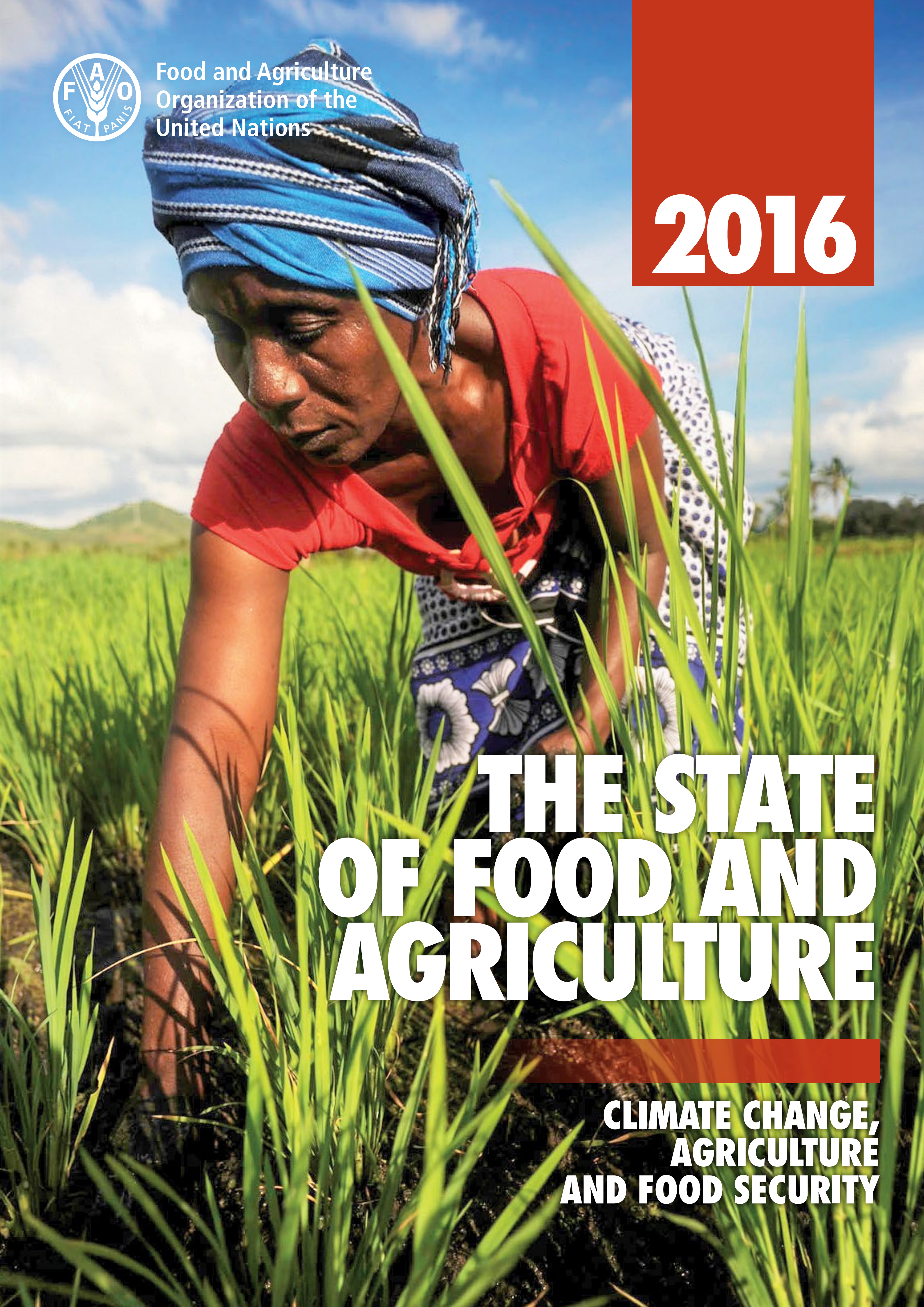

Food and Agriculture Organization of the United Nations

2016

THE STATE OF FOOD AND AGRICULTURE

CLIMATE CHANGE, AGRICULTURE AND FOOD SECURITY

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COVER PHOTOGRAPH ©FAO/D. Hayduk

KIROKA, UNITED REPUBLIC OF TANZANIA.
Hand weeding a rice paddy forms part of the System of Rice Intensification method in this climate-smart agriculture project.

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Food and Agriculture Organization of the United Nations
Rome, 2016

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FOREWORD

Following last year's historic Paris Agreement and the 2030 Agenda for Sustainable Development – marking a path towards a more sustainable future – 2016 is about putting commitments into action. The rapid change in the world's climate is translating into more extreme and frequent weather events, heat waves, droughts and sea-level rise.

The impacts of climate change on agriculture and the implications for food security are already alarming – they are the subjects of this report. A major finding is that there is an urgent need to support smallholders in adapting to climate change. Farmers, pastoralists, fisherfolk and community foresters depend on activities that are intimately and inextricably linked to climate – and these groups are also the most vulnerable to climate change. They will require far greater access to technologies, markets, information and credit for investment to adjust their production systems and practices to climate change.

Unless action is taken now to make agriculture more sustainable, productive and resilient, climate change impacts will seriously compromise food production in countries and regions that are already highly food-insecure. These impacts will jeopardize progress towards the key Sustainable Development Goals of ending hunger and poverty by 2030; beyond 2030, their increasingly negative impacts on agriculture will be widespread.

Through its impacts on agriculture, livelihoods and infrastructure, climate change threatens all dimensions of food security. It will expose both urban and rural poor to higher and more volatile food prices. It will also affect food availability by reducing the productivity of crops, livestock and fisheries, and hinder access to food by disrupting the livelihoods of millions of rural people who depend on agriculture for their incomes.

Hunger, poverty and climate change need to be tackled together. This is, not least, a moral imperative as those who are now suffering most have contributed least to the changing climate. The report describes ways of adapting smallholder production to climate change and making the livelihoods of rural populations more resilient. Diversification and better integration of food production systems into complex ecological processes create synergies with the natural habitat instead of depleting natural resources. Agroecology and sustainable intensification are examples of approaches that improve yields and build resilience through practices such as green manuring, nitrogen-fixing cover crops and sustainable soil management, and integration with agroforestry and animal production.

More resilient agriculture sectors and intelligent investments into smallholder farmers can deliver transformative change, and enhance the prospects and incomes of the world's poorest while buffering them against the impacts of climate change. This report shows how the benefits of adaptation outweigh the costs of inaction by very wide margins. For this transformation towards

FOREWORD

sustainable and more equitable agriculture, access to adequate extension advice and markets must improve, while insecurity of tenure, high transaction costs, and lower resource endowments, especially among rural women, are barriers that will need to be overcome.

Livelihood diversification can also help rural households manage climate risks by combining on-farm activities with seasonal work, in agriculture and in other sectors. In all cases, social protection programmes will need to play an important role – in helping smallholders better manage risk, reducing vulnerability to food price volatility, and enhancing the employment prospects of rural people who leave the land.

In order to keep the increase in global temperature below the crucial ceiling of 2 °C, emissions will have to be reduced by as much as 70 percent by 2050. Keeping climate change within manageable levels can only be achieved with the contribution of the agriculture sectors. They now account for at least one-fifth of total emissions, mainly from the conversion of forests to farmland as well as from livestock and crop production. The challenge is to reduce those emissions while meeting unprecedented demand for food.

The agriculture sectors can substantially contribute to balancing the global carbon cycle. Similarly, in the forestry sector, avoiding deforestation, increasing the area under forest, and adopting sustained-yield management in timber production can bind large amounts of atmospheric carbon dioxide (CO_2). Soils are pivotal in regulating emissions of CO_2 and other greenhouse gases. Appropriate land use and soil management lead to improved soil quality and fertility and can help mitigate the rise of atmospheric CO_2.

It is essential that national commitments – the country pledges that form the basis of the 2015 Paris Agreement on climate change – turn into action. The Conference of the Parties that will be held in November 2016 in Morocco will have a clear focus on implementation in the agriculture sectors. This report identifies strategies, financing opportunities and data and information needs, and describes transformative policies and institutions that can overcome barriers to implementation. As countries revise and, hopefully, ramp up their national plans, success in implementing their commitments – particularly in the agriculture sectors – will be vital to creating a virtuous circle of higher ambition.

Climate change is a cornerstone of the work undertaken by FAO. To assist its Members, we have invested in areas that promote food security hand in hand with climate change adaptation and mitigation. FAO is helping to reorient food and agricultural systems in countries most exposed to climate risks, with a clear focus on supporting smallholder farmers.

FAO works in all its areas of expertise, pursuing new models of sustainable, inclusive agriculture. Through the Global Soil Partnership, FAO promotes investment to minimize soil degradation and restore productivity in regions where people are most vulnerable, thus stabilizing global stores of soil organic matter.

We participate in the Global Agenda for Sustainable Livestock, and have launched a programme to reduce enteric emissions of methane from ruminants using measures suited to local farming systems. In the fisheries sector, our Blue Growth Initiative is integrating fisheries and sustainable environmental management, while a joint programme with the European Union aims at protecting carbon-rich forests. We provide guidance on including genetic diversity in national climate change adaptation planning, and have joined forces with the United Nations Development Programme to support countries as they integrate agriculture in adaptation plans and budgeting processes. FAO also helps link developing countries to sources of climate financing.

The international community needs to address climate change today, enabling agriculture, forestry and fisheries to adopt climate-friendly practices. This will determine whether humanity succeeds in eradicating hunger and poverty by 2030 and producing food for all. “Business as usual” is not an option. Agriculture has always been the interface between natural resources and human activity. Today it holds the key to solving the two greatest challenges facing humanity: eradicating poverty, and maintaining the stable climatic corridor in which civilization can thrive.

José Graziano da Silva

FAO Director-General

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ACRONYMS AND ABBREVIATIONS

AFOLU
agriculture, forestry and other land use

AgMIP
Agricultural Model Intercomparison and Improvement Project

ASAP
Adaptation for Smallholder Agriculture Programme

BCR
benefit-cost ratio

C
carbon

CFU
ODI Climate Fund Update

CH_4
methane

CO_2
carbon dioxide

COP
UNFCCC Conference of the Parties

CRS
OECD Creditor Reporting System

CSA
climate-smart agriculture

GDP
gross domestic product

GEF
Global Environment Facility

GHG
greenhouse gas

Gt
gigatonne (billion tonnes)

GtC
Gt of carbon

$GtCO_2$-eq
Gt of carbon dioxide equivalent

ha
hectare

IDA
International Development Association

IFAD
International Fund for Agricultural Development

IFPRI
International Food Policy Research Institute

IMPACT
International Model for Policy Analysis of Agricultural Commodities

INDC
Intended Nationally Determined Contributions

IPCC
Intergovernmental Panel on Climate Change

LDC
Least developed country

LULUCF
land use, and land-use change and forestry

N
nitrogen

N_2O
nitrous oxide

NAMA
Nationally Appropriate Mitigation Actions

NAP
National Adaptation Plans

NAPA
National Adaptation Programmes of Action

NDC
Nationally Determined Contributions

NPV
net present value

ODI
Overseas Development Institute

OECD
Organisation for Economic Co-operation and Development

RCP
Representative Concentration Pathway

REDD
Reducing emissions from deforestation and forest degradation

SOC
soil organic carbon

SSP
Shared Socio-economic Pathway

SME
small and medium enterprises

t
tonne

UNDP
United Nations Development Programme

UNFCCC
United Nations Framework Convention on Climate Change

WTO
World Trade Organization

EXECUTIVE SUMMARY

THE WORLD FACES AN UNPRECEDENTED DOUBLE CHALLENGE: TO ERADICATE HUNGER AND POVERTY AND TO STABILIZE THE GLOBAL CLIMATE BEFORE IT IS TOO LATE

In adopting the goals of the 2030 Agenda on Sustainable Development and the Paris Agreement on Climate Change, the international community took responsibility for building a sustainable future. But meeting the goals of eradicating hunger and poverty by 2030, while addressing the threat of climate change, will require a profound transformation of food and agriculture systems worldwide.

Achieving the transformation to sustainable agriculture is a major challenge. Changes will need to be made in a way that does not jeopardize the capacity of the agriculture sectors – crops, livestock, fisheries and forestry – to meet the world's food needs. Global food demand in 2050 is projected to increase by at least 60 percent above 2006 levels, driven by population and income growth, as well as rapid urbanization. In the coming decades, population increases will be concentrated in regions with the highest prevalence of undernourishment and high vulnerability to the impacts of climate change. At the same time, efforts by the agriculture sectors to contribute to a carbon-neutral world are leading to competing demands on water and land used to produce food and energy, and to forest conservation initiatives that reduce greenhouse gas emissions but limit land available for crop and livestock production.

The transformation will also need to involve millions of food producers in adapting to climate change impacts, which are already being felt in the agricultural sectors and especially so in tropical regions, which are home to most of the poor and food insecure. It must also reverse the widespread degradation of agriculture's natural resource base – from soil to forests to fisheries – which threatens the very sustainability of food production.

A broad-based transformation of food and agriculture systems is needed, therefore, to ensure global food security, provide economic and social opportunities for all, protect the ecosystem services on which agriculture depends, and build resilience to climate change. Without adaptation to climate change, it will not be possible to achieve food security for all and eradicate hunger, malnutrition and poverty.

BECAUSE ADVERSE IMPACTS WILL WORSEN WITH TIME, A GLOBAL TRANSFORMATION TO SUSTAINABLE FOOD AND AGRICULTURE MUST BEGIN NOW

The effects of climate change on agricultural production and livelihoods are expected to intensify over time, and to vary across countries and regions. Beyond 2030, the negative impacts of climate change on the productivity of crops, livestock, fisheries and forestry will become increasingly severe in all regions.

Productivity declines would have serious implications for food security. Food supply shortfalls would lead to major increases in food prices, while increased climate variability would accentuate price volatility. Since the areas most affected would be those with already high rates of hunger and poverty, food price increases would directly affect millions of low-income people. Among the most vulnerable will be those who depend on agriculture for their livelihood and income, particularly smallholder producers in developing countries.

While climate change is but one driver of poverty and food insecurity, its impacts are expected to be substantial. In the absence of climate change, and with continuing economic progress, most regions are projected to see a decline in the number of people at risk of hunger by 2050. With climate change, however, the population living in poverty could increase by between 35 and 122 million by

2030 relative to a future without climate change, largely due to its negative impacts on incomes in the agricultural sector. The increase in the number of poor would be biggest in sub-Saharan Africa, partly because its population is more reliant on agriculture.

Food and agriculture must be central to global efforts to adapt to climate change, through policies and actions that address vulnerabilities and risks and promote agricultural systems that are resilient and sustainable. This action must begin now – with the increasing intensity of climate change impacts, building resilience will become ever more difficult. Delaying the transformation of the agricultural sectors will force poorer countries to fight poverty, hunger and climate change at the same time.

ECONOMICALLY VIABLE AND SUSTAINABLE FARMING PRACTICES ARE AVAILABLE, BUT BARRIERS TO THEIR ADOPTION MUST BE OVERCOME

Significant improvements in food security, as well as resilience to climate change can be achieved with the introduction of sustainable agricultural practices. Wide adoption of practices such as the use of nitrogen-efficient and heat-tolerant crop varieties, zero-tillage and integrated soil fertility management would boost productivity and farmers' incomes, and help lower food prices. By one estimate, the number of people at risk of undernourishment in developing countries in 2050 could be reduced by more than 120 million through widespread use of nitrogen-efficient crop varieties alone.

Despite this potential, the adoption by farmers of improved practices is still very limited. Often, adoption is hampered by policies, such as input subsidies, that perpetuate unsustainable production practices rather than those that promote resource-use efficiency, soil conservation and the reduction in the intensity of agriculture's own greenhouse gas emissions. Smallholders, especially, face a broad range of barriers on the path to sustainable agriculture, such as limited access to markets, credit, extension advice, weather information, risk management tools and social protection. Women, who make up around 43 percent of the agricultural labour force in developing countries, are especially disadvantaged, with fewer endowments and entitlements than men, even more limited access to information and services, gender-determined household responsibilities, and increasingly heavy agricultural workloads owing to male out-migration.

There is no simple "technological fix". What is needed is a reorientation of agricultural and rural development policies that resets incentives and lowers the barriers to the transformation of food and agricultural systems. Particular attention should be given to supporting low-income smallholder farmers in strengthening their capacity to manage risks and adopt effective climate change adaptation strategies.

MOVING BEYOND FARMING PRACTICES: SMALLHOLDERS' ADAPTATION TO CLIMATE CHANGE RISKS WILL BE CRITICAL FOR GLOBAL POVERTY REDUCTION AND FOOD SECURITY

The sheer number of smallholder farm families in developing countries – some 475 million – justifies a specific focus on the threat posed by climate change to their livelihoods and the urgent need to transform those livelihoods along sustainable pathways. It will be difficult, if not impossible, to eradicate global poverty and end hunger without building resilience to climate change in smallholder agriculture through the widespread adoption of sustainable land, water, fisheries and forestry management practices. With other enabling factors in place – such as adequate access to credit and markets, but also action to eliminate legal, socio-cultural and mobility constraints on rural women – those practices have been found to yield significant productivity improvements. However, improved management practices may not be enough to sustain farmer incomes.

Farmers can further enhance their resilience through diversification, which can reduce the impact of climate shocks on income and provide households with a broader range of options when managing future risks. One form of diversification is to integrate production of crops, livestock and trees – for example, some agroforestry systems use the leaves of nitrogen-fixing leguminous trees to feed cattle, use manure to fertilize the soil, and grow pulses to provide extra protein during periods of seasonal food insecurity.

For farm households with limited options for on-farm diversification, livelihood diversification through non-farm rural employment or migration to cities may be essential. Adaptation through sustainable intensification and agricultural diversification may have to be combined, therefore, with the creation of off-farm opportunities, both locally and through strengthened rural-urban linkages. Gender issues may need to be addressed – social norms often prevent women from pursuing off-farm activities. Social protection, education and active labour market policies are needed to mitigate many of the risks associated with diversification and migration.

ONE-FIFTH OF GREENHOUSE GAS EMISSIONS ARE GENERATED BY AGRICULTURE, FORESTRY AND LAND-USE CHANGE; THE AGRICULTURE SECTORS NEED TO CONTRIBUTE TO CONTAINING GHG EMISSIONS

The challenge of adaptation to climate change will become greater over time if we do not act now to reduce emissions of the greenhouse gases responsible for global warming. Emissions will have to be drastically reduced in order to keep climate change in check and keep the global temperature increase no higher than 1.5 °C or 2 °C, compared with pre-industrial levels. This is a global responsibility and requires all economic sectors to shift to low emission intensity.

Agriculture, and the food sector at large, have an important responsibility in climate change mitigation. Taken together, agriculture, forestry and land-use change account for about one-fifth of global GHG emissions. Carbon dioxide emissions from agriculture are mainly attributable to losses of above and below ground organic matter, through changes in land use, such as conversion of forests to pasture or cropland, and land degradation such as caused by over-grazing. The bulk of direct emissions of methane and nitrous oxide, two potent GHGs, are the result of enteric fermentation in livestock, rice production in flooded fields, and the application of nitrogen fertilizer and manure, all of which can be reduced through the implementation of better management practices.

The share of the food system as a whole in total global GHG emissions is even greater – further emissions are generated by the manufacture of agrochemicals, by fossil energy use in farm operations, and in post-production transportation, processing and retailing.

AGRICULTURE'S CONTRIBUTION TO CLIMATE CHANGE ADAPTATION AND MITIGATION IS FEASIBLE – BUT REQUIRES ACTION ON A BROAD FRONT

Broad-based agricultural and rural development can help reduce exposure and sensitivity to climate shocks and enable farmers to benefit from new opportunities for improving rural livelihoods and food security. This report shows how the adoption of improved management practices will help to achieve a significant reduction in the number of food insecure. However, improvements in infrastructure, extension, climate information, access to credit, and social insurance, which are at the heart of rural development, need to go hand in hand in order to foster the adoption of improved practices and the diversification of rural livelihoods.

Available estimates suggest that the aggregate cost of adaptation and making farm systems more resilient are only a fraction of the costs of inaction. Adaptation efforts make good economic sense and also have considerable potential to reduce the GHG emissions generated by agriculture, forestry and land-use change. Increasing resource-use efficiency, cutting the use of fossil fuels and avoiding direct environmental degradation will save farmers money, enhance productivity sustainably and reduce dependence on external inputs.

Multiple concrete examples exist of how efforts at adaptation and mitigation can go hand in hand. Improvements in crop production and fertilizer management appear to offer the greatest potential for reducing nitrous oxide emissions, while also reducing input costs. Increasing stocks of soil organic carbon improves crop yields and builds resilience to drought and flooding, but also sequesters carbon. Alternate wetting and drying of rice fields reduces methane emissions from paddies by 45 percent, while saving water and producing yields similar to those of fully flooded rice. In both temperate and tropical regions, farming system diversification and crop-livestock-tree integration could increase farm-scale efficiency, reduce emissions intensity and raise productivity. In the livestock sector, the general adoption of sustainable practices could cut livestock methane emissions by up to 41 percent while also increasing productivity through better animal feeding, animal health and herd structure management. However, the uptake of these practices is often low in many areas. Efforts to foster their adoption by smallholders need to be informed by a thorough understanding of the existing financial, institutional and policy barriers.

