi, L.H., Rodrigues, L.N. 2012. Economic impacts of regional water scarcity in the São Francisco river Basin, Brazil: An application of a linked hydro-economic model. *Environment and Development Economics* 17(2), 227-248.

Tolk, J.A., Howell, T.A. 2008. Field water supply: Yield relationships of grain sorghum grown in three USA Southern Great Plains soils. *Agricultural Water Management* 95(12): 1303-1313.

Totin, E., Stroosnijder, L., Agbossou, E. 2013. Mulching upland rice for efficient water management: A collaborative approach in Benin. *Agricultural Water Management* 125, 71-80.

Troell, M., Naylor, R.L., Metian, M., Beveridge, M., Tyedmerse, P.H., Folke, C., Arrow, K.J., Barrett, S., Crépin, A., Ehrlich, P.R., Gren, A., Kautsky, N., Levin, S.A., Nyborg, K., Österblom, H., Polasky, S., Scheffer, M., Walker, B.H., Xepapadeas, T., De Zeeuw, A. 2014. Does aquaculture add resilience to the global food system? *Proc. of the National Academy of Sciences of the United States of America* 111(37), 13257-13263.

Tscharntke, T., Clough, Y., Wanger, T.C., Jackson, L., Motzke, I., Perfecto, I., Vandermeer, J., Whitbread, A. 2012. Global food security, biodiversity conservation and the future of agricultural intensification. *Biological Conservation* 151(1), 53-59.

Turral, H., Burke, J., Faurès, J.M. 2011. Climate change, water and food security. *FAO Water Reports* 36. Rome, FAO.

Turral, H., Svendsen, M., Faurès, J.M. 2010. Investing in irrigation: Reviewing the past and looking to the future. *Agricultural Water Management* 97 (4), 551-560.

United Nations, 2014. Open Working Group of the General Assembly on Sustainable Development Goals. issued as document A/68/970. (Available at http://undocs.org/A/68/970).

Vadez, V., Palta, J., Berger, J. 2014. Developing drought tolerant crops: Hopes and challenges in an exciting journey. *Functional Plant Biology* 41(11), v-vi.

Van der Horst, D., Vermeylen, S. 2011. Spatial scale and social impacts of biofuel production. *Biomass and Bioenergy* 35(6), 2435-2443.

Van der Kooij, S., Zwarteveen, M., Boesveld, H., Kuper, M. 2013. The efficiency of drip irrigation unpacked. *Agricultural Water Management* 123, 103-110.

Vasileiou, K., Mitropoulos, P., Mitropoulos, I. 2014. Optimizing the performance of irrigated agriculture in eastern england under different water pricing and regulation strategies. *Natural Resource Modeling* 27(1), 128-150.

Veettil, P.C., Speelman, S., Frija, A., Buysse, J., Van Huylenbroeck, G. 2011. Complementarity between water pricing, water rights and local water governance: A Bayesian analysis of choice behaviour of farmers in the Krishna river basin, India. *Ecological Economics* 70(10), 1756-1766.

Vengosh, A. 2014. Salinization and saline environments. In: *Treatise on Geochemistry: Second Edition* 11.9, 325-378. Elsevier.

Viaggi, D., Raggi, M., Bartolini, F., Gallerani, V. 2010. Designing contracts for irrigation water under asymmetric information: Are simple pricing mechanisms enough? *Agricultural Water Management* 97(9), 1326-1332.

Vico, G., Porporato, A. 2011. From rainfed agriculture to stress-avoidance irrigation: II. Sustainability, crop yield, and profitability. *Advances in Water Resources* 34(2), 272-281.

Wada, Y., Van Beek, L.P.H., Van Kempen, C.M., Reckman, J.W.T.M., Vasak, S., Bierkens, M.F.P. 2010. Global depletion of groundwater resources. *Geophysical Research Letters* 37(20), L20402.