As agricultural production increases to meet demand, so too will its emissions. Major improvements in the management of the carbon and nitrogen cycles in agriculture would be needed to achieve a reduction in emission intensities – or emissions per unit of agricultural output – to counterbalance the tendency of the agriculture sectors to emit more as they produce more. Hence, achieving the mitigation potential in the agriculture sectors will not be easy – not only because of the major transformations needed in agriculture for broader adoption of improved practices, but also because of projected increases in demand for agricultural products.

Not all mitigation options can be seen as adaptation measures with important mitigation co-benefits. Other initiatives are intrinsically driven by a mitigation motive. For example, putting a halt to deforestation and forest degradation arguably has the largest potential for emission reduction in the agriculture sectors. This should be a top priority, but will require accepting trade-offs: reducing deforestation often comes at a cost to the farmer. Efforts in this direction are under way through the REDD+ initiative, under the umbrella of the United Nations Framework Convention on Climate Change (UNFCCC). Although emissions from the conversion of forests have declined significantly over the past two decades, the trade-offs involved make these gains fragile. Unlike other economic sectors where adaptation and mitigation actions are generally independent of each other, in the agriculture sectors the objectives of food security, adaptation and mitigation, are interlinked.

Even the widespread adoption of climate-smart, sustainable agriculture may fall short of what is needed to meet global climate targets. Big adjustments are required in food systems at large. About one-third of all food produced in the world is lost or wasted post-harvest. Reducing food losses and waste would not only improve the efficiency of the food system, but would also reduce both pressure on natural resources and emissions of greenhouse gases. The energy use and emission-intensity of food processing, conservation and transportation are high and increasing. Reducing emission intensity along the entire food chain will require significant changes in consumer awareness, as well as price incentives that favour food items with much smaller environmental footprints. Rebalancing diets towards less animal-sourced foods would make an important contribution in this direction, with probable co-benefits for human health.

PARIS AGREEMENT COMMITMENTS NEED TO UNDERPIN SYSTEM-WIDE ACTION IN FOOD AND AGRICULTURE

Transformative change in agriculture and food systems appears to be economically and technically feasible. However, change will only come about if supported by appropriate policies, institutional frameworks and investment finance mechanisms. These enabling factors are important for agricultural development in general, but are made even more necessary by climate change. Policy frameworks need to be drastically modified to align agricultural development, food security and nutrition, and climate stability objectives.

The Intended Nationally Determined Contributions (INDCs), which formed the basis of the 2015 Paris Agreement on Climate Change, are now to become Nationally Determined Contributions (NDCs) to global climate objectives, through policies and actions. The agriculture sectors feature prominently in the INDCs, with 94 percent of all countries including them in their mitigation and/or adaptation contributions. Developing countries highlight the importance of agriculture and food security for adaptation; often, they also include the agriculture sectors as contributing to their mitigation targets. Around one-third of all countries refer in their INDCs to the potential co-benefits between mitigation and adaptation in agriculture. There is a clear willingness of countries to respond to climate change by transforming and investing in the agriculture sectors.

Many countries have designed broad climate change policies and strategies, which establish global objectives and targets. However, few have spelled out the details of action plans to achieve climate targets. The INDCs are a first step in a much broader process of rethinking agricultural and rural development under climate change. The UNFCCC has already established meaningful mechanisms, such as National Adaptation Plans, to underpin concerted actions to address climate change. In line with the policy recommendations of this report, those mechanisms should be integrated into broader agricultural and food security and nutrition policies, and vice-versa.

POLICIES ON CLIMATE, AGRICULTURE, FOOD AND NUTRITION SHOULD BE REALIGNED AND INTEGRATED

Policies, market forces and environmental constraints drive the use of inputs and other resources in agriculture, influencing productivity and the degree of conservation or depletion of natural resources. Policy-making for agriculture under climate change should start from an understanding of those drivers and their impacts on farmers' livelihoods and the environment. This is a complex task and win-win solutions may not always be possible. Drivers vary significantly between countries and regions – smallholder farmers do not have the same capacity as global agribusinesses to respond to policy and market signals.

Policymakers must recognize the need to manage trade-offs, and set out concrete measures for better aligning multiple objectives and incentive structures. For example, the gender equity trade-offs of planned actions need to be systematically analysed – a shift to more resilient intercropping systems has sometimes cost women their control over specific crops. One area with a large potential for policy realignment is the redesign of agricultural support measures in a way that facilitates, rather than impedes, the transition to sustainable agriculture. In 2015, developed and major developing countries spent more than US$560 billion on agricultural production support, including subsidies on inputs and direct payments to farmers. Some measures, such as input subsidies, may induce inefficient use of agrochemicals and increase the emissions intensity of production. Making support conditional upon the adoption of practices that lower emissions and conserve natural resources is one way of aligning agricultural development and climate goals.

Policies on nutrition, food consumption, food price support, natural resources management, infrastructure development, energy and so on, may similarly need to be re-set. To address trade-offs, the process must ensure greater inclusiveness and transparency in decision-making, as well as incentives that provide long-term public and collective benefits. For example, experience shows that forests can be well managed and degradation reversed by involving local communities, supported by legitimate decentralized institutional arrangements developed through consultative processes.

Climate change brings new risks. Managing them requires enhanced forms of collective action and systems that assess risks, vulnerabilities and adaptation options. Well-designed social protection programmes, which guarantee minimum incomes or access to food, have an important role to play, but should be aligned with other forms of climate risk management. Instead of simply responding to extreme events, disaster risk reduction should be embedded in broader strategies for climate change adaptation.

In responding to climate change, international cooperation and multi-stakeholder partnerships and alliances are essential. For example, climate change will lead to new pests and disease problems and increase the risks of their transboundary movement. Strengthened regional and international cooperation will be needed to facilitate information and knowledge sharing, to manage common resources such as fish stocks, and to conserve and utilize agrobiodiversity. Cooperation is also needed to close gaps in our knowledge of climate change impacts on agriculture, food security and nutrition, to evaluate the scalability and economic viability of sustainable farming practices, and to assess the ecological footprint of food systems at large.

AGRICULTURAL AND CLIMATE FINANCE NEED TO BE LINKED AND LEVERAGED TO INDUCE TRANSFORMATIVE CHANGE IN AGRICULTURE

More climate financing and agricultural investments are need to facilitate the transition to sustainable agricultural practices. However, available finance for investment in agriculture falls well short of needs. Smallholder producers in developing countries face major hurdles in accessing credit for investing in new technologies and practices, and female farmers even more so. The shortfall in finance limits investment in agriculture and food security and, with it, the capacity of smallholders to adapt to climate change.

More climate finance needs to flow to agriculture to fund the investment cost associated with the required large-scale transformation of its sectors and the development of climate-smart food production systems. Additional finance from public sources, as well as customized financial products, will be needed in two areas of financing.

First, more upfront support is necessary for increasing farmers' productivity, building capacity to adapt to climate change and reducing the emissions intensity of production. This will require a significant increase in the amount of finance available, and more flexible conditions, such as repayment schedules adjusted to cash flows. This approach would allow farmers to make the investments that maintain current yields using fewer resources, and apply climate-smart practices and technologies that increase resilience while reducing emissions. However, for this to be successful, a second area requires financing – building capacity through appropriate institutions and policies, so that farmers are enabled to undertake transformational changes. Improving the enabling environment is especially needed for the vast majority of smallholder farmers, who are effectively disenfranchised from climate financing and denied opportunities for investing in productive activities that would improve their livelihoods, productivity and incomes.

Although more climate finance is needed for the transformation envisioned by this report, additional funding will also require improving countries' capacity to make things happen on the ground. Systemic capacity constraints currently hamper developing country access to and effective use of climate finance for agriculture. This "capacity gap" in policy-making and institutional development, which can manifest itself at both funding and receiving ends, hinders support for the transition to sustainable agriculture. Closing these capacity gaps should be made a priority by funders and countries alike, so that climate finance – if countries ramp up funding as planned – can serve its transformative role for food and agriculture.

Climate finance can also act as a catalyst to leverage larger flows of public and private funding for sustainable agriculture, provided policies and institutional frameworks that promote transformative change are in place. Climate finance could help address the funding gap by demonstrating the viability of climate-smart agricultural investments, and designing and piloting innovative mechanisms to leverage additional sources of investment. Climate funds – if used strategically to build the enabling environment essential for climate-smart agricultural development, to ensure that public agricultural investment is climate-smart, and to leverage private finance – could become an important catalyst for climate change adaptation and mitigation.

By filling the financing gap and catalysing investment, climate finance can strengthen risk management mechanisms, foster development of appropriate financial products, and address the capacity constraints of lenders and borrowers. It is crucial, therefore, to strengthen the enabling environment for climate-smart agricultural investments, mainstream climate change considerations in domestic budget allocations and implementation, and unlock private capital for climate-smart agricultural development. Until that happens, the climate financing needed for investment in smallholder agriculture will continue to be inadequate, with serious consequences in terms of loss of livelihoods and increased food insecurity.

The time to invest in agriculture and rural development is now. The challenge is garnering diverse financing sources, aligning their objectives to the extent possible, and creating the right policy and institutional environments to bring about the transformational change needed to eradicate poverty, adapt to climate change and contribute to limiting greenhouse gas emissions. ■

CHAPTER 1

HUNGER, POVERTY AND CLIMATE CHANGE: THE CHALLENGES TODAY AND TOMORROW

ARBA GERAMSO, KENYA
Mother and daughter prepare maize for dinner in an area where most pastoralists have lost almost 90 percent of their animals to drought.
©FAO/A. Vitale

NAROK, KENYA
Maasai pastoralists grazing their livestock.
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KEY MESSAGES

1 **CLIMATE CHANGE ALREADY AFFECTS AGRICULTURE AND FOOD SECURITY** and, without urgent action, will put millions of people at risk of hunger and poverty.

2 While **IMPACTS ON AGRICULTURAL YIELDS AND LIVELIHOODS** will vary across countries and regions, they will become increasingly adverse over time and potentially catastrophic in some areas.

3 **LIMITING GLOBAL TEMPERATURE INCREASES TO 1.5 °C ABOVE PRE-INDUSTRIAL LEVELS** would significantly reduce the risks and impacts of climate change.

4 **DEEP TRANSFORMATIONS IN AGRICULTURE AND FOOD SYSTEMS**, from pre-production to consumption, are needed in order to maximize the co-benefits of climate change adaptation and mitigation efforts.

5 **THE AGRICULTURE SECTORS HAVE POTENTIAL TO LIMIT THEIR GREENHOUSE GAS EMISSIONS**, but ensuring future food security requires a primary focus on adaptation.

CHAPTER 1

HUNGER, POVERTY AND CLIMATE CHANGE: THE CHALLENGES TODAY AND TOMORROW

Climate change poses a major and growing threat to global food security. The expected effects of climate change – higher temperatures, more frequent extreme weather events, water shortages, rising sea levels, ocean acidification, land degradation, the disruption of ecosystems and the loss of biodiversity – could seriously compromise agriculture's ability to feed the most vulnerable, impeding progress towards the eradication of hunger, malnutrition and poverty. Action is urgently needed, therefore, to prepare crop and livestock production, fisheries and forestry for the prospect of rapidly changing environmental conditions and to reduce agriculture's own contribution to the greenhouse gas (GHG) emissions responsible for global warming.

Even without climate change, world agriculture and food security face daunting challenges. Population growth and rising incomes in much of the developing world have pushed demand for food and other agricultural products to unprecedented levels. The Food and Agriculture Organization (FAO) has estimated that in order to meet the demand for food in 2050, annual world production of crops and livestock will need to be 60 percent higher than it was in 2006. About 80 percent of the required increase will need to come from higher yields and 10 percent from increases in the number of cropping seasons per year (Alexandratos and Bruinsma, 2012). However, widespread land degradation and increasing water scarcity limit the potential for yield increases. Without heightened efforts to reduce poverty, and to make the transition to an agriculture that is both productive and sustainable, many low-income countries will find it difficult to ensure access to adequate quantities of food for all of their populations.

Through its impacts on agriculture, climate change will exacerbate the negative effects of all those trends, and will make it even more difficult to meet the key Sustainable Development Goals of ending hunger, achieving year-round food security, and ensuring sustainable food production systems by 2030. In the longer term, the magnitude and speed of climate change, and the effectiveness of economy-wide mitigation efforts and of adaptation in agriculture, will be critical to the future of large segments of the world's population and, possibly, to humanity at large. ■

COMPLEX INTERACTIONS AND INEXTRICABLE LINKS

The agriculture sectors – crops, livestock, fisheries, aquaculture and forestry – have unique characteristics that place them at the centre of global efforts to adapt to climate change. First, agriculture is essential to our food supply and, therefore, to meeting the most basic of human needs. Further, food production depends directly on natural resources – including biodiversity, land, vegetation, rainfall and sunlight – which are, in turn, intimately and inextricably linked to climate and weather conditions. Since agriculture also provides livelihoods for almost two-thirds of the world's extremely poor, or some 750 million people, climate change impacts on agriculture directly affect already vulnerable rural populations, with far-reaching implications for their food security.

The agriculture sectors are also a major contributor to the greenhouse gas emissions that cause global warming and associated climate change. The agriculture sectors are, therefore, also unique in their potential contribution to stabilizing the world's climate, through better management of crops, land and livestock, in a way that reduces emissions and increases carbon sequestration in plant biomass and soils.

How climate change affects agriculture

In many regions, agricultural production is already being adversely affected by rising temperatures, increased temperature variability, changes in levels and frequency of precipitation, a greater frequency of dry spells and droughts, the increasing intensity of extreme weather events, rising sea levels, and the salinization of arable land and freshwater. As climate change impacts on agriculture intensify, it will become increasingly difficult to grow crops, raise animals, manage forests and catch fish in the same ways and in the same places as we have done in the past.

The crops that we grow for food, fibre and energy need specific conditions in order to thrive, including optimal temperature and sufficient water. Up to a certain point, warmer temperatures may benefit the growth of certain crops in some parts of the world. However, if temperatures exceed a crop's optimal level, or if sufficient water and nutrients are not available, yields are likely to fall. An increased frequency of extreme events, especially floods and droughts, also harms crops and reduces yields. Dealing with drought could become a major challenge in areas where average temperatures are projected to increase and precipitation is projected to decrease. Many weeds, insect pests and diseases thrive under warmer temperatures, wetter climates and increased levels of atmospheric carbon dioxide (CO_2). More extreme temperatures, combined with decreasing rainfall, can prevent crops from growing at all.

Heat waves, which are projected to become more common under climate change, directly threaten livestock. Over time, heat stress increases animals' vulnerability to disease, thereby reducing fertility and meat and milk production. Climate change will also modify the prevalence of livestock parasites and diseases. In areas where rainfall increases, moisture-reliant pathogens are expected to thrive. Climate change also threatens the carrying capacity of grasslands and rangelands as well as feed production for non-grazing systems.

Fisheries and aquaculture – which provide at least 50 percent of animal protein to millions of people in low-income countries – are already under multiple stresses, including overfishing, habitat loss and water pollution (FAO, 2012). Climate change will exacerbate those stresses. Warmer water temperatures are likely to cause the extinction of some fish species, a shift in the habitat ranges of others, and increased risks of disease throughout the production chain. The world's oceans are becoming more acidic owing to increases in levels of atmospheric CO_2, with particularly severe consequences for fisheries depending on shellfish and squid, mangroves and coral reef systems. The increased frequency and intensity of storms, hurricanes and cyclones will harm aquaculture, mangroves and coastal fisheries.

Forests provide paid employment for more than 100 million people and support the livelihoods of many of the world's rural poor. They are home to more than 80 percent of the world's terrestrial biodiversity, and provide food, medicines, fuel and critical ecosystem services. Climate change and increased climate variability have both direct and indirect effects on forests and on the people who depend on them, and limit the capacity of forests to provide these crucial goods and services. While some forests will benefit from higher concentrations of atmospheric carbon dioxide, higher temperatures and changes in precipitation, most will experience losses of important species, a decline in yields and an increase in the frequency and intensity of storms and other disturbances (FAO, 2013).

While the precise impacts of climate change on agriculture are extremely difficult to predict, most studies indicate that they will change over time and will differ across locations. A review of studies conducted for the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) suggests that while positive and negative projections of impacts on crop yields counterbalance each other at global level until about 2030, the balance after that becomes increasingly negative (Porter *et al.*, 2014; see also Chapter 2).

Impacts will also vary strongly across crops and regions. Figure 1 shows this variability in cereal yields projected for 2050 under different pathways of global warming; it assumes a "middle-of-the-road" pathway for economic and population growth as well as limited adaptation, and does not include "CO_2 fertilization", i.e. the stimulatory effect of increased levels of atmospheric carbon dioxide on plant growth. As their growing seasons lengthen, higher latitudes tend to see smaller yield losses, or even yield gains, for some crops, compared to those expected without climate change. Yield losses in lower latitude regions are generally greater. Maize yields would decline in most regions under most climate scenarios, with progressively greater losses under more extreme scenarios. While impacts on wheat yields are small at the global level, they are considerable in South Asia and sub-Saharan Africa.

How agriculture contributes to climate change

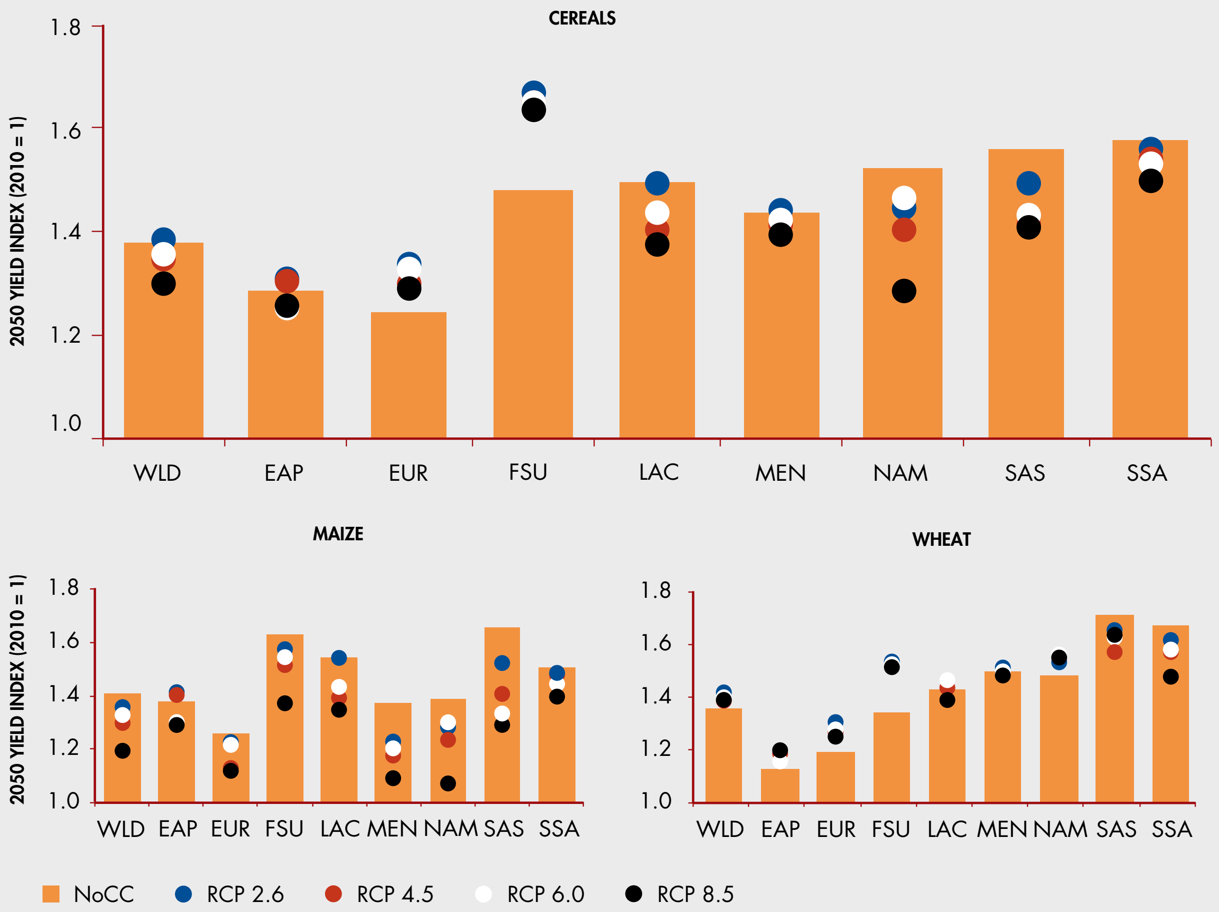
Agriculture is not only affected by climate change. It also contributes directly and indirectly to significant emissions of the three major greenhouse gases: carbon dioxide, methane and nitrous oxide. Annual anthropogenic GHG emissions that are classified in IPCC reports as originating in "agriculture, forestry and other land use" (AFOLU) are caused mainly by deforestation, livestock production and soil and nutrient management. They have been estimated at 21 percent of total global emissions (Figure 2). While this was less than the 27 percent recorded during the 1990s, the apparent reduction is due to the fact that emissions have grown more rapidly in other sectors.

Emissions from agriculture and those from net forest conversion contributed broadly comparable amounts of greenhouse gases in the 1990s; however, since the turn of the century, emissions from forest conversion have declined, while agricultural emissions have increased. Crop and livestock production, in particular, release significant amounts of methane and nitrous oxide, two potent GHGs. Methane is produced by ruminant livestock during digestion and also escapes from stored manure and organic waste. Nitrous oxide emissions are an indirect product of organic and mineral nitrogen fertilizers after they have been applied to cropland.

Unaccounted for in the AFOLU category are greenhouse gases that are produced in the pre- and post-production stages of modern food supply chains but classified in IPCC reporting as originating in other sectors, mainly industry, energy generation and transportation. They include the production of inputs such as synthetic fertilizers, which, unlike organic fertilizer production, is an energy intensive process; emissions resulting from fossil energy use (e.g. for powering farm machinery); and post-production transportation, processing and retailing (Smith *et al.*, 2014). At every stage, food provisioning adds to the buildup of greenhouse gases in the atmosphere. If emissions caused by »

FIGURE 1

IMPACTS OF CLIMATE CHANGE ON CEREAL YIELDS ACROSS REGIONS BY 2050

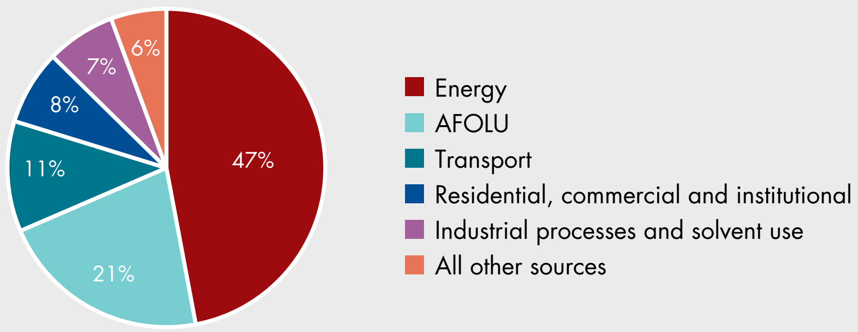


WLD: World
EAP: East Asia and the Pacific
EUR: Europe
FSU: Former Soviet Union
LAC: Latin America and the Caribbean
MEN: Middle East and North Africa
NAM: North America
SAS: South Asia
SSA: sub-Saharan Africa
NoCC: no climate change
RCP: Representative Concentration Pathways (global warming scenarios)

Notes: Cereals refer to the area-weighted average for the following commodities: barley, maize, millet, rice, sorghum, wheat, and other cereals considered by the IMPACT model. Simulations assume a "middle-of-the-road" Shared Socioeconomic Pathway (SSP) scenario. See Chapter 2, Box 7 for an explanation of RCPs and SSPs.
SOURCE: Simulations using IFPRI's IMPACT model, as cited in De Pinto, Thomas and Wiebe (2016).

FIGURE 2

SHARES OF GREENHOUSE GAS EMISSIONS FROM ECONOMIC SECTORS IN 2010



Notes: Emissions from energy include industries, manufacturing and fugitive emissions. AFOLU means "Agriculture, forestry and other land use". "All other sources" includes international bunkers, waste and other sources.
SOURCE: FAO, forthcoming.

» direct and indirect energy use by the agrifood chain were included, the AFOLU share of total greenhouse emissions would increase by one-third (FAO, 2011).

The contribution of food systems to total GHG emissions varies among countries and regions, according to the structure of local supply chains. Estimates by the Consultative Group for International Agricultural Research (CGIAR) indicate that in high-income countries emissions from the pre- and post-production stages equal those from production. In contrast, agricultural production is still the dominant stage in terms of GHG emissions in developing countries (Vermeulen, Campbell and Ingram, 2012).

The implications for food security

Through its impacts on agriculture, climate change will have negative effects on food security in all of its dimensions (Box 1). While food security will be affected through other channels – for example, by extreme weather events that reduce urban dwellers' incomes and thus access to food – agriculture is a key channel through which climate change affects food security, and is the focus of this report.

Climate change affects *food availability* through its increasingly adverse impacts on crop yields, fish stocks and animal health and productivity, especially in sub-Saharan Africa and South Asia, where most of today's food insecure live. It limits *access to food* through negative impacts on rural incomes and livelihoods. Along with a more volatile climate, there is expected to be an increase in the intensity and frequency of climate-related natural disasters. Poor people, including many smallholder farmers and agricultural workers, are more vulnerable to the impacts of such disasters. Severe droughts or floods can sharply reduce incomes and cause asset losses that erode future income earning capacity. In addition, to the extent that food supply is reduced by climate change, food prices will increase. Both urban and rural poor would be most affected, as they spend much higher shares of their income on food. Also affected will be poor smallholder family farmers, most of whom are net buyers of food (Zezza *et al.*, 2008; World Bank, 2008; Porter *et al.*, 2014).

Changes in the *utilization of food* will impact the nutrition status of the poor and vulnerable. For example, because higher temperatures favour the development of pathogens, and water scarcity affects water quality and hygiene habits, climate impacts could increase the burden of diarrhoea by up to 10 percent by 2030 in some regions. Again, the most severely affected would be the poor, and especially poor children (WHO, 2003). Climate change will affect nutrition status in many others ways, from reductions in caregiving and the nutrient content of staple food crops, to higher risk of food contamination (Box 2).

Finally, climate variability and a higher frequency and intensity of extreme events will affect the *stability* of food availability, access and utilization through changes in seasonality, more pronounced fluctuations in ecosystem productivity, increased supply risks and reduced supply predictability. This will be a major problem especially for landlocked countries and small island states, which are more vulnerable to both food supply disruptions and damage caused by extreme and climate events.

Climate change is just one of several drivers now shaping trends in poverty and food security. Those two trends, and the severity of climate change impacts on them, will be determined largely by future socio-economic development. A recent World Bank study (Hallegatte *et al.*, 2016) estimated that, in the absence of economic growth, high impact climate change would increase the projected number of extremely poor in 2030 by 122 million people; in a scenario of prosperity, the increase would be just 16 million. In a similar exercise, using the International Model for Policy Analysis of Agricultural Commodities (IMPACT), developed by the International Food Policy Research Institute (IFPRI), it was estimated that by 2050 about 50 million more people could be at risk of undernourishment because of climate change. »

BOX 1

FOUR DIMENSIONS OF FOOD SECURITY

The 1996 World Food Summit agreed on the following definition of food security, which is used by FAO: "Food security exists when all people, at all times, have physical and economic access to sufficient safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life". The definition encompasses four dimensions:

- Availability of sufficient quantities of food of appropriate quality, supplied through domestic production or imports (including food aid).
- Access by individuals to adequate resources (also called entitlements) for acquiring appropriate foods for a nutritious diet.
- Utilization of food through adequate diet, clean water, sanitation and health care to reach a state of nutritional well-being where all physiological needs are met.
- Stability in the availability of and access to food, regardless of sudden shocks (e.g. an economic or climatic crisis) or cyclical events (e.g. seasonal food scarcity).

SOURCE: FAO, 2006.

BOX 2

CLIMATE CHANGE AND NUTRITION

Climate change affects nutrition status and dietary choices through its impacts on food security, diseases, water safety, sanitation, livelihoods and caregiving. In turn, people's capacity to adapt to, or mitigate, climate change is also affected (IFPRI, 2015).

Climate change amplifies the impact of droughts, floods and storms and exposes large numbers of people – especially the poor and most vulnerable – to the risk of undernutrition following extreme climate events (Confalonieri *et al.*, 2007).

Seasonal patterns of inadequate food availability and access, a major cause of undernutrition among poor rural communities, are accentuated by climate change, which has impacts also on livelihood security and on intra-family food distribution, affecting in turn the nutrition status of children and women in particular (Wijesinha-Bettoni *et al.*, 2013).

Some studies indicate that the nutritional quality of key food crops could suffer under climate change. A study by Myers *et al.* (2014) estimated that when grown under the high levels of CO_2 expected by 2050, wheat grain had 9 percent less zinc, 5 percent less iron, and 6 percent less protein, while losses in rice were 3 percent, 5 percent and 8 percent, respectively, compared to expected yields without climate change. Maize would suffer similar losses of nutrients; soybeans would not lose protein but would contain less zinc and iron.

Food safety may be compromised by an increase in food-borne pathogens, as well as contamination or chemical changes that increase the prevalence of toxic compounds in food. For example, upsurges in algal surface blooms contaminate drinking water and shellfish with cyanotoxins (Paerl and Huisman, 2009), while higher temperatures and humidity increase the risk of mycotoxin contamination of stored cereals and pulses (Paterson and Lim, 2010). In addition, changes in patterns of plant and animal diseases may lead to increased use of potentially harmful agricultural chemicals.

» However, the overall impact of climate change during the period up to 2050 is smaller than that of the other drivers, such as growth in population and incomes (see Chapter 2). ■

THE URGENCY OF CONCERTED GLOBAL ACTION NOW

All available evidence confirms that the climate is changing and that the changes are unlikely to be halted or reversed in the immediate future. There is also no doubt that climate change will affect the agriculture sectors and food security and that its negative impact will become more severe as it accelerates. In some particularly vulnerable places, such as small islands or in areas affected by large-scale extreme weather and climate events, the impact could be catastrophic.

Much will depend on the speed of climate change and the magnitude of its impacts. In a best-case scenario, changes would progress at a pace and magnitude that allow the agriculture sectors to adapt through relatively simple means, at least in the medium term. Declines in productivity, if any, would be relatively minor and gradual, with no or few instances of abrupt non-linear effects. In that case, impacts on food security globally would be modest.

A quite different, but plausible, scenario would see – even in the medium term – widespread instances of abrupt non-linear changes, making adequate adaptation by the agriculture sectors almost impossible in many locations, and causing drastic declines in productivity. The impacts on productivity would be, if not global, at least extremely widespread both geographically and in terms of the size of affected populations. The impacts on food security would be very significant. Supply shortfalls would lead to major increases in food prices, while increased climate variability would result in increased food price volatility. Climate variability would also affect the stability of rural household incomes in areas already subject to high variability in yields (Thornton *et al.*, 2014). Productivity declines and losses of income would tend to be concentrated in some of the most food-insecure and vulnerable geographic areas and population groups. In the longer run, unless measures are put in place to halt and reverse climate change, food production could become impossible in large areas of the world.

Urgent action must be taken to address the potential impacts of climate change on agriculture and food security. Uncertainty does not justify delays in implementing climate change adaptation and mitigation. The urgency derives from two main concerns. Firstly, impacts of climate change are already evident, will become larger over time and could become very large indeed. Secondly, both drivers and responses to climate change involve long time lags. Today's GHG emissions are pushing our planet towards irreversible global warming, with impacts that will be felt decades from now. These long-term risks are the main reason why the international community is committed to the goal of stabilizing the Earth's climate.

Societies at large need to take decisive action, today, to *mitigate climate change* in order to avoid the risk of serious food insecurity. The possibility that climate change may make it impossible to feed humanity at some unknown, more or less distant, point in the future cannot be discarded. Even with a shorter time horizon, food security impacts in some locations may be severe. Agriculture and forestry have a large potential to reduce GHG emissions, but future food security will depend to a large extent on emission reductions achieved in other economic sectors. Changes will also be needed on the consumption side – reducing demand for emission- and resource-intensive food products will help to accelerate the transition towards sustainable agriculture, as well as promoting climate change mitigation.

At the same time, the agriculture sectors and the populations who depend on them need to *adapt to current or expected climate changes*, in a way that minimizes their harmful effects or takes advantage of the opportunities they may create.

Resilience to climate change needs to be strengthened across biophysical, economic and social spheres, worldwide. To some degree, adaptation in agriculture will be a spontaneous response by farmers, fisherfolk and foresters; however, many of them, and especially small-scale producers, may face both a lack of feasible options and constraints to adopting appropriate solutions. An enabling environment that facilitates adaptation, therefore, is critical.

In the short term, adaptation at the level of the production unit or farm household, where possible, may be sufficient. However, longer-term adaptation is necessary in order to cope with the changes already "locked in" by past and ongoing increases in the concentration of greenhouse gases in the atmosphere. That will require more systemic changes, such as major shifts in the *loci* of production of specific products and species, compensated by changes in both trading and consumption patterns.

However, adaptation by itself is insufficient – mitigation is essential for ensuring the long-term food security of the world's population. There is a fundamental difference between adaptation and mitigation and the incentives needed to promote them. Adaptation is something everyone will want to do in their own interest. Mitigation is something that has to be done together, in the interests of everyone. It is a global public good and a social responsibility to which the agriculture sectors must also contribute.

The urgency – and benefits – of a concerted and effective global response to climate change is underscored by the very significant differences in impacts between even small temperature increases. A recent meta-analysis has found that reductions in water availability and increases in the length of dry spells accelerate between 1.5 °C and 2 °C for several sub-tropical regions, particularly the Mediterranean, Central America, the Caribbean, South Africa and Australia. In tropical regions, agricultural production is projected to be strongly affected if temperature increases beyond 1.5 °C (Table 1), and even more so if other factors – such as nitrogen and phosphorus limitations or heat stress – constrain the positive effects of CO_2 fertilization.

Under 2 °C warming, the risks posed by extreme heat to crop yields in tropical regions of Africa and South and Southeast Asia become particularly critical, given projected trends in their population growth. Other important benefits of limiting temperature increases to 1.5 °C include a significant reduction in areas of coral reefs at risk of severe degradation, and a 30 percent reduction in sea level rise (Schleussner *et al.*, 2016). In fact, a key message of the UNFCCC's structured expert dialogue, concluded in 2015, was that an increase in the global temperature[1] of 2 °C above pre-industrial levels is "an upper limit, a defence line that needs to be stringently defended, while less warming would be preferable" (UNFCCC, 2015). The IPCC will present in 2017 the findings of an assessment of the differences between 2 °C and 1.5 °C scenarios.

The UNFCCC's Paris Agreement of December 2015 has set the long-term goal of holding the increase in global average temperature to "well below 2 °C" above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C, recognizing that this would significantly reduce the risks and impacts of climate change. The IPCC reports that scenarios consistent with keeping temperature increase below 2 °C include substantial cuts in anthropogenic GHG emissions by mid-century, through large-scale changes in energy systems and, potentially, in land use. Scenarios that do not exceed the 2 °C limit set global GHG emission levels in 2050 at 40 to 70 percent lower than those in 2010, and near zero or below in 2100 (IPCC, 2014). If the growth in agriculture that is needed to ensure world food security in the future is attained with emissions growth similar to that of the recent past, the goal of keeping global temperature increase under 2 °C will be very difficult to achieve (see also, Searchinger *et al.*, 2015; Wollenberg *et al.*, 2016).

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1 Note: "Global temperature" is an average for the whole planet for a whole year. The Arctic region will warm more rapidly than the global mean, and mean warming over land will be larger than over the ocean. There will be more frequent episodes of high temperature extremes over most land areas (IPCC, 2014).

TABLE 1

CLIMATE IMPACTS ON SELECTED CROP YIELDS, GLOBALLY AND IN TROPICAL AREAS, UNDER WARMING OF 1.5 °C AND 2 °C ABOVE PRE-INDUSTRIAL LEVELS OVER THE 21ST CENTURY

Crop	Region	Increase over pre-industrial temperatures (percent)	
		1.5 °C	2.0
Wheat	Global	2 (−6 to +17)	0 (−8 to +21)
	Tropical	−9 (−25 to +12)	−16 (−42 to +14)
Maize	Global	−1 (−26 to +8)	−6 (−38 to +2)
	Tropical	−3 (−16 to +2)	−6 (−19 to +2)
Soybean	Global	7 (−3 to +28)	1 (−12 to +34)
	Tropical	6 (−3 to +23)	7 (−5 to +27)
Rice	Global	7 (−17 to +24)	7 (−14 to +27)
	Tropical	6 (0 to +20)	6 (0 to +24)

Note: The figures in parentheses indicate a likely (66 percent) confidence interval.
SOURCE: Adapted from Schleusner *et al.* (2016), Figure 15.

BOX 3

AGRICULTURE IS PROMINENT IN GUIDES TO COUNTRY-LEVEL ACTION

Adaptation and mitigation objectives in agriculture, land use, land-use change and forestry figure prominently in the Intended Nationally Determined Contributions (INDCs) which, under the Paris Agreement of December 2015, will guide country-level action on climate change in the coming years. They include not only targets, but also concrete strategies for addressing the causes of climate change and responding to its consequences.

An FAO analysis of the INDCs shows that, in all regions, agriculture will play a pivotal role in accomplishing the goals related to climate change by 2030. Of the 188 countries that submitted INDCs, more than 90 percent included agriculture as a sector considered for mitigation and adaptation initiatives.

The analysis also shows that the agriculture sectors are expected to provide the greatest number of opportunities for adaptation-mitigation synergies, as well as socio-economic and environmental co-benefits. Around one third of all countries acknowledge (and in some cases prioritize) actions that would create synergies between mitigation and adaptation in agriculture. Almost 30 percent of countries mention social, economic and environmental co-benefits, particularly rural development and health, poverty reduction and job creation, and the conservation of ecosystems and biodiversity. With regard to gender equality, agriculture is highlighted as a sector which – more than any other – provides diverse opportunities for empowering women as well as reducing their vulnerability to climate change.

SOURCE: FAO, 2016.

» Decisions taken today will determine the kind of world we will live in 15 years from now, and beyond. The agriculture sectors must respond, therefore, by building resilience to the impacts of climate change, while contributing to the extent possible to mitigation efforts. Responses must be designed in line with the national development objectives and priorities of different countries, and must not in themselves jeopardize efforts to reduce food insecurity. In this context, it is important to note that, unlike other economic sectors where adaptation and mitigation actions are generally independent of each other, in the agriculture sectors there are synergies – but also a need to accept trade-offs – among the objectives of food security, adaptation and mitigation. ■

THE SPECIAL ROLE AND RESPONSIBILITY OF AGRICULTURE

An agricultural response to climate change

Implementing an effective, sustained response to climate change in agriculture – in terms of both adaptation and mitigation – will be far more difficult than in most, if not all, other sectors, owing to its dependence on biophysical processes and the enormous range of agro-ecological and socio-economic conditions. A further complicating factor is the large number of actors involved – hundreds of millions of farmers, fisherfolk and forest-dependent populations, many of whom are poorly linked to markets, information and public services. This diversity calls for different and often extremely context-specific solutions. The agriculture sectors are likely, therefore, to be slower than others in adjusting, and a significant degree of inertia in the system is to be expected. This only adds to the urgency of taking action now.

The vulnerability of agriculture to climate change has not always received the attention it deserves. Assessments of climate change impacts, using mainly global economic models, have tended to overlook the impacts on agriculture because of its declining contribution, globally, to gross domestic product (GDP). Today, the importance of an agriculture response to climate change is widely recognized. This awareness is reflected clearly in the Intended Nationally Determined Contributions (INDCs) submitted by countries in the lead-up to the 21st Conference of Parties to the UNFCCC in Paris in 2015 (Box 3). The INDCs are discussed in more detail in Chapter 5.

There is also increasing recognition that agriculture has a special role to play in climate change mitigation. Scenarios indicate that limiting the global temperature increase to 2 °C can only be achieved by reducing GHG emissions from energy, industry and transport to zero, and limiting emissions from agriculture, land use and land-use change. The agriculture sectors can contribute to mitigation, first, by reducing their emission intensity (or the quantity of emissions per unit of product), and avoiding the further loss of carbon stored principally in forests and soil. This effort can be complemented by actions aimed at reducing food losses and waste, and changing food consumption patterns. In addition, the agriculture sectors have a unique potential to act as carbon sinks, which capture carbon dioxide and sequester carbon in biomass and soils, through forestry and land restoration (see Chapter 4).

A key challenge in framing climate change responses is to ensure that they do not jeopardize food security or progress in poverty reduction, particularly in countries with persistent, high levels of hunger and poverty. This is recognized in the preamble to the UNFCCC, which affirms that "responses to climate change should be coordinated with social and economic development in an integrated manner with a view to avoiding adverse impacts on the latter, taking into full account the legitimate priority needs of developing countries for the achievement of sustained economic growth and the eradication of poverty" (UNFCCC, 1992). Similarly, the preamble to the Paris Agreement, concluded in December 2015, recognizes "the fundamental priority of safeguarding food security and ending hunger, and particular vulnerabilities of food production systems to the adverse impacts of climate change" (UNFCCC, 2015).

Climate-smart agriculture

The responses to climate change that are to be applied in different countries must be seen in the broader context of sustainable agricultural development, and will reflect countries' individual priorities for achieving it. The FAO approach to sustainable food and agriculture recognizes that countries will pursue multiple objectives across the economic, social and environmental dimensions of sustainability, and will need to balance trade-offs between objectives and between short-term and long-term needs (Box 4). Such trade-offs will differ among countries, depending on natural resource endowments, socio-economic characteristics, political systems and stages of development. Similarly, countries will have different priorities, according to their specific circumstances, which need to be taken into account when designing climate change responses.

More specifically for managing agriculture for food security under the changing realities of global warming, FAO has developed the "climate-smart agriculture" (CSA) approach, which it presented in 2010 at The Hague Conference on Agriculture, Food Security and Climate Change (FAO, 2010). The principles of CSA implicitly underpin and guide this report as well as the responses to climate change envisaged for the food and agriculture sectors.

The CSA approach has three objectives: sustainably increasing agricultural productivity to support equitable increases in incomes, food security and development; increasing adaptive capacity and resilience to shocks at multiple levels, from farm to national; and reducing greenhouse gas emissions and increasing carbon sequestration where possible.