Wang, H., Guan, H., Gutiérrez-Jurado, H.A., Simmons, C.T. 2014. Examination of water budget using satellite products over Australia. *Journal of Hydrology* 511, 546-554.

Wei, T., Cherry, T.L., Glomrød, S., Zhang, T. 2014. Climate change impacts on crop yield: Evidence from China. *Science of the Total Environment* 499, 133-140.

Weinhold, D., Killick, E., Reis, E.J. 2013. Soybeans, poverty and inequality in the Brazilian Amazon. *World Development* 52, 132-143.

Wellens, J., Nitcheu, M., Traore, F., Tychon, B. 2013. A public-private partnership experience in the management of an irrigation scheme using decision-support tools in Burkina Faso. *Agricultural Water Management* 116, 1-11.

Wichelns, D., Drechsel, P. 2011. Meeting the challenge of wastewater irrigation: Economics, finance, business opportunities and methodological constraints. *Water International* 36(4), 415-419.

Wossen, T., Berger, T. 2015. Climate variability, food security and poverty: Agent-based assessment of policy options for farm households in Northern Ghana. *Environmental Science and Policy* 47, 95-107.

Wright, B.D. 2013. Grand missions of agricultural innovation. *Research Policy* 41(10), 1716-1728.

Wu, B., Meng, J., Li, W., Yan, N., Du, X., Zhang, M. 2014. Remote sensing-based global crop monitoring: experiences with China's CropWatch system. *International Journal of Digital Earth* 7(2), 113-137.

Xiong, W., Holman, I., Lin, E., Conway, D., Jiang, J., Xu, Y., Li, Y. 2010. Climate change, water availability and future cereal production in China. *Agriculture, Ecosystems and Environment* 135(1-2), 58-69.

Yami, M. 2013. Sustaining participation in irrigation systems of Ethiopia: What have we learned about water user associations? *Water Policy* 15(6), 961-984

Young, M.D. 2014. Designing water abstraction regimes for an ever-changing and ever-varying future. *Agricultural Water Management* 145, 32-38.

Zhang, L., Heerink, N., Dries, L., Shi, X. 2013. Water users associations and irrigation water productivity in Northern China. *Ecological Economics* 95, 128-136.

Zhang, L., Wang, J., Huang, J., Huang, Q., Rozelle, S. 2010. Access to groundwater and agricultural production in China. *Agricultural Water Management* 97(10), 1609-1616.

Zhou, L., Turvey, C.G. 2014. Climate change, adaptation and China's grain production. *China Economic Review* 28, 72-89.

Ziadi, N., Whalen, J.K., Messiga, A.J., Morel, C. 2013. Assessment and modeling of soil available phosphorus in sustainable cropping systems. *Advances in Agronomy* 122, 85-126.

Zinzani, A. Irrigation Management Transfer and WUAs' dynamics: evidence from the South-Kazakhstan Province. *Environmental Earth Sciences* 73(2), 765-777.

Zwart, S.J., Bastiaanssen, W.G.M. 2004. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agricultural Water Management* 69(2), 115-133.

TOWARDS A WATER AND FOOD SECURE FUTURE

Critical Perspectives for Policy-makers

The aim of this paper is to provide policy-makers with a helpful overview of the technical and economic aspects of water use in agriculture, with particular emphasis on crop and livestock production. Through 2050, in many countries, agriculture will remain an important determinant of economic growth, poverty reduction, and food security, even as, over time, the proportion of agricultural revenue in national gross income declines. Water use in agriculture will remain substantial, irrigated areas will expand and competition for water will increase in all sectors. Most likely, overall supplies of land and water will be sufficient to achieve global food production goals in 2050; although poverty and food insecurity will remain pressing challenges in several regions and countries. Thus, the focus of this report is on the regional and national aspects of food security.

WWW.WORLDWATERCOUNCIL.ORG
WWW.FAO.ORG

Food and Agriculture Organization of the United Nations

WORLD WATER COUNCIL