Since local conditions vary, an essential feature of CSA is to identify the impacts of agricultural intensification strategies on food security, adaptation and mitigation in specific locations. This is particularly important in developing countries, where agricultural growth is generally a top priority. Often, but not always, practices with strong adaptation and food security benefits can also lead to reduced GHG emissions or increased carbon sequestration. However, implementation of these synergistic practices may entail higher costs, particularly for up-front financing. Therefore, CSA programmes include capacity development for local stakeholders to assist them in tapping into sources of funding for agricultural and climate-related investment. Not every practice applied in every location will, can or even should generate "triple wins"; but all three objectives must be considered in order to arrive at locally acceptable solutions that reflect local or national priorities.

The point of departure for the CSA analysis is the technologies and practices that countries have already prioritized in their agricultural policy and planning. Information on recent and near-term projected climate change trends is used to assess the food security and adaptation potential of these technologies and practices under *site-specific* climate change conditions, and to determine what adjustments may be needed. Examples of such adjustments include: modifying planting times and adopting varieties resistant to heat and drought; developing new cultivars; changing the farm portfolio of crops and livestock; improving soil and water management practices, including conservation agriculture; integrating the use of climate forecasts into cropping decisions; expanding the use of irrigation; increasing regional farm diversity; and shifting to non-farm livelihood sources (Asfaw *et al.*, 2014; Branca *et al.*, 2011; FAO, 2010; FAO, 2013).

Since the introduction of climate-smart agriculture, there has been growing support at international and national levels for adoption of the approach. In their INDCs, more than 30 countries, most prominently in sub-Saharan Africa, specifically refer to CSA (see Chapter 5). ■

BOX 4

A COMMON VISION OF SUSTAINABLE FOOD AND AGRICULTURE

The FAO common vision of sustainable food and agriculture (SFA) is highly relevant to the design of climate change adaptation and mitigation measures. In the SFA approach, agricultural practices and technologies are evaluated according to how closely they adhere to five key principles that should guide the global transition to sustainability:

- Improving the efficiency of natural resource use;
- Conserving, protecting and enhancing natural resources;
- Improving and protecting rural livelihoods and social well-being;
- Enhancing the resilience of people, communities and ecosystems;
- Promoting and improving effective governance.

These principles are designed to ensure a coherent and uniform approach to achieving SFA across agriculture sectors and subsectors. The approach creates synergies and recognizes trade-offs among and within the different social, economic and environmental dimensions of sustainability, as well as across sectors, over time and space, in a continuously evolving process.

SOURCE: FAO, 2014.

STRUCTURE OF THIS REPORT

This year's edition of *The State of Food and Agriculture* explores in-depth the relationships between climate change, agriculture and food security and describes how the agriculture sectors can respond effectively to climate change through both adaptation and mitigation. The whole food supply chain, from producer to consumer, is affected by – and contributes to – climate change, sometimes to a larger extent than primary agriculture itself. However, the main focus of this report will be on the primary agriculture sectors: crops, livestock, fisheries and forestry. The remainder of this report is organized as follows:

CHAPTER 2 reviews the empirical evidence of the current and expected future impacts of climate change on the agriculture sectors, food security and nutrition in different parts of the world under different global warming scenarios. It further assesses how and to what extent current agricultural production and food systems are contributing to climate change.

CHAPTER 3 looks at the special challenge of adaptation to climate change in small-scale family farming and small-scale production systems. It suggests feasible pathways for farm households and others dependent on such systems to build greater resilience through adaptation and diversification strategies that also improve their livelihoods and, therefore, contribute to ending hunger and rural poverty.

CHAPTER 4 discusses how the agriculture sectors can respond to climate change to the benefit of both food security and climate stabilization. Key responses aim at reducing emission-intensity in agriculture and food systems, and maximizing co-benefits from adaptation and mitigation efforts, through better management of carbon and nitrogen cycles, increased resource-use efficiency, the conservation of carbon-rich landscapes, measures to strengthen resilience and – on the demand side – a reduction in food losses and improvements in diets.

CHAPTER 5 discusses the design of policies to ensure an effective climate change response by governments and agricultural sector stakeholders.

CHAPTER 6 presents ways of leveraging climate finance – and, more broadly, development finance – to support adaptation and mitigation objectives in agriculture.

CHAPTER 2

CLIMATE, AGRICULTURE AND FOOD SECURITY: A CLOSER LOOK AT THE CONNECTIONS

SIEM REAP, CAMBODIA
Participatory natural resource management in the Tonle Sap region.
©FAO/J. Thompson

TEROKHADA, BANGLADESH
Intentional flooding of rice fields can increase their productivity and reduce farmers' vulnerability to drought, floods and tidal waves.
©FAO/M. Zaman

KEY MESSAGES

1 **UNTIL ABOUT 2030, GLOBAL WARMING IS EXPECTED TO LEAD TO BOTH GAINS AND LOSSES** in the productivity of crops, livestock, fisheries and forestry, depending on places and conditions.

2 **BEYOND 2030, THE NEGATIVE IMPACTS OF CLIMATE CHANGE ON AGRICULTURAL YIELDS** will become increasingly severe in all regions.

3 **IN TROPICAL DEVELOPING REGIONS**, adverse impacts are already affecting the livelihoods and food security of vulnerable households and communities.

4 **BECAUSE AGRICULTURE, LAND-USE AND FORESTRY** make a considerable contribution to greenhouse gas emissions, they have significant mitigation potential.

CHAPTER 2

CLIMATE, AGRICULTURE AND FOOD SECURITY: A CLOSER LOOK AT THE CONNECTIONS

This chapter examines in detail the linkages between climate change, agriculture and food security. It discusses the biophysical impacts of climate change on the agriculture sectors and how they translate into socio-economic impacts with consequences for food security and nutrition. It also reviews how greenhouse gas emissions and removals from the agriculture sectors contribute to climate change. The implication is that the agriculture sectors need to both adapt to climate change by building resilience and contribute to climate change mitigation. ■

CASCADING IMPACTS FROM CLIMATE TO PEOPLE

The IPCC's Fifth Assessment Report confirms the main findings of its previous reports on the evolution of the world's climate, the expected changes – such as increases in temperature, rainfall variability and extreme weather events – and the main biophysical impacts of global warming, such as sea-level rise, ocean acidification, reductions in the extent of glaciers, the degradation of ecosystems, increased risks of fires and insect pest upsurges. As well as providing a better understanding of potential changes in precipitation, the report uses improvements in modelling and data collection to make better medium-term projections. Accordingly, the cascading impacts of climate change can now be attributed along chains of evidence from physical climate through to intermediate systems and then to people (Kirtman *et al.*, 2014).

Climate change profoundly affects the conditions under which agricultural activities are conducted. In every region of the world, plants, animals and ecosystems have adapted to prevailing climatic conditions. As those conditions change, they will be affected in ways that are difficult to predict precisely. Several studies document the biophysical impacts of the expected changes specifically on agroecosystems (Box 5). The impacts range from yield reductions and increased yield variability to displacement of crops and the loss of agrobiodiversity and ecosystem services. Most, but not all, of the impacts of climate change on agriculture are expected to be negative. All the agriculture sectors – crops, livestock, fisheries and forestry – will be affected in different ways.

Climate change already affects the agriculture sectors in many parts of the world, and its impacts will be amplified in the years and decades ahead. A large body of evidence points to a prevalence of negative outcomes, with many agricultural systems becoming less productive and some plant and animal species disappearing. Those changes will have direct effects on agricultural production, which will have economic and social consequences and finally impacts on food security (Figure 3). The impacts will be transmitted through different channels and will affect food security in all four of its dimensions: access, availability, utilization and stability. At each stage of the transmission chain, the severity of impact will be determined by both the shock itself and by the vulnerability of the system or population group under stress (FAO, 2016a). ■

BOX 5

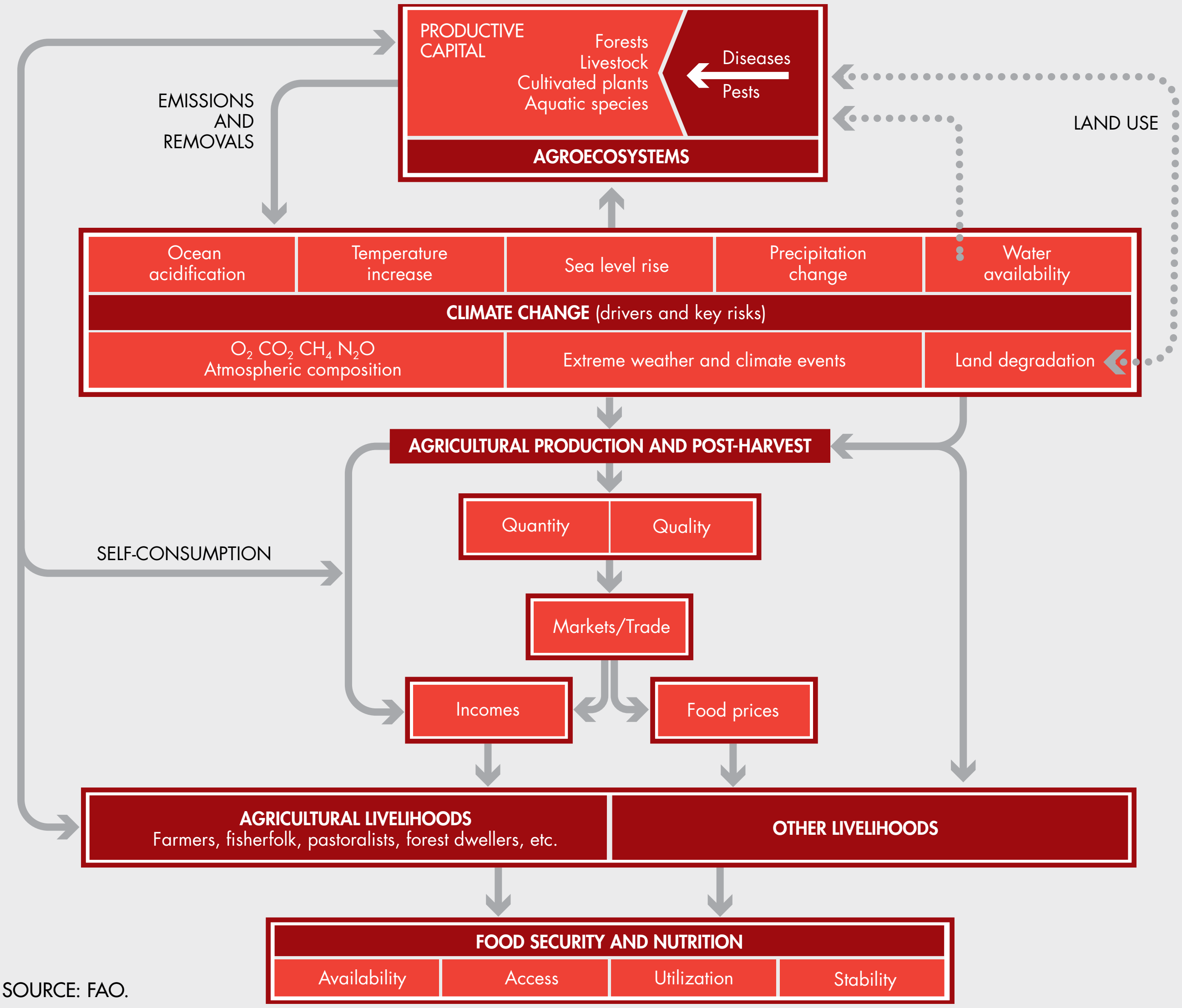
SUMMARY OF CLIMATE CHANGE IMPACTS ON AGRICULTURE

- Increased frequency and intensity of extreme climate events such as heat waves, droughts and floods, leading to loss of agricultural infrastructure and livelihoods
- Decrease in fresh water resources, leading to water scarcity in arable areas
- Sea-level rise and coastal flooding, leading to salinization of land and water, and risks to fisheries and aquaculture
- Water and food hygiene and sanitation problems
- Changes in water flows impacting inland fisheries and aquaculture
- Temperature increase and water scarcity affecting plant and animal physiology and productivity
- Beneficial effects on crop production through carbon dioxide "fertilization"
- Detrimental effects of elevated tropospheric ozone on crop yields
- Changes in plant, livestock and fish diseases and in pest species
- Damage to forestry, livestock, fisheries and aquaculture
- Acidification of the oceans, with extinction of fish species

SOURCES: Adapted from Tirado *et al.* (2010) and updated using Porter *et al.* (2014), HLPE (2012) and IPCC (2014).

FIGURE 3

IMPACT PATHWAYS: FROM CLIMATE CHANGE TO FOOD SECURITY



SOURCE: FAO.

IMPACTS ON AGRICULTURE

Climate change affects the agriculture sectors in a multitude of ways, which vary from region to region (Table 2). For example, it increases temperature and precipitation variability, reduces the predictability of seasonal weather patterns and increases the frequency and intensity of severe weather-related events such as floods, cyclones and hurricanes. Some regions are expected to face prolonged drought and water shortages. The widespread melting of glaciers and snow cover in major mountain ranges, particularly in Asia, will affect the volume and timing of water flows, ultimately reducing the availability of irrigation water downstream. Increasing temperatures lead to changes in the location and incidence of pest and disease outbreaks. Even slight warming will decrease yields in low-latitude regions. Greater frequency and intensity of extreme weather events, such as the El Niño-Southern Oscillation, will increasingly affect climate patterns and food production (Box 6).

Crops

Climate change impacts on the yields of major crops is probably the food security related issue on which there are the most studies. A wide literature on observed and projected impacts on yields includes more than two decades of work since the global assessment by Rosenzweig and Parry (1994) of the potential impact of climate change on world food supply; some other key studies are Parry, Rosenzweig and Livermore (2005), Cline (2007), World Bank (2010), and Rosenzweig *et al*. (2014). Most studies are limited to major crops, and the effects of climate change on many other important crops are much less known.

The observed effects of past climate trends on crop production are evident in several regions of the world (Porter *et al.*, 2014), with negative impacts being more common than positive ones. There is evidence that climate change has already negatively affected wheat and maize yields. Widely cited estimates show that over the period 1980 to 2008 there was a 5.5 percent drop in wheat yields and a 3.8 percent drop in maize yields globally, compared to what they would have been had climate remained stable (Lobell, Schlenker and Costa-Roberts, 2011).

The precise future effects of climate change on crop yields are very difficult to predict and will depend on many parameters. These include: physical ones, such as temperature, precipitation patterns and CO_2 fertilization; changes in agroecosystems (e.g. through loss of pollinators and increased incidence of pest and diseases); and the adaptive responses of human systems. Effects of temperature changes are generally well understood up to the optimum temperature for crop development; however, beyond these optimum temperatures, effects are much less known. Recent results have confirmed the damaging effects of elevated tropospheric ozone on yields, with estimates of losses for soybean, wheat and maize in 2000 ranging from 8.5 to 14 percent, 3.9 to 15 percent, and 2.2 to 5.5 percent respectively (Porter *et al.*, 2014). Several other possible impacts of climate change on the functioning of ecosystems – such as the balance between crops and pests, and effects on pollinators – are difficult to assess and are generally not taken into account by the models used to make projections of crop yields.

Within certain limits, a changing climate could have both positive and negative effects on crops. Indeed, increases in temperatures and levels of carbon dioxide in the atmosphere may be beneficial for some crops in some places. Yields of wheat and soybeans, for example, could increase with increased CO_2 concentrations under optimal temperatures. However, while projections of future yields vary according to the scenario, model and time-scale used, there is consistency in the main expected directions of change: yields suffer more in tropical regions than at higher latitudes and impacts are more severe with increased warming (Porter *et al.*, 2014).

Importantly, the IPCC Fifth Assessment Report provides new evidence that crop yields are expected to decline in areas that already suffer food insecurity. It presents projected estimates of changes in crop yields owing to climate change over the 21st century (Figure 4). The data used include results from 91 studies with 1 722 estimates of changes in crop yields by Challinor *et al.*, 2014. There are wide variations among the studies, in terms of time-frame, crop coverage, crop and climate models, and emission levels. Some studies include the effects of adaptation measures, but others do not. The scales and geographical coverage also vary, with some estimates being for localities while others are national, regional or global.

In spite of the heterogeneity of the studies, their long-term projections clearly point to a prevalence of negative outcomes. They show that in the medium term – that is, until about 2030 – the positive and negative effects on yields could offset each other at the global level, the balance after this date would be increasingly negative as climate change accelerates. The data also show that projected impacts of climate change on yields of maize, wheat and rice in the second half of the 21st century are more often negative for tropical regions than for temperate regions. However, in many locations in temperate regions, as well, crop yields may decrease (Porter *et al.*, 2014 and Challinor *et al.*, 2014).

Further analysis of the same data, undertaken by FAO for this report, reveals quite distinct patterns for developing and developed countries. For the developing countries, most estimates for crop yield impacts are negative, with the share of negative estimates increasing the further into the future the study projects (Figure 5). Compared with developing countries, estimates for developed countries show a much larger share of potential positive changes (Figure 6).[2]

2 In the datasets analysed, more estimates are available for developing countries than developed countries. Among the developing regions, the largest number of estimates is for locations in sub-Saharan Africa, followed by East Asia and the Pacific, and South Asia. A smaller share of estimates is provided for locations in Latin America and the Caribbean, North Africa and West Asia. In terms of crops, most estimates are for maize or wheat yields, followed by rice and soybean. For most country groups, the number of projections for 2090–2109 is very limited: only five for the developed countries and 16 for developing countries; all of the 16 projections for developing countries refer to sub-Saharan Africa, and all suggest declines in crop yields of more than 10 percent. However, they are derived from only two studies.

Other estimates of the impact of climate change on crop yields are provided by the recent consolidated study conducted in the framework of the Agricultural Model Intercomparison and Improvement Project (AgMIP) and the Inter-Sectoral Impact Model Intercomparison Project. Both point to dramatic long-term impacts, compared to a world without climate change and in the absence of climate change mitigation.[3] The impact on yields by the year 2100 under high-emission climate scenarios ranges between -20 and -45 percent for maize, between -5 and -50 percent for wheat, between -20 and -30 percent for rice, and between -30 and -60 percent for soybean (Rosenzweig *et al.*, 2013). Assuming the full effectiveness of CO_2 fertilization, climate change impacts on yields are reduced to a range of between -10 and -35 percent for maize, between +5 and -15 percent for wheat, between -5 and -20 percent for rice, and between 0 and -30 percent for soybean. If limits on access to nitrogen are explicitly considered, crops benefit less from CO_2 fertilization and negative climate impacts are amplified (Müller and Elliott, 2015).

Livestock

Climate change affects livestock production in multiple ways, both directly and indirectly (Table 2). The most important impacts are on animal productivity, animal health and biodiversity, the quality and amount of feed supply, and the carrying capacity of pastures. Increasing variability in rainfall leads to shortages of drinking water, an increased incidence of livestock pests and diseases, and changes in their distribution and transmission. It also affects the species composition of pastures, pasture yields and forage quality.

Continues on page 28 »

3 The Agricultural Model Intercomparison and Improvement Project is a framework linking climate, crops, livestock and economics. It provides analyses at field-to-regional scales and includes simulations with guided climate sensitivity tests and climate change scenarios. Protocols of AgMIP have helped to narrow the uncertainty and understand the reasons for differences in modelling outcomes and projections of climate change impacts on food security.

TABLE 2

SELECTED POTENTIAL IMPACTS OF CLIMATE CHANGE, BY REGION

	NORTH AMERICA	LATIN AMERICA AND THE CARIBBEAN	EUROPE
CROPS AND LIVESTOCK	‣ Yields of major crops decline modestly by mid-century but more steeply by 2100 ‣ Climate favours fruit production in the Great Lakes region, while late season heat stress challenges US soybean yields ‣ Reduced precipitation restricts water availability as irrigation demand increases ‣ Heat stress and lower forage quality reduce milk production and weight gain in cattle	‣ In temperate areas, soybean, wheat and pasture productivity increases ‣ Drier soils and heat stress reduce productivity in tropical and subtropical regions ‣ Increased salinization and desertification in arid zones of Chile and Brazil ‣ Rainfed agriculture in semi-arid zones faces higher crop losses	‣ Temperate and polar regions benefit from changes ‣ Initial benefits in mid-latitude countries turn negative with higher temperatures ‣ Climate-induced variability in wheat production increases in Southern and Central Europe ‣ High temperatures and humidity increase livestock mortality risk
FISHERIES AND AQUACULTURE	‣ Many warm- and cool-water species move to higher latitudes ‣ Arctic freshwaters experience the greatest warming and most negative impacts ‣ Warmer waters and lower water quality increase disease risks to North Atlantic cetaceans and tropical coral reefs	‣ Primary production in the tropical Pacific declines and some species move southwards ‣ More frequent storms, hurricanes and cyclones harm Caribbean aquaculture and fishing ‣ Changes in freshwater fish species physiology, collapse of coral reef systems	‣ Warming displaces some fish populations northwards or to deeper waters ‣ Invasive tropical species alter coastal ecosystems in southern Europe's semi-enclosed seas ‣ Aquaculture impacted by sea-level rise, acidification, temperature increases
FORESTRY	‣ Pine forest pest damage increases with higher spring temperatures ‣ Warmer summers boost forest fire risk by up to 30 percent ‣ Warmer winters favour bark beetles responsible for forest die-off	‣ Tropical forests are affected more by changes in the water availability and CO_2 fertilization than by temperature changes ‣ In Amazonia, increased risk of frequent fires, forest loss and "savannization" ‣ In Central America, 40 percent of mangrove species are threatened with extinction	‣ In Northern and Atlantic Europe, higher temperatures and atmospheric CO_2 levels increase forest growth and wood production ‣ Shrubs increasingly replace trees in Southern Europe ‣ An increase in wildfires leads to a significant increase in greenhouse gas emissions

SOURCE: Compiled from IPCC (2007, 2014) and FAO (2011, 2016c).

- Overall impacts on yields of cereals, especially maize, are negative across the region
- The frequency of extremely dry and wet years increases
- Much of southern Africa is drier, but rainfall increases in East and West Africa
- Rangeland degradation and drought in the Sahel reduce forage productivity

- Sea-level rise threatens coastlands, especially in West Africa
- By 2050, declining fisheries production in West Africa reduces employment in the sector by 50 percent
- East African fisheries and aquaculture are hit by warming, oxygen deficit, acidification, pathogens
- Changes along coasts and deltas (e.g. death of coral reefs) impact productivity

- Deforestation, degradation and forest fires affect forests in general
- Forest losses reduce wildlife, bush meat and other non-wood forest production
- Water scarcity affects forest growth more than higher temperatures

- Rising temperatures threaten wheat production in North Africa and maize yields region-wide
- There is a general decline in water availability, but a slight increase in Sudan and southern Egypt
- In mid-latitudes, higher temperatures lead to richer pastures and increased livestock production
- Warmer winters benefit livestock, but summer heat stress has negative impacts

- Usable water resources in many Mediterranean and Near East basins decline further
- Warming boosts productivity in the Arabian Sea
- Catch potential falls by as much as 50 percent in some parts of the Mediterranean and Red Seas

- Soil moisture depletion reduces the productivity of major forest species, increases fire risk, and changes pest and disease patterns
- In the Near East, declining summer rains lead to severe water shortages that affect forest growth

- Agricultural zones shift northwards as freshwater availability declines in South, East and Southeast Asia
- Higher temperatures during critical growth stages cause a decline in rice yields over a large portion of the continent
- Demand for irrigation water increases substantially in arid and semi-arid areas
- Heat stress limits the expansion of livestock numbers

- Coastal flooding seriously affects capture fisheries and aquaculture in large river deltas
- A general decline in coastal fisheries production and greater risk of extreme events in the aquatic systems
- Redistribution of marine capture fisheries, with numbers declining in the tropics
- Freshwater aquaculture faces major risks of freshwater scarcity
- By 2050, the body weight of marine fish falls by up to 24 percent

- Boreal forests and Tibetan plateau alpine vegetation shift northwards
- Many forest species face extinction owing to combined effects of climate change and habitat fragmentation
- A general increase in the frequency and extent of forest fires and the risk of invasive species, pests and diseases

- In New Zealand, wheat yields rise slightly but animal production declines by the 2030s
- In Australia, soil degradation, water scarcity and weeds reduce pasture productivity
- In the Pacific islands, farmers face longer droughts but also heavier rains
- Higher temperatures increase the water needs of sugarcane

- Changes in water temperature and currents increase the range of some pelagic species, reduce that of others
- Changes in water temperature and chemistry strongly affect fisheries and aquaculture
- Nutrient decline reduces krill populations along Australia's east coast
- Small island states, highly exposed and highly reliant on fisheries, suffer most

- Productivity increases owing to CO_2 fertilization are counterbalanced by the effects of rising temperatures and reduced rainfall
- In the Pacific, extreme weather events damage mangrove forests

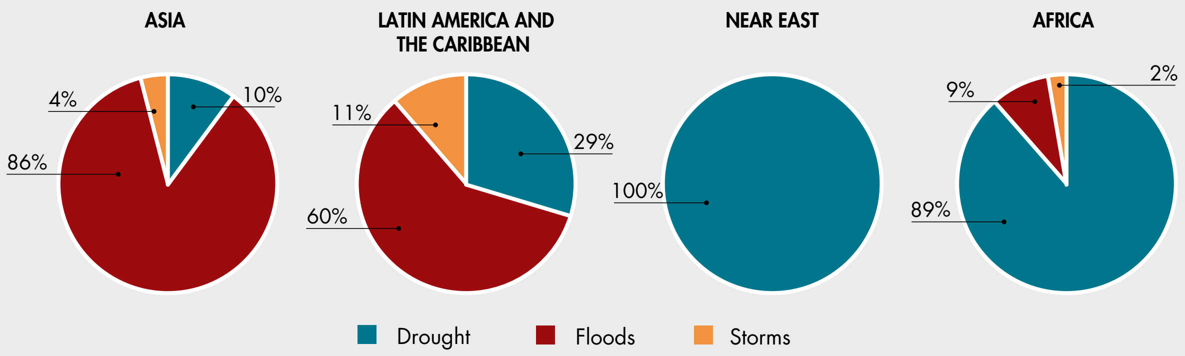
BOX 6

THE IMPACTS OF EXTREME CLIMATE EVENTS

The El Niño-Southern Oscillation is an increase in surface temperatures in the tropical Pacific Ocean, which occurs roughly every two to seven years and lasts from six to 24 months. Its effects can include huge increases in rainfall, tropical cyclones, drought, forest fires, floods and other extreme weather events worldwide. The current El Niño has been one of the most intense and widespread of the past 100 years. It has harmed crop and livestock production, and agricultural livelihoods around the globe, threatening the food security and nutrition of 60 million people (FAO, 2016b).

Extreme weather events are of major significance to agriculture. An FAO study estimated that, between 2003 and 2013, some 25 percent of the total economic impact of climate-related disasters in developing countries was felt in agriculture; when only drought is considered, the share rises to 84 percent (FAO, 2015). The types of hazard vary widely by region (see Figure).

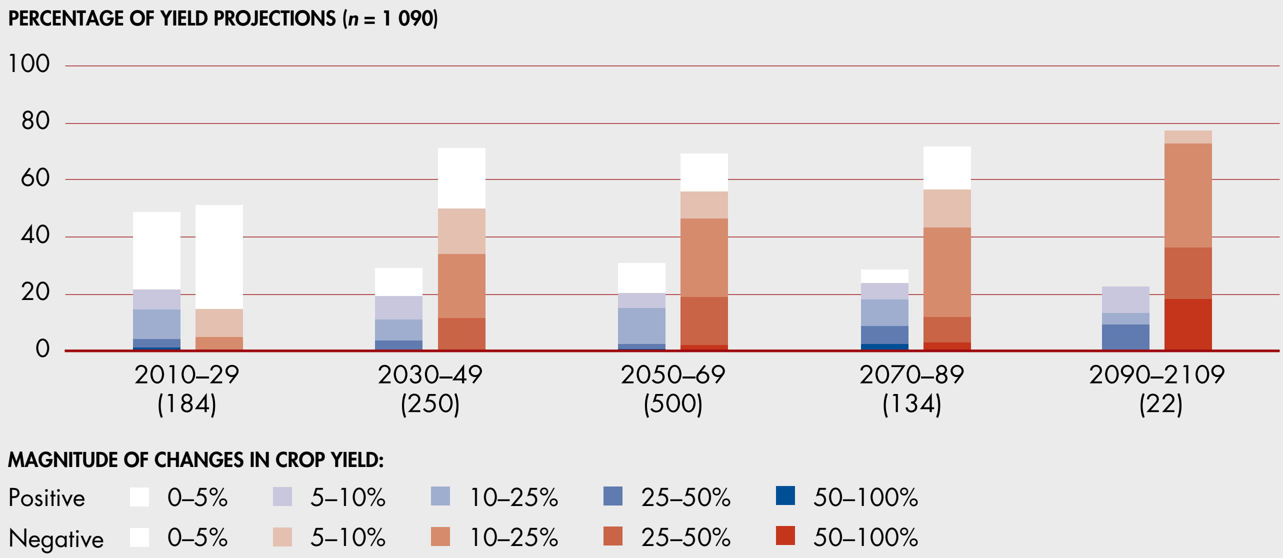
CROP AND LIVESTOCK PRODUCTION LOSSES AFTER MEDIUM- TO LARGE-SCALE, CLIMATE-RELATED DISASTERS, BY TYPE OF HAZARD, 2003–13



SOURCE: FAO, 2015.

FIGURE 4

PROJECTED CHANGES IN CROP YIELDS FOR ALL LOCATIONS WORLDWIDE OWING TO CLIMATE CHANGE

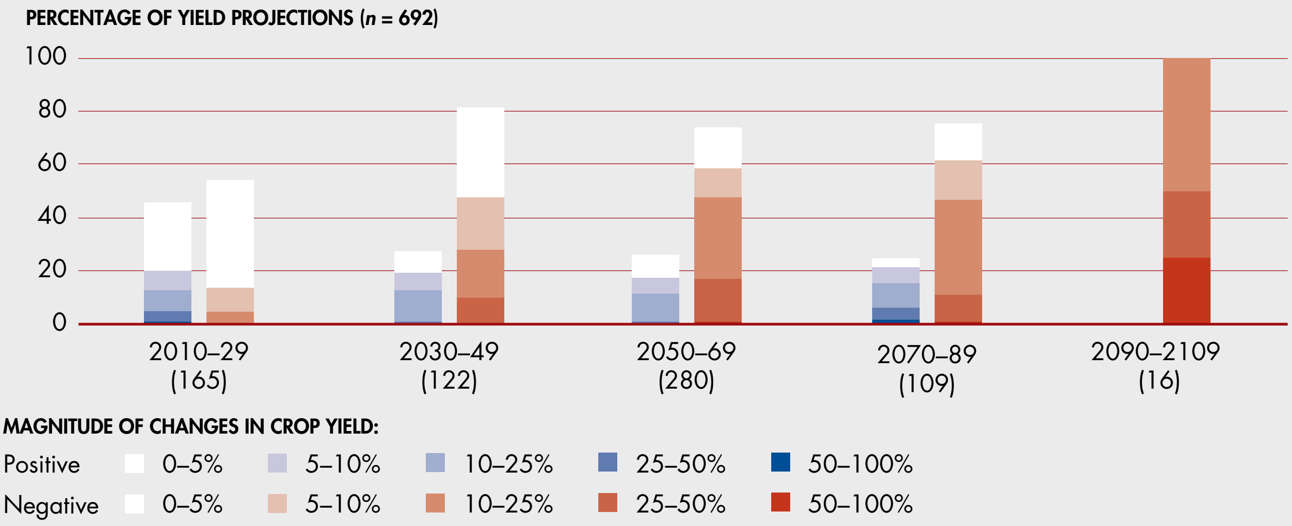


Note: Number of estimates of change in crop yield is shown in parentheses.

SOURCES: Data are the same as those used in Porter *et al.* (2014) and Challinor *et al.* (2014). See Annex table A.1 for details. An updated version of the data is available at CGIAR, CCAFS and University of Leeds (2016).

FIGURE 5

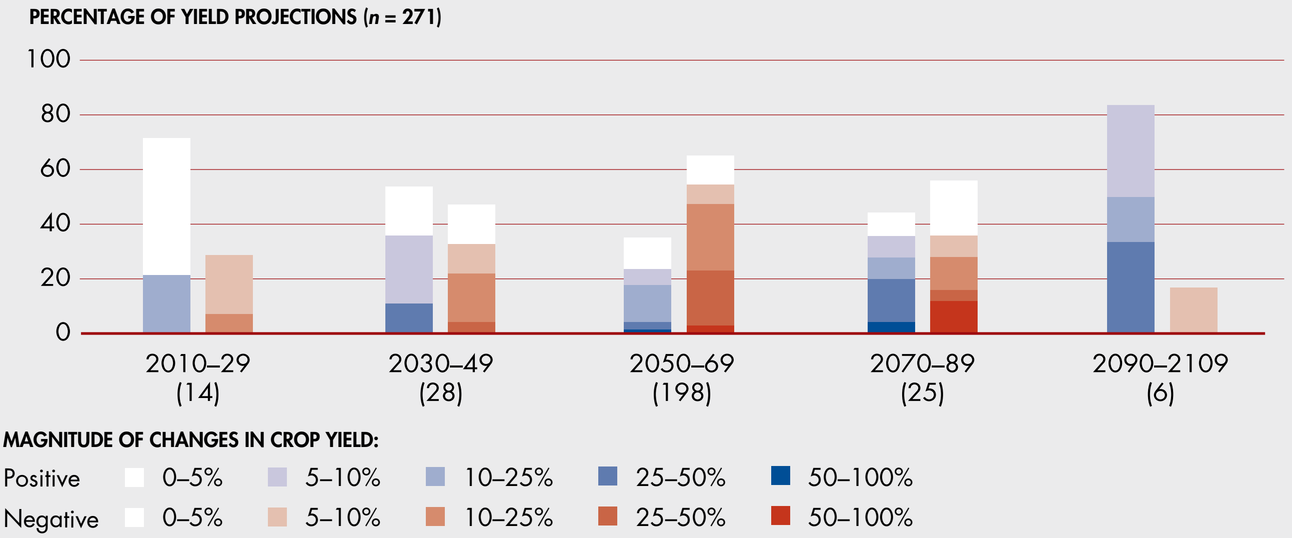
PROJECTED CHANGES IN CROP YIELDS IN DEVELOPING REGIONS OWING TO CLIMATE CHANGE



Notes: Number of estimates of change in crop yield is shown in parentheses. Developing regions include all observations from locations in developing regions of Africa, Latin America, Oceania and all of Asia other than Central Asia. See Annex table A1 for details.
SOURCES: See Figure 4.

FIGURE 6

PROJECTED CHANGES IN CROP YIELDS IN DEVELOPED REGIONS OWING TO CLIMATE CHANGE



Notes: Number of estimates of change in crop yield is shown in parentheses. Developed regions include all observations from locations in developed regions such as Europe, Northern America and Australasia. See Annex table A.1 for details.
SOURCES: See Figure 4.

» *Continued from page 23*

Higher temperatures cause heat stress in animals, which has a range of negative impacts: reduced feed intake and productivity, lower rates of reproduction and higher mortality rates. Heat stress also lowers animals' resistance to pathogens, parasites and vectors (Thornton *et al.*, 2009; Niang *et al.*, 2014). Multiple stressors greatly affect animal production, reproduction and immune status. Research in India found that a combination of climate-related stresses on sheep – for example, excessive heat and lower nutritional intake – had severe impacts on the animals' biological coping mechanisms (Sejian *et al.*, 2012).

The effects of higher temperatures may be reduced in intensive cattle, pig and poultry production units, through climate control (Thornton *et al.*, 2009), provided appropriate housing and energy are available. However, projected drier conditions in the extensive rangelands of southern Africa would increase water scarcity; in Botswana, the costs of pumping water from boreholes increases 23 percent by 2050. In the Near East, declining forage quality, soil erosion and water scarcity will most likely be exacerbated in the semi-arid rangelands (Turral, Burke and Faurès, 2011).

Impacts of climate change on animal health are also documented, especially for vector-borne diseases, with rising temperatures favouring the winter survival of vectors and pathogens. In Europe, global warming is likely to increase sheep tick activity, and the risk of tick-borne diseases, in the autumn and winter months (Gray *et al.*, 2009). Outbreaks of Rift Valley fever in East Africa are associated with increased rainfall and flooding due to El Niño-Southern Oscillation events (Lancelot, de La Rocque and Chevalier, 2008; Rosenthal, 2009; Porter *et al.*, 2014).

Fisheries and aquaculture

Climate change, climate variability and extreme weather events compound threats to the sustainability of capture fisheries and aquaculture in marine and freshwater environments (Table 2). Small-scale fisheries in tropical, less developed and economically poor regions are particularly vulnerable to climate change impacts (Porter *et al.*, 2014). Fisheries and aquaculture systems are likely to suffer from higher impacts such as water temperatures, oxygen deficit, sea-level rise, decreased pH and changes in productivity patterns.

Various fish species are already migrating towards the poles. Models based on predicted changes in environmental conditions, habitat types and phytoplankton primary production forecast a large-scale redistribution of global marine fish catch potential, with an average 30 to 70 percent increase in high-latitude regions and a drop of up to 40 percent in the tropics (Cheung *et al.*, 2010).The production from inland fisheries and aquaculture is threatened by changes in precipitation and water management, increased stress on freshwater resources, and the frequency and intensity of extreme climate events (Brander, 2007; Porter *et al.*, 2014).

Coral reef systems, which sustain one out of four marine species, will be at increased risk owing to the dual pressure of rising temperatures and ocean acidification. Sea surface temperature fluctuations caused mass coral bleaching and mortality around Kiribati's Phoenix Islands in 2002–2003, leading to a decline in coral cover of about 60 percent (Alling *et al.*, 2007; Obura and Mangubhai, 2011). In October 2015, the United States National Oceanic and Atmospheric Administration declared the third global coral reef bleaching event; the previous two took place in 1998 and 2010. These global shocks, brought on by climate change, and coupled with events such as the El Niño phenomenon are the largest and most pervasive threats to coral reefs around the world (NOAA, 2015).

Forestry

Climate change and climate variability threaten the provision of a range of crucial goods and environmental services from forests (Table 2). They include the delivery of a clean and reliable water supply, protection against landslides, erosion and land degradation, provision or enhancement of the habitats of aquatic and terrestrial animals, provision of a range of wood and non-wood products for household use or sale, and the generation of employment.

Recent studies suggest that, in a wide range of forest systems, higher temperatures and changes in precipitation are increasing tree mortality through heat stress, drought stress and pest outbreaks (Allen *et al.*, 2010). Many areas of boreal forests have experienced biomass productivity declines that have been attributed to warming-induced drought (Williams *et al.*, 2013). Warming and drying, coupled with productivity decline, insect disturbance and associated tree mortality, also favour greater fire disturbance (Settele *et al.*, 2014).

The overall trend for temperate forests has until recently been an increase in growth rates, due to a combination of increases in the length of the growing season, higher atmospheric CO_2 and nitrogen deposition, and forest management (Ciais *et al.*, 2008). Models predict that the potential climatic space for most tree species will shift towards higher latitudes and altitudes, at a faster rate than natural migration.

For tropical forests, a key uncertainty is the impact of direct CO_2 effects on photosynthesis and transpiration. Moist tropical forests have many species that are vulnerable to drought- and fire-induced mortality. In addition, there is evidence that in many forests, including those of the Amazon, forest fire frequency and severity are increasing, due to a combination of land use change and drought. Climate change, deforestation, fragmentation, fire and human pressure place virtually all dry tropical forests at risk of replacement or degradation (Miles *et al.*, 2006). In Southeast Asia, increased inter-annual variability in forest fires owing to El Niño-induced droughts increases health risks, and the loss of biodiversity and ecosystem services (Marlier *et al.*, 2013). ■

IMPACTS ON INCOMES AND LIVELIHOODS

The effect of climate change on the production and productivity of the agriculture sectors will translate into mostly negative economic and social impacts, with implications for all four dimensions of food security. Climate change can reduce incomes at both the household and national levels. Given the high dependency on agriculture of hundreds of millions of poor and food-insecure rural people, the potential impacts on agricultural incomes – with economy-wide ramifications in low-income countries that are highly dependent on agriculture – are a major concern. By exacerbating poverty, climate change would have severe negative repercussions on food security.

Much uncertainty surrounds the future evolution of climate change, its precise impacts and the possible responses. The implications for the environment and society depend not only on the response of the Earth system to changes in atmospheric composition, but also on the forces driving those changes and on human responses, such as changes in technology, economies and lifestyle.

Assessing climate change impacts on agriculture requires integrated use of climate, crop, and economic models to take into account the reaction to changing conditions in the sector, including management decisions, land-use choices, international trade and prices, as well as consumers. For this reason, the climate research community has developed over the past two decades sets of scenarios that describe plausible future trajectories and represent many of the major driving forces that are important for informing climate change policy.

A variety of those scenarios have been used to analyse the impacts of climate change on agroecosystems, the agriculture sectors, socio-economic trends and ultimately food security. In order to ensure a better and more consistent analysis of future climate and its impacts, the

IPCC's Fifth Assessment Report adopted a set of Representative Concentration Pathways (RCPs), which are hypothetical climate scenarios based on the magnitude of global annual greenhouse gas emissions. The IPCC also helped catalyse the development of Shared Socio-economic Pathways (SSPs), which describe alternative development futures, to be used alongside the RCPs to analyse feedback between climate change and socio-economic factors (Box 7).

Nelson *et al.* (2014a) have designed a common protocol to compare results of a set of nine climate, crop, and economic models under the scenario RCP 8.5 (global annual GHG emissions continuing to rise throughout the 21st century), without accounting for CO_2 fertilization of crops. The authors compare the effects of the exogenous climate change shock on yields of four crop aggregates – coarse grains, oil seeds, wheat and rice – which account for about 70 percent of the global crop harvested area. The mean biophysical effect of the climate change shock on yields is a 17 percent decline. The economic models transfer the shock effect to the response variables. Producers respond to the price increases associated with the shock by both intensifying management practices, which leads to a final mean yield change of -11 percent, and increasing the cropping area by a mean of 11 percent.

The combined yield decline and area increase result in a mean decline in production of only 2 percent. Consumption declines slightly, with a mean decline of 3 percent. Changes in trade shares cancel out across regions, but the share of global trade in world production increases by 1 percent on average. Average producer prices increase by 20 percent. The direction of responses is common to all models, but the magnitude of responses varies significantly across models, crops and regions. Although the average consumption decline is relatively small, the price increases caused by the inelastic nature of global demand are likely to increase food costs significantly for the poor.

The key role of agriculture in supporting the livelihoods of the majority of the world's poor, and their particular vulnerability to climate change, was confirmed in a World Bank study, which compared worst-case and more optimistic scenarios with a scenario of no climate change (Hallegatte *et al.*, 2015). A scenario with high-impact climate change, rapid population growth and a stagnant economy indicated that an additional 122 million people would be living in extreme poverty by 2030 (Table 3). With the same level of climate change impacts, but with universal access to basic services, reduced inequality and extreme poverty affecting less than 3 percent of the world's population, the number of additional poor is projected to be just 16 million (Rozenberg and Hallegatte, 2015). Under the worst-case scenario, much of the forecast increase in the number of poor occurs in Africa (43 million) and South Asia (62 million). Reduced income in the agricultural sector explains the largest share of increased poverty as a result of climate change. This is because the most severe reductions in food production and increases in food prices occur in Africa and India, which account for a large share of the world's poor. The second most important factor leading to increased poverty is health impacts, followed by the impacts of higher temperatures on labour productivity.

Recent FAO studies of adaptation to climate changes in smallholder agriculture systems in sub-Saharan Africa show how dry spells, the late onset of rains and high temperatures affect incomes at the farm level.[4] In all cases, climate shocks reduced productivity or harvest value significantly and, in turn, reduced access to food. The shocks impinge on physical capital, when assets are destroyed – for example, through the death of livestock – or when farmers are forced to sell productive capital, such as cattle, to absorb the income shock. They also reduce farmers' capacity to invest, with negative consequences for future food security.

Bárcena *et al.* (2014) summarized the results of a series of studies of the projected impacts of »

4 See for Ethiopia: Asfaw, Coromaldi and Lipper (2015a,b); Niger: Asfaw, DiBattista and Lipper (2015); Malawi: Asfaw, Maggio and Lipper (2015); United Republic of Tanzania: Arslan, Belotti and Lipper (2016); Zambia: Arslan *et al.* (2015)

BOX 7

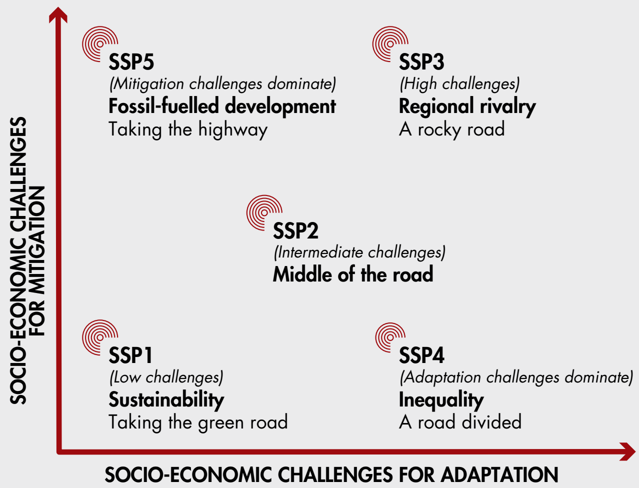
PROJECTING CLIMATE CHANGE: RCPS AND SSPS

Representative Concentration Pathways are four hypothetical greenhouse gas concentration trajectories during the 21st century (Moss *et al.*, 2008) adopted by the IPCC for its Fifth Assessment Report. The RCPs represent a wide range of possible changes in future anthropogenic greenhouse gas emissions*:
RCP 2.6 – emissions peak between 2010 and 2020 and decline substantially thereafter.
RCP 4.5 – emissions peak around 2040 and then decline.
RCP 6.0 – emissions peak around 2080 and then decline.
RCP 8.5 – emissions continue to rise throughout the 21st century.
The RCP 2.6 pathway is consistent with the aim of keeping global warming at less than 2 °C above pre-industrial levels. Scenarios in which no additional efforts are made to mitigate emissions lead to pathways between RCP 6.0 and RCP 8.5.

Shared socio-economic pathways describe plausible alternative trends in the evolution of society and ecosystems over the 21st century. The SSPs are being used alongside the RCPs to analyse feedback between climate change and factors such as world population growth, economic development and technological progress. They are based on storylines for possible futures which present different challenges to adaptation and mitigation (O'Neill *et al.*, 2014; Van der Mensbrugghe, 2015):

SSP1: Sustainability. Sustainable development proceeds at a high pace, inequalities narrow, technological change is rapid and environmentally friendly, including lower carbon energy sources and high productivity of land.
SSP2: Business-as-usual (or middle-of-the-road). Population peaks in 2070, GDP growth is moderate, and inequality declines steadily, GDP shares of sub-Saharan Africa and South Asia rise significantly.
SSP3: Regional rivalry. Rapid population growth, moderate economic growth and slow technological change in the energy sector. High inequality leads to reduced trade flows, leaving many parts of the world vulnerable, and with low adaptive capacity.
SSP4: Inequality. Rapid development of low carbon energy technologies in key GHG emitting regions leads to relatively large mitigative capacity, but in other regions development is slow, inequality high, and adaptive capacity limited.
SSP5: Fossil-fuelled development. High GDP growth using conventional energy technologies, associated with continuing high emissions. But because growth is relatively equitable, the world is better able to adapt to climate impacts.

FIVE SHARED SOCIO-ECONOMIC PATHWAYS



Note: SSP = Shared socio-economic pathway.
SOURCE: O'Neill *et al.* (2015).

* The RCPs are named after a possible range of radiative forcing values in the year 2100, relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 W/m²). Radiative forcing values are the difference between the energy from sunlight absorbed by the Earth and the energy radiated back into space.

» climate change on agricultural revenues in South America. While there is a wide degree of variation among models and scenarios, projected impacts are generally found to be negative across a wide range of locations. Table 4 shows selected results from countries in South America as well as for the region as a whole.

At the national level, reduced production due to climate change can trigger an increase in the prices of food and feed, negatively affecting the socio-economic status of the whole population and its food security. Such impacts are particularly critical in countries where an important part of the household budget is spent on food. They can be accompanied by major macro-economic effects where agriculture makes an important contribution to national GDP and/or employment.

Lam *et al.* (2012) modelled the economic and social implications of climate-change induced modifications in the availability of marine fisheries species in 14 countries in West Africa, by 2050. Using the high range IPCC Special Report on Emission Scenarios (SRES) A1B scenario, they project a decrease in landed fish value of 21 percent, a total annual loss of US$311 million compared to values for 2000, and a loss in fisheries-related jobs of almost 50 percent, with Côte d'Ivoire, Ghana, Liberia, Nigeria, Sierra Leone and Togo suffering the most severe impacts.

Most projections of the food price impacts of climate change point to increases, although the magnitude and locations vary considerably across models and climate scenarios. A study that coupled scenarios for population growth and income growth with climate change scenarios looked at the potential impacts under 15 different combinations. Using an optimistic scenario of low population growth and high income growth, and the mean results from four climate change scenarios, it plotted mean projected price increases by 2050, compared to 2010 levels, of 87 percent for maize, 31 percent for rice and 44 percent for wheat (Nelson *et al.*, 2010). Another potential impact of climate change is food price volatility (Porter *et al.*, 2014), although the extent of volatility is greatly influenced by domestic policies, such as export bans and other trade restricting measures that exacerbate price fluctuations on international markets.

Increased trade is expected to play an important role in adjusting to the shifts in agricultural and food production patterns resulting from climate change (Nelson *et al.*, 2010; Chomo and De Young, 2015).The adaptive role of trade is addressed in a study by Valenzuela and Anderson (2011), which finds that climate change could cause a substantial decline in the food self-sufficiency ratio of developing countries of about 12 percent by 2050. While trade can help in adaptation to climate change and to shifting international patterns of production, ultimately global markets will only be accessible to those countries and segments of population that have sufficient purchasing power. This makes inclusive economic growth an essential precondition for stable food security.

Climate change may also lead to changes in investment patterns that would lead to reductions in the long-term productivity and resilience of agricultural systems at household and national levels. Uncertainty discourages investment in agricultural production, potentially offsetting the benefit to food producers of higher prices. This is particularly true for poor smallholders with limited or no access to credit and insurance. Greater exposure to risk, in the absence of well-functioning insurance markets, can lead to greater emphasis on low-risk/low-return subsistence crops, a lower likelihood of applying purchased inputs such as fertilizer and adopting new technologies, and reduced levels of investment (Antle and Crissman, 1990; Dercon and Christiaensen, 2011; Fafchamps, 1992; Feder, Just and Zilberman, 1985; Heltberg and Tarp, 2002; Kassie *et al.*, 2008; Roe and Graham-Tomasi, 1986; Sadoulet and de Janvry, 1995; Skees, Hazell and Miranda, 1999). All of these responses generally lead to both lower current and future farm profits (Hurley, 2010; Rosenzweig and Binswanger, 1993). ■

TABLE 3

NUMBER OF PEOPLE LIVING IN EXTREME POVERTY IN 2030 WITH AND WITHOUT CLIMATE CHANGE, UNDER DIFFERENT CLIMATE AND SOCIO-ECONOMIC SCENARIOS

		Climate change scenario				
		No climate change	Low-impact		High-impact	
		Number of people in extreme poverty	Additional number of people in extreme poverty due to climate change			
Socio-economic Scenario	Prosperity	142 million	+3 million		+16 million	
			Minimum	Maximum	Minimum	Maximum
			+3 million	+6 million	+16 million	+25 million
	Poverty	900 million	+35 million		+122 million	
			Minimum	Maximum	Minimum	Maximum
			−25 million	+97 million	+33 million	+165 million

Notes: The main results use the two representative scenarios for prosperity and poverty. The ranges are based on the 60 alternative scenarios for each category. See Box 7 for an explanation of RCPs and SSPs.
SOURCE: Adapted from Rozenberg and Hallegatte (2015).

TABLE 4

CHANGES IN AGRICULTURAL REVENUES ASSOCIATED WITH RISING TEMPERATURES, IN SELECTED AREAS OF LATIN AMERICA

Geographical coverage	Reference	Increases in temperature (degrees Celsius)	Revenue change
		(°C)	(Percent)
Argentina	Lozanoff and Cap (2006)	2.0 to 3.0	−20 to −50
Brazil	Sanghi and Mendelsohn (2008)	1.0 to 3.5	−1.3 to −38.5
Mexico	Mendelsohn, Arellano and Christensen (2010)	2.3 to 5.1	−42.6 to −54.1
South America	Seo and Mendelsohn (2007)	1.9, 3.3 and 5	−20, −38 and −64 (small farms)
			−8, −28 and −42 (large farms)
	Seo and Mendelsohn (2008)	1.9, 3.3 and 5 by 2020	2.3 to −14.8
		1.9, 3.3 and 5 by 2060	−8.6 to −23.5
		1.9, 3.3 and 5 by 2100	−8.4 to −53
	Seo (2011)	1.2, 2.0 and 2.6	17 to −36 (private irrigation)
			−12 to −25 (public irrigation)
			−17 to −29 (dry farming)

SOURCE: Adapted from Bárcena *et al.* (2014).

MILLIONS MORE AT RISK OF HUNGER

Although climate change poses concrete threats to future food security, the likely impacts will differ by region, country and location and will affect different population groups according to their vulnerability. Future food security trends will also be influenced by overall socio-economic conditions, which, in turn, have implications for the vulnerability of countries and populations around the world.

The IPCC's Fourth Assessment Report estimated that, depending on the climate change scenario and socio-economic development path, from 34 million to 600 million more people could suffer from hunger by 2080 (Yohe *et al.*, 2007; Parry, Rosenzweig and Livermore, 2005). Arnell *et al.* (2002) projected that, with no climate change, 312 million people globally would be at risk of hunger in the 2050s, and 300 million people in the 2080s. Without climate change mitigation, those numbers would grow to 321 million in the 2050s and 391 million in the 2080s. Among the developing regions, Southern Asia and Africa would be the most exposed to an increased risk of hunger as a result of climate change. The very broad range of estimates of the number of people at risk of hunger owing to climate change points to uncertainties concerning some of the processes, both biophysical and socio-economic; however, the numbers indicate that the impact should not be underestimated.

When analysing the possible future impact of climate change on food security, it is important to bear in mind that food and agriculture will be affected by a range of other drivers of change, including growth in population and income. This is illustrated by an analysis of climate change impacts based on 15 scenarios – three economic development and five climate change scenarios combined – which found that up to 2050, economic growth will have a much greater effect on global food security than climate change, although climate change does aggravate negative impacts (Nelson *et al.*, 2009).

The International Food Policy Research Institute (IFPRI) and several other global economic modelling groups, collaborating as part of the Agricultural Model Intercomparison and Improvement Project, and building on the earlier work by Nelson *et al.* (2014b), used different combinations of RCPs and SSPs to explore the possible effects of climate change – together with other socio-economic changes – on production, yields, cultivated area, prices and trade of major crops (Wiebe *et al.*, 2015).

The results show that by 2050, relative to a world with no climate change, global average crop yields will decline by between 5 and 7 percent, depending on assumptions about rates of socio-economic and climate change, while the area harvested will increase by around 4 percent (Figure 7). The impact of climate change on total production will be relatively small. However, both the area harvested and staple food prices will increase at about twice the rate projected in the absence of climate change, with potentially significant impacts on both the environment and food security.

Impacts will vary according to crop and region and rate of climate change. Higher latitudes will see smaller losses in yields, and even some gains as growing seasons lengthen. Losses in lower latitude regions will be greater. Maize yields decline in most regions under most scenarios. Impacts on wheat are small at the global level, since losses in South Asia and sub-Saharan Africa are offset by increases elsewhere (see Figure 1).

In a related analysis, IFPRI found that in the absence of climate change, most regions would see declining numbers of people at risk of hunger between 2010 and 2050. However, climate change will partly offset those gains. Results from IFPRI's IMPACT model suggest that, by the year 2050, under a high emissions scenario (RCP 8.5), more than 40 million more people could be at risk of undernourishment than there would be in the absence of climate change. While the increase due to climate change is smaller than the projected global reduction in the number of undernourished, thanks to economic growth and development, it is a significant number. It is also likely to be a conservative estimate because it is based on the SSP2 "business-as-usual" assumption of economic growth, and does not account for the impacts of extreme events, sea-level rise, melting glaciers, changes in pest and disease patterns, and other factors that are expected to change with climate, especially after 2050.

Under the RCP 8.5 high emissions scenario, most of the expected slow-down in the reduction in the number of people at risk of hunger is in sub-Saharan Africa (Figure 8). The loss is concentrated in that region partly because other regions benefit from some production in higher latitude areas, and partly because other regions are less reliant on agriculture for incomes and food security.

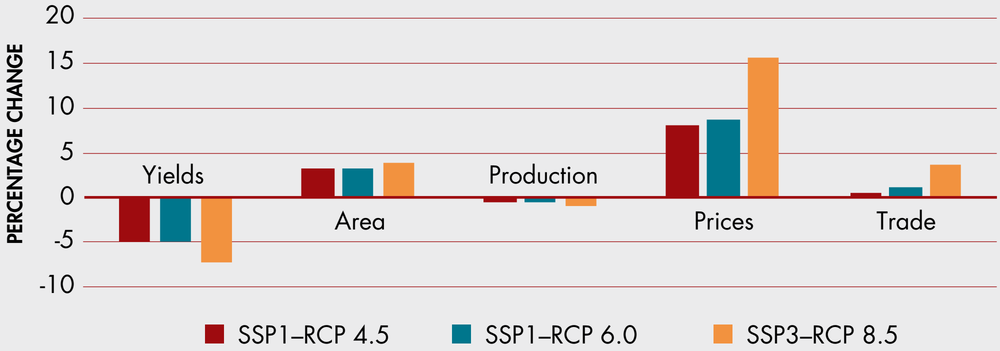
However, it must be remembered that climate change is not the only driver of future trends in poverty and food insecurity. How climate change is projected to affect the global risk of hunger over time, for a range of climate change impacts and the SSP2 "middle-of-the-road" socio-economic scenario, is shown in Figure 9. The declining trend in the number of undernourished with or without climate change indicates that the overall impact of climate change during the period until 2050 is smaller than that of the other drivers embedded in the socio-economic scenario, particularly income growth. In the absence of climate change, most regions are projected to see declining numbers of people at risk of hunger. These improvements are partially reduced by climate change, especially in sub-Saharan Africa.

The vulnerability of populations in sub-Saharan Africa, as well as in parts of South Asia, to food insecurity resulting from climate change also emerges in projections by the World Food Programme and the Met Office Hadley Centre (United Kingdom). Their joint work largely follows methods used by Krishnamurthy, Lewis and Choularton (2014), with vulnerability defined by a composite index based on measures of exposure, sensitivity and adaptive capacity. Projections of future levels of vulnerability were made for two time periods: 2050 and 2080. Three climate change scenarios were considered: low emissions (RCP 2.6), medium emissions (RCP 4.5) and high emissions (RCP 8.5). Each scenario was projected using twelve different climate models, and the median result was taken as the value for the respective drought and flood indicators. Scenarios of no adaptation as well as low and high adaptation were taken into consideration.

Figure 10 illustrates vulnerability today and in 2050 under two different scenarios: a worst case scenario, with high emissions (RCP 8.5) and no adaptation, and a best case scenario with low emissions (RCP 2.6) and high levels of adaptation. The greatest vulnerabilities are seen in areas of sub-Saharan Africa and South and South East Asia, where millions of people are likely to face greater risk of food insecurity as a result of climate change by the 2050s. The increase in vulnerability is dramatic under the worst-case scenario. Under a best case scenario, vulnerabilities are greatly reduced, and for some countries actually decrease from present-day levels. ■

FIGURE 7

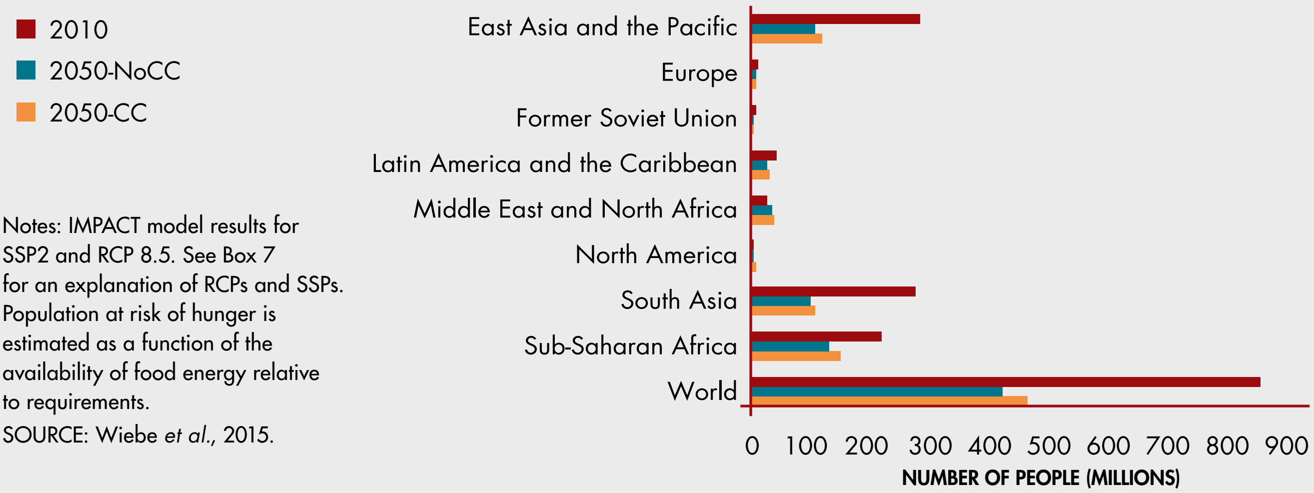
IMPACTS OF CLIMATE CHANGE ON CROP YIELDS, AREA, PRODUCTION, PRICES AND TRADE BY 2050 AT THE GLOBAL LEVEL



Notes: : Crops included are coarse grains, rice, wheat, oilseeds and sugar. See Box 7 for an explanation of RCPs and SSPs.
SOURCE: Wiebe *et al.*, 2015.

FIGURE 8

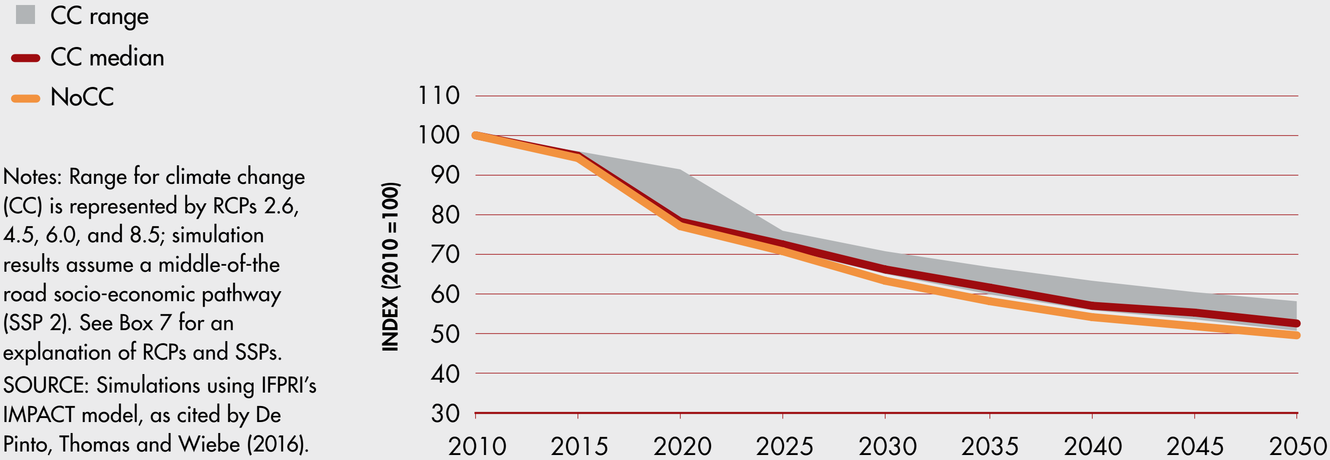
IMPACTS OF CLIMATE CHANGE ON POPULATION AT RISK OF HUNGER IN 2050, BY REGION



Notes: IMPACT model results for SSP2 and RCP 8.5. See Box 7 for an explanation of RCPs and SSPs. Population at risk of hunger is estimated as a function of the availability of food energy relative to requirements.
SOURCE: Wiebe *et al.*, 2015.

FIGURE 9

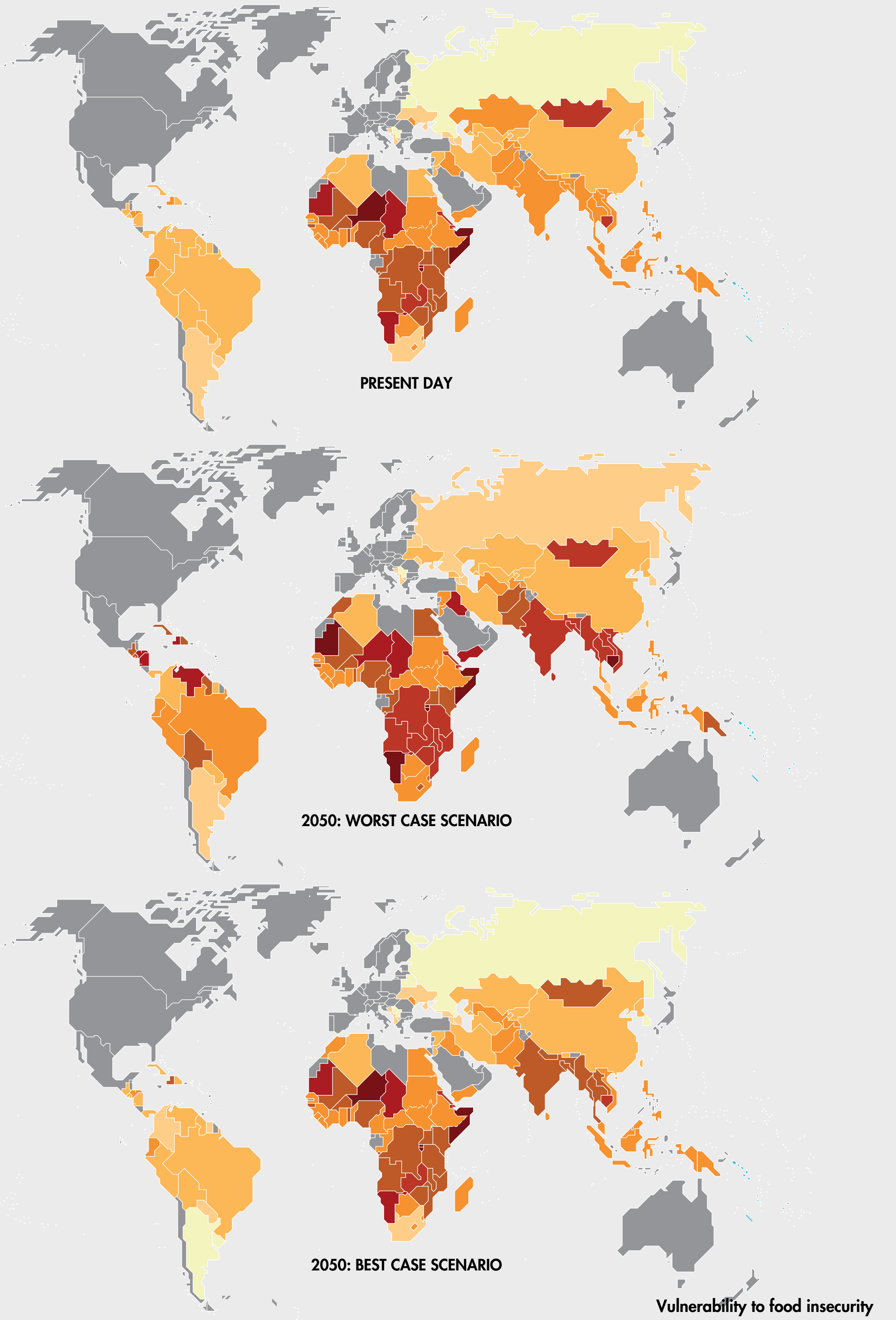
POPULATION AT RISK OF HUNGER, WITH AND WITHOUT CLIMATE CHANGE



Notes: Range for climate change (CC) is represented by RCPs 2.6, 4.5, 6.0, and 8.5; simulation results assume a middle-of-the road socio-economic pathway (SSP 2). See Box 7 for an explanation of RCPs and SSPs.
SOURCE: Simulations using IFPRI's IMPACT model, as cited by De Pinto, Thomas and Wiebe (2016).

FIGURE 10

FOOD INSECURITY AND CLIMATE CHANGE VULNERABILITY: PRESENT DAY, WORST CASE AND BEST CASE SCENARIOS



SOURCE: Met Office Hadley Centre and WFP, 2015.

THE AGRICULTURE SECTORS' ROLE IN CLIMATE CHANGE

By FAO estimates (Table 5), emissions from agriculture, forest and other land use (AFOLU) stood at 10.6 gigatonnes (Gt) of carbon dioxide equivalent in the year 2014. The sector emits three types of anthropogenic greenhouse gases: carbon dioxide (CO_2), the hydrocarbon methane (CH_4) and nitrous oxide (N_2O). The main sources of those emissions are deforestation, enteric fermentation in livestock, manure left on fields, applied chemical fertilizers and rice cultivation practices. Deforestation and land degradation have also reduced the sector's capacity to absorb (or sequester) carbon dioxide from the atmosphere. Carbon dioxide and methane account for 49 and 30 percent, respectively, of the emissions generated by agriculture, forestry and land use. This represents 14 percent of total anthropogenic emissions of carbon dioxide and 42 percent of all methane emissions. The share of nitrous oxide in total AFOLU emissions is small, but accounts for as much as 75 percent of global anthropogenic emissions of the gas.

Agriculture accounts for the largest share of emissions from AFOLU, followed by net conversion of forest land; since the 1990s, emissions from forest conversion have decreased while agricultural emissions have increased (Figure 11). Organic soils (those with a high concentration of organic matter, such as peatlands) and the burning of biomass (e.g. savanna fires) account for relatively smaller amounts of emissions. Forests also mitigate climate change by removing GHG from the atmosphere through forest growth, as seen in the negative values. However, the average contribution of forests to carbon sequestration has fallen from 2.8 Gt annually in the 1990s to 2.3 Gt in the 2000s, and is estimated at 1.8 Gt in 2014.

Across regions, AFOLU emission levels and sources are starkly different (Figure 12). Emissions from net forest conversion represent the largest share of GHG emissions in Latin America and the Caribbean and sub-Saharan Africa, but are less significant in other regions. The contribution of forest sinks is important in countries in developed regions as well as in Latin America and the Caribbean, but less so elsewhere. Agricultural emissions make up a significant share of total AFOLU emissions in all regions, and represent more than half of emissions in all regions except sub-Saharan Africa and Latin America and the Caribbean, where net forest conversion is the major source. Different emission patterns have been recorded at regional level over the last two decades. For example, there has been a sharp reduction in the positive contribution of forest sinks in Southeast, Eastern and Southern Asia, and an opposite trend in Europe. Other regions report more stable trends (FAO, 2016d).

Of the sources of specific GHG emissions from agriculture, the most significant contribution at the global level – amounting to 40 percent in CO_2 equivalent – comes from enteric fermentation in ruminants, which is a major source of methane emissions (Figure 13). In terms of the magnitude of emissions, this is followed by manure left on pasture (16 percent), the use of synthetic fertilizers (12 percent) and rice cultivation (10 percent).

Enteric fermentation is the largest source of emissions from agriculture in all regions except Oceania and Eastern and Southeast Asia, with the share of total emissions ranging from 58 percent in Latin America and the Caribbean to 37 percent in countries in developed regions (Table 6). The importance of other emission sources varies at regional level. Rice cultivation is the most important source of agricultural emissions in Eastern and Southeast Asia (at 26 percent), while in Oceania the cultivation of organic soils is the source of 59 percent of agricultural emissions. The second main source is manure left on pastures in sub-Saharan Africa, Northern Africa and Western Asia, and Latin America and the Caribbean; rice cultivation in Southern Asia; and synthetic fertilizers in countries in developed regions.

Agriculture must contribute to mitigation if global temperature increase is to be kept below 2 °C (Wollenberg *et al.*, 2016). It needs to be recognized, however, that the source of some 75 percent of global GHG emissions is fossil fuel used for energy

Continues on page 41 »

TABLE 5

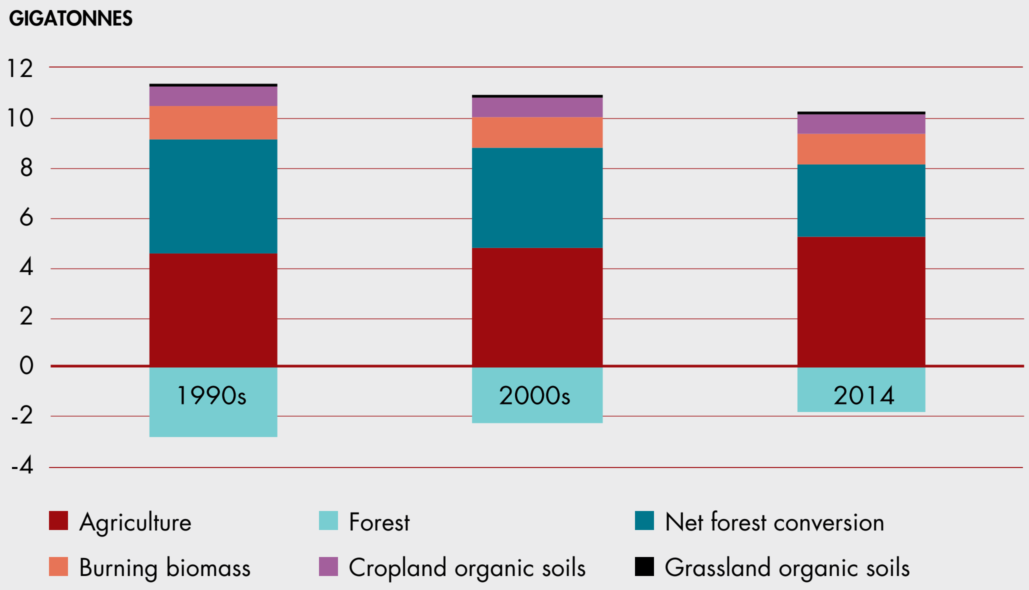
EMISSIONS AND REMOVALS OF MAIN GREENHOUSE GASES, BY ALL SECTORS AND BY AGRICULTURE, FORESTRY AND LAND USE (AFOLU) IN 2010

	All sectors	AFOLU	AFOLU: Agriculture	AFOLU: Forestry and land use	AFOLU contribution as share of total	Share of gases in total AFOLU emissions
	Gigatonnes of CO_2 equivalent				Percent	
Emissions						
Carbon dioxide (CO_2)	38.0	5.2		5.2	13.6	48.7
Methane (CH_4)	7.5	3.2	2.9	0.3	42.3	29.7
Nitrous oxide (N_2O)	3.1	2.3	2.2	0.1	75.0	21.6
Others	0.8				0	0
Total emissions	49.4	10.6	5.1	5.5	21.5	100
Removals (sinks)						
Carbon dioxide (CO_2)		-2.6		-2.6		

SOURCE: FAO, forthcoming.

FIGURE 11

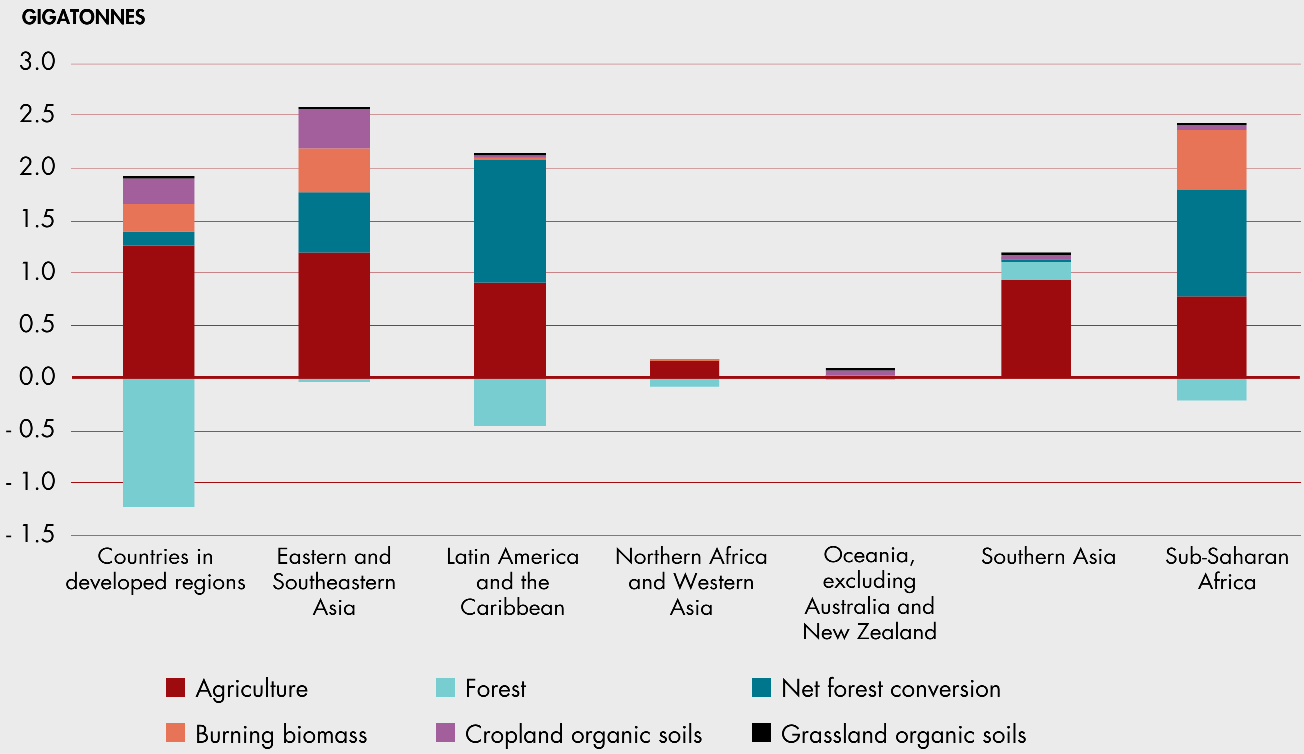
ANNUAL AVERAGE NET EMISSIONS/REMOVALS FROM AFOLU IN CO_2 EQUIVALENT



Note: See Notes on the Annex tables for definitions.
SOURCE: FAO, 2016d. See Annex table A.2 for details.

FIGURE 12

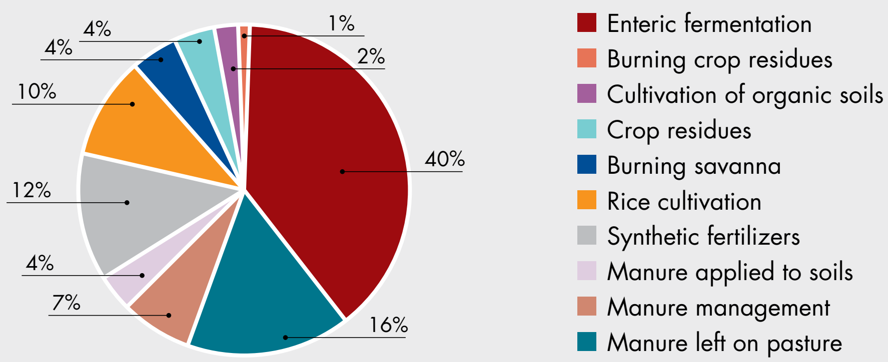
NET EMISSIONS/REMOVALS FROM AFOLU IN CO_2 EQUIVALENT IN 2014, BY REGION



SOURCE: FAO, 2016d. See Annex table A.2 for details.

FIGURE 13

SHARE OF AGRICULTURAL EMISSIONS IN CO_2 EQUIVALENT IN 2014, BY SOURCE AND AT GLOBAL LEVEL



Note: See Notes on Annex tables for definitions of sources.
SOURCE: FAO, 2016d. See Annex table A.3.

TABLE 6

THREE MAIN SOURCES OF AGRICULTURAL GREENHOUSE GAS EMISSIONS IN 2014, BY REGION

Ranking	Countries in developed regions	Eastern and Southeast Asia	Latin America and the Caribbean	Northern Africa and Western Asia	Oceania, excluding Australia and New Zealand	Southern Asia	Sub-Saharan Africa
1	Enteric fermentation (37%)	Rice cultivation (26%)	Enteric fermentation (58%)	Enteric fermentation (39%)	Cultivation of organic soils (59%)	Enteric fermentation (46%)	Enteric fermentation (40%)
2	Synthetic fertilizers (17%)	Enteric fermentation (24%)	Manure left on pasture (23%)	Manure left on pasture (32%)	Enteric fermentation (14%)	Rice cultivation (15%)	Manure left on pasture (28%)
3	Manure management (12%)	Synthetic fertilizers (17%)	Synthetic fertilizers (6%)	Synthetic fertilizers (18%)	Manure management (14%)	Synthetic fertilizers (15%)	Burning savannah (21%)

SOURCE: FAO, 2016d.

» *Continued from page 38*

production, while only 21 percent is linked to the agriculture sectors. Emissions from the energy sector could be reduced, even to zero, through greater energy use efficiency and a transition to renewable energy sources. If that were to happen, emissions from agriculture would represent a progressively larger part of total emissions, for three reasons: (1) because emissions from other sectors would decrease; (2) because food production is increasing and, with it, the tendency towards higher emissions; and (3) because reducing agriculture's emissions is far more challenging owing to the enormous diversity in its sectors and the complex biophysical processes involved.

The agriculture sectors can contribute to climate change mitigation by decoupling emissions increases from production increases. However, they also have the unique capacity to sequester carbon. At the present state of technology, one of the main means of extracting CO_2 from the atmosphere is through forestry and the rehabilitation of degraded land. Transforming this theoretical potential into an actual sink depends on biophysical conditions, as well as on the available technical options and appropriate institutions and policies. Emissions from agriculture, as well as sinks, are part of the global carbon and nitrogen cycles. Optimizing the mitigation potential of the agriculture sectors requires, therefore, an understanding of these cycles and of how agricultural activities interact with them. Some – but not all – of the options for enhanced mitigation also carry co-benefits in terms of adaptation (see Chapter 4). ■

CONCLUSIONS

This chapter has traced the potential impacts of climate change on agriculture, socio-economic development and, ultimately, food security. Among the main impacts on agriculture are the increased incidence of drought and extreme weather events, more intense pest and disease pressures and the loss of biodiversity. Long-term projections point to negative effects on food production that will become increasingly severe after 2030. Reductions in crop yields and the productivity of livestock, fisheries and forestry are more likely in tropical developing regions than in temperate, developed countries.

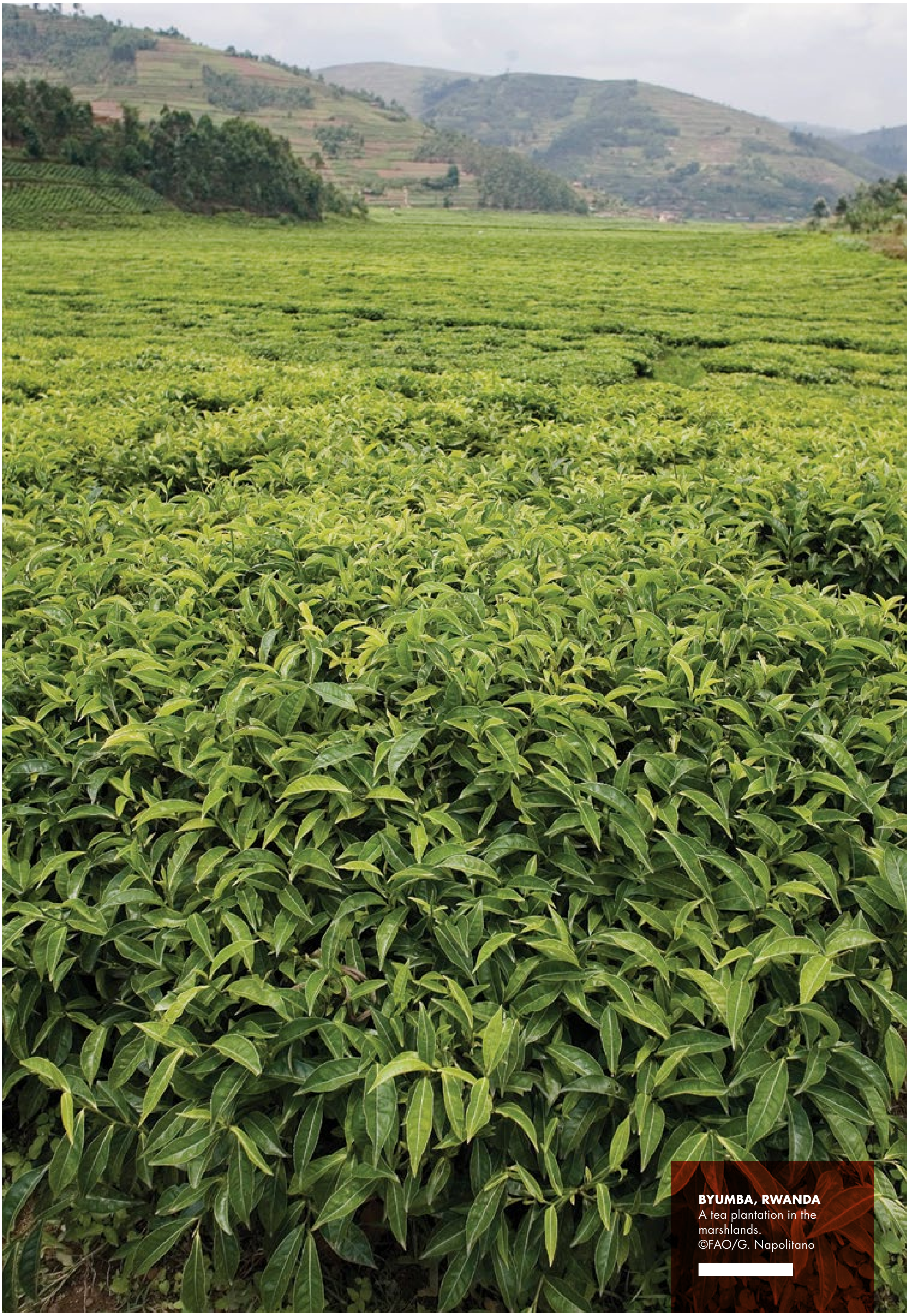
As the impact of climate change on agricultural production and productivity deepens, an increase in both international food prices and the number of people at risk of food insecurity is expected. While socioeconomic and technological development will be a stronger driver of food security trends than climate change until 2050, climate change impacts on agriculture and food security should not be underestimated, especially at the regional level – the socio-economic knock-on effects will be felt most by low-income rural populations and by countries with a high dependency on agriculture.

The following chapter examines how the agriculture sectors can adapt to current or expected changes, in a way that minimizes their harmful effects and takes advantage of opportunities, with a focus on smallholders and small-scale production systems. The potential for climate change mitigation and the potential co-benefits of adaptation and mitigation measures will be addressed in Chapter 4.

CHAPTER 3

ADAPTING TO CLIMATE CHANGE IN SMALLHOLDER AGRICULTURE

RUGEZI, RWANDA
A farmer sowing seeds.
©FAO/G. Napolitano



BYUMBA, RWANDA
A tea plantation in the marshlands.
©FAO/G. Napolitano

KEY MESSAGES

1 **GLOBAL POVERTY CANNOT BE ERADICATED WITHOUT STRENGTHENING** the resilience of smallholder agriculture to climate change impacts.

2 **SMALLHOLDER AGRICULTURAL SYSTEMS CAN ADAPT TO CLIMATE CHANGE** by adopting climate-smart practices, diversifying on-farm agricultural production and diversifying into off-farm income and employment.

3 **SUSTAINABLE MANAGEMENT OF NATURAL RESOURCES** will be key for adaptation to climate change and to ensure food security.

4 **IMPROVEMENTS IN INFRASTRUCTURE, EXTENSION, CLIMATE INFORMATION, MARKET ACCESS, CREDIT AND SOCIAL INSURANCE** are needed to facilitate adaptation and diversification of smallholder livelihoods.

5 **THE COSTS OF INACTION ARE MUCH GREATER THAN THE COSTS OF THE INTERVENTIONS** that would enable farmers, fisherfolk, herders and foresters to respond effectively to climate change.

CHAPTER 3

ADAPTING TO CLIMATE CHANGE IN SMALLHOLDER AGRICULTURE

Most of the world's poor and hungry are rural people who earn meagre livings from agriculture. In 2010, some 900 million of the estimated 1.2 billion extremely poor lived in rural areas. About 750 million of them worked in agriculture, usually as smallholder family farmers (Olinto *et al.*, 2013). While 200 million rural poor may migrate to towns and cities over the next 15 years, most will remain in the countryside. In that period, the rural population in less developed regions is projected to increase slightly (UN-DESA, 2012), and an estimated 700 million rural people would be living in poverty. Without concerted action to improve rural livelihoods, the eradication of poverty by 2030 will be impossible.

The sheer number of smallholder farm families worldwide justifies a specific focus on the threats posed by climate change to their livelihoods and the urgent need to transform those livelihoods along sustainable pathways. This chapter explores the key vulnerabilities of smallholder farming systems to climate change risks, and assesses the options for minimizing vulnerabilities through sustainable intensification, diversification and risk management strategies. After assessing the available evidence of the cost of adaptation, it concludes that the costs of inaction exceed by far the cost of interventions that would make smallholder farming systems resilient, sustainable and more prosperous. ■

RETHINKING PATHWAYS OUT OF POVERTY

Eliminating rural poverty is essential to eradicating hunger and poverty globally. Over recent decades, poverty reduction across a wide range of countries and conditions has been associated with growth in the value of agricultural production, increased rural-urban migration and a shift away from economies highly dependent on agriculture to more diversified sources of income and employment. In every country that has seen rapid poverty reduction, growth in agricultural labour productivity, and consequently rural wages, has been a feature (Timmer, 2014). Rwanda and Ethiopia, for example, have achieved very significant productivity growth and correspondingly large reductions in rural poverty.

However, the opportunities and challenges for agricultural productivity growth today are markedly different from those of the past. Growth in markets for food and agricultural products creates opportunities for smallholders, but sometimes also barriers which lead to their exclusion. Growth in the private sector's share of agricultural technology development and dissemination has opened up new opportunities but has also changed the terms under which those technologies are accessed.

Facing different constraints and opportunities, rural populations across the world have different possible pathways out of poverty (Wiggins, 2016). Those with good linkages to rapidly expanding markets have a different set of opportunities to those in more remote areas. Demography also matters. In sub-Saharan Africa, the future agricultural population will be young, with smaller areas of land to farm; in parts of Asia, the population is likely to be older and farm sizes bigger. In some cases, farmland consolidation will be needed to facilitate access to high value market chains (Masters *et al.*, 2013). Other possible pathways are diversification into non-farm sources of income through migration of

TABLE 7

IMPACT OF CLIMATE SHOCKS ON AGRICULTURAL OUTPUT AND PRODUCTIVITY

	Ethiopia	Malawi	Niger	Uganda	United Republic of Tanzania	Zambia
Average rainfall	++	+++	+++	+	+	+++
Rainfall variability	-	NA	---	NS	-	NS
Average maximum temperature	---	---	--	--	+	-
Maximum temperature variability	---	NA	--	--	NS	NA
Total amount of dry spells	NA	---	NA	NA	NA	NA

Notes: NS = not significant; NA = not available; + = significant positive impact on yields; – = significant negative impact on yields. One, two or three "+" or "–"signs refer to significance at, respectively 10, 5 or 1 percent confidence level. Results for Malawi, the United Republic of Tanzania and Zambia refer to impact on maize productivity only.

SOURCES: Asfaw *et al.*, 2016a; Asfaw, Maggio and Lipper, 2016; Asfaw, Di Battista and Lipper, 2016; Asfaw, Coromaldi and Lipper, 2016; Arslan *et al.*, 2015; FAO, 2016b, 2016c.

some household members, or a full exit from agriculture and one-way migration to cities (Wiggins, 2016). For smallholders, the feasibility of any of these strategies depends on their location and the level of economic development in the non-farm and agriculture sectors.

Climate change is projected to have mainly negative impacts on food and agricultural production in large areas of the developing world. The success of efforts to develop rural economies and eradicate rural poverty will also depend crucially, therefore, on building resilience to climate change in agricultural systems – especially those managed by smallholders – and the widespread adoption of land, water, fisheries and forestry management practices that are environmentally, socially and economically sustainable. ■

KEY VULNERABILITIES TO CLIMATE CHANGE RISKS

Smallholder agriculture producers in developing countries are considered to be highly vulnerable to climate change and stand to gain the most from increased resilience. Vulnerability is defined by the IPCC as the extent to which a natural or social system is susceptible to sustaining damage from climate change impacts, and is a function of exposure, sensitivity and adaptive capacity (IPCC, 2001).

Chapter 2 summarized the nature of climate change risks to agricultural systems globally. Overall, the extent of ***exposure*** to risks is diverse and changes over time. For most developing countries, the impacts of climate change on crop and livestock productivity tend to be adverse and increasing. Localized weather shocks and emerging pests and diseases are already compromising the stability of crop production, highlighting the urgent need for immediate, adaptable management responses (FAO, 2016a).

Recent FAO studies on the impact of climate shocks on smallholder agriculture in sub-Saharan Africa (summarized in Table 7) found that yields rise significantly with more rainfall in most cases, but suffer when rainfall is below average and more variable; likewise, above-average temperatures reduce productivity significantly. However, specific weather anomalies affect yields in some countries but not in others. Knowing what weather variables constrain yields is the first step to addressing such constraints, and there is no recipe that applies across countries. Rainfall variability is highly significant in Malawi and Niger, but not in Uganda and Zambia. Although average rainfall and temperatures appear to be significant across a broader set of countries, variability can be a key constraining factor in some regions, even if it is not associated with an extreme event.

The consequences of exposure to climate hazards depend on ***sensitivity***, i.e. the degree to which an agro-ecological or socio-economic system responds, both positively and negatively, to a given change. Increasing scarcity and degradation of natural resources heighten the sensitivity of smallholder agriculture to climate hazards, because degraded resources are less capable of maintaining productivity under climate stresses (FAO, 2012). For example, while there is sufficient water to satisfy the demand for food at the global level, an increasing number of regions face growing water scarcity, which will impact rural and urban livelihoods, food security and economic activities (FAO, 2011a; FAO and World Water Council, 2015). Further degradation of water quality and quantity under climate change reduces the supply of water for food production, affecting food availability, stability, access and utilization, especially in the arid and semi-arid tropics and in Asian and African mega-deltas (Bates *et al.*, 2008). Rationalizing water use in agriculture will greatly facilitate adaptation to climate change in smallholder production systems.

Rural women are especially sensitive to climate hazards, owing to their gender-determined household responsibilities (such as collecting wood and water) and the increasing agricultural workloads they bear because of male out-migration (see e.g. Jost *et al.*, 2015; Agwu and Okhimamwe, 2009; Goh, 2012; Wright and Chandani, 2014). Increases in the incidence of drought and water shortages add to their workloads, affecting both agricultural productivity and household welfare (UNDP, 2010). See also Box 8.

The limited capacity of smallholders to manage risks is another source of sensitivity to climate hazards. During extreme events, they adopt precautionary strategies – for example, selling cattle – which may protect them against catastrophic losses but undermine long-term livelihood opportunities and can trap them in chronic poverty (Carter and Barrett, 2006; Dercon, 1996; Dercon and Christiaensen, 2007; Fafchamps, 2003; Morduch, 1994; Kebede, 1992; Simtowe, 2006). Climate uncertainties and risk aversion also impact rural financial markets and supply chains in ways that further reduce opportunities and deepen farm-level poverty traps (Barrett and Swallow, 2006; Kelly, Adesina and Gordon, 2003; Poulton, Kydd and Dorward, 2006).

In smallholder agriculture, ***adaptive capacity*** – or the ability to identify and implement effective actions in response to changing circumstances – is limited by barriers to the adoption of improved, climate-smart technologies and practices. For example, the lack of access to credit for investment affects, particularly, the poorest households, which are usually unable to provide collateral for loans, and female producers, who often have no formal title to assets. Other barriers include lack of land tenure security, very limited access to information, extension advice and markets, a lack of safety nets to protect livelihoods against shocks, and gender-bias in all of those institutions.

Most of the interventions needed to improve smallholders' capacity to adapt to climate change are the same as those required for general rural development, but with a stronger focus on climate risks. For example, extension packages need to take into account site-specific climate change projections; investments in the breeding of improved crop varieties and animal breeds should consider not only high yield but also resistance to shocks expected in specific locations (Box 9). Investments are urgently needed in irrigation and other water management infrastructure. These issues are taken up in more detail in the following sections. ■

TOWARDS RESILIENT PRODUCTION SYSTEMS AND LIVELIHOODS

The vulnerability of smallholders to climate change adds to the more general difficulties they face in enhancing their productivity and improving their livelihoods. Consequently, »

BOX 8

RURAL WOMEN ARE AMONG THE MOST VULNERABLE

Rural women represent a quarter of the world's population. They make up around 43 percent of the agricultural labour force in developing countries. In South Asia more than two out of every three employed women work in agriculture (FAO, 2011a). Globally, with few exceptions, every gender and development indicator for which data are available reveals that rural women fare worse than rural men and urban women, and that they disproportionately experience poverty, exclusion and the effects of climate change (United Nations, 2010).

Smallholder women farmers are more exposed than men to climate risks, and for many of the same reasons that female farmers' productivity is lower than men's – they have fewer endowments and entitlements, have more limited access to information and services, and are less mobile (FAO, 2007; Nelson, 2011). The gendered nature of resource entitlements means that women tend to rely more on resources and technologies that are sensitive to climate hazards (Dankelman, 2008; Huynh and Resurrección, 2014; Nelson and Stathers, 2009; Nelson, 2011). The nature and intensity of poverty and vulnerability to risks is also gender-specific (Holmes and Jones, 2009).

To ensure that interventions aimed at increasing productivity and reducing risks linked to climate change are effective and sustainable, it is important to address gender inequalities and discrimination in access to productive resources, services and employment opportunities, so that men and women can benefit equally.

BOX 9

GENETIC DIVERSITY IMPROVES RESILIENCE

FAO has published *Voluntary guidelines to support the integration of genetic diversity into national climate change adaptation planning*. If properly conserved and used in breeding programmes, genetic diversity can provide crop varieties that are more tolerant to increased aridity, frost, flooding and soil salinity, and livestock breeds that are both highly productive and tolerant to harsh production environments. Policies that anticipate future needs, and plan the management of genetic resources as a pivotal reservoir and tool, can help build resilient agricultural production systems.

Greater efforts are needed to conserve and support the sustainable use of plant varieties and livestock breeds and to collect and conserve the wild relatives of important food crops. Maintenance of on-site farm diversity allows for evolution in step with environmental changes, while regional and global gene banks provide backup collections of genetic material that can be drawn upon to support climate change adaptation measures. Given that all countries depend on genetic diversity from other countries and regions, international cooperation and exchange is crucial. The International Treaty on Plant Genetic Resources for Food and Agriculture allows researchers and breeders to access genetic resources from other countries.

SOURCE: FAO, 2015a.

» responses aimed at reducing vulnerability need to go hand in hand with policies for broader agricultural and rural development. Such an approach creates conditions that help to reduce exposure and sensitivity to weather shocks, while building adaptive capacity in ways that can provide new opportunities for improving rural livelihoods and food security.

Resilient livelihoods imply conditions, such as adequate income and food security, which allow people to withstand, recover from and adapt to the climate risks they are exposed to. Since smallholders' circumstances and opportunities differ greatly across locations, pathways for adaptation and building resilience must be designed specifically for each context, taking into account the degree of exposure to climate shocks as well as adaptation capacity. This section identifies the main features of possible pathways to reduced vulnerability to climate change for smallholder systems and the populations that depend on them. It addresses two dimensions: ways to increase the resilience of agricultural production systems and ways to enhance the resilience of vulnerable populations' livelihoods.

Innovation: the key to farming system adaptation

Addressing the new challenges posed by climate change will require innovations in farming systems. Innovation happens when individuals and groups adopt new ideas, technologies or processes which, when successful, spread through communities and societies. The process is complex, involving many actors, and it cannot function in a vacuum. It is furthered by the presence of an effective *innovation system*. An agricultural innovation system includes the general enabling, economic and institutional environment required by all farmers. Other key components are research and advisory services and effective agricultural producers' organizations. Innovation often builds on and adjusts local knowledge and traditional systems, in combination with new sources of knowledge from formal research systems (FAO, 2014a).

Innovations that strengthen the resilience of smallholder farming systems to climate change include enhanced resource-use efficiency through sustainable intensification of production, and the adoption of agroecological production systems. Improving water resource management is another area where innovation can be effective in addressing climate change impacts. All of these approaches improve carbon and nitrogen management (see below and Chapter 4).

Biotechnologies, both low- and high-tech, can help small-scale producers in particular to be more resilient and to adapt better to climate change. While the subsections that follow focus mainly on innovation through management practices, some practices may depend on the outcomes of biotechnology, such as improved seed.

Sustainable intensification

Sustainable intensification raises productivity, lowers production costs and increases the level and stability of returns from production, while conserving natural resources, reducing negative impacts on the environment and enhancing the flow of ecosystem services (FAO, 2011b). The nature of sustainable intensification strategies varies across different types of farming systems and locations. However, one of the core principles is increasing the efficiency of resource use.

FAO's approach to sustainable crop production intensification is the "Save and Grow" model. Save and Grow promotes a productive agriculture that conserves and enhances natural resources. It uses an ecosystem approach that draws on nature's contribution to crop growth, such as soil organic matter, water flow regulation, pollination and natural predation of pests. It applies appropriate external inputs at the right time and in the right amount to improved crop varieties that are resilient to climate change and use nutrients, water and external inputs more efficiently. Increasing resource use efficiency, cutting the use of fossil fuels and reducing direct environmental degradation are key components of the approach, saving money for farmers and preventing the negative effects of overusing particular inputs. This approach has been extended to other agriculture sectors.

Through better management of carbon and nitrogen cycles (see below), sustainable agricultural intensification also builds greater resilience to climate change impacts and contributes to reducing GHG emissions (Burney *et al.*, 2010; Wollenberg *et al.*, 2016).

Agroecology

According to HLPE (2016), agroecology applies ecological concepts and principles to farming systems. Through its focus on the interactions between plants, animals, humans and the environment, it fosters sustainable agricultural development, which in turn ensures food security and nutrition. Agroecology goes beyond input use efficiency and input substitution by: harnessing key ecological processes, such as natural pest predation and the recycling of biomass and nutrients; enhancing beneficial biological interactions and synergies among the components of agrobiodiversity; and optimizing the use of resources. Agroecological principles, as defined by Nicholls, Altieri and Vazquez (2016), are of particular relevance to climate change adaptation, as they aim to:

- enhance the recycling of biomass, with a view to optimizing organic matter decomposition and nutrient cycling;
- strengthen the "immune system" of agricultural systems through the enhancement of functional biodiversity, e.g. by creating habitats for natural enemies of pests;
- provide the most favourable soil conditions for plant growth, particularly by managing organic matter and by enhancing soil biological activity;
- minimize losses of energy, water, nutrients and genetic resources by enhancing conservation and regeneration of soil and water resources and agrobiodiversity;
- diversify species and genetic resources in the agroecosystem over time and space, at the field and landscape level; and
- enhance biological interactions and synergies among the components of agrobiodiversity, thereby promoting key ecological processes and services.

Agroecology builds on the local and traditional knowledge of farmers to create solutions based on farmers' needs. For example, Swiderska (2011) found that access to diverse traditional crop varieties was essential for climate change adaptation and survival among poor farmers in China, Bolivia and Kenya. In China, farmers who grew four different mixtures of rice varieties suffered 44 percent less blast incidence and achieved 89 percent higher yields, when compared to single-variety fields, and without the need to use fungicides (Zhu *et al.*, 2000). Agroecological diversification contributes to yield stability under climatic variability. Polycultures exhibit greater yield stability and suffer fewer productivity declines during a drought than monocultures (Altieri *et al.*, 2015).

Efficient water management

As climate change alters rainfall and water availability patterns, the capacity to deal with water scarcity or water excess will be crucial in efforts to sustainably improve productivity. The areas with the highest potential for water productivity improvements are those with a high incidence of poverty, including many parts of sub-Saharan Africa, South Asia and Latin America, as well as areas where competition for water is intense, such as the Indus Basin and Yellow River (HLPE, 2015).

Increasing water use efficiency in agricultural systems under climate change may require action in the fields of policy, investment and water management, and institutional and technical changes applied at different scales: on fields and farms, in irrigation schemes, in watersheds or aquifers, in river basins and at the national level (FAO, 2013a). As a first step towards adaptation to longer-term climate change impacts, information about current climate variability needs to be incorporated into water management (Sadoff and Muller, 2009; Bates *et al.*, 2008 as cited in Pinca, 2016).

In rainfed systems, which account for 95 percent of farmland in sub-Saharan Africa, better management of rainwater and soil moisture is the key to raising productivity and reducing yield losses during dry spells and periods of variable rainfall. Supplemental irrigation, using water harvesting or shallow groundwater resources, is an important but underused strategy for increasing water productivity in rainfed agriculture (HLPE 2015; Oweis, 2014).

In irrigated systems, water use efficiency can be promoted through institutional changes, such as the creation of water users' associations, and infrastructural improvements, such as lining canals, more efficient drainage networks and wastewater reuse. Water-efficient irrigation technologies, such as drip emitters, and better maintenance of irrigation infrastructure, combined with appropriate training to build farmers' technical knowledge, can be effective in dealing with climate change impacts on water availability and food security (Box 10). However, some technologies that improve water use efficiency, such as drip irrigation, require energy. More broadly, there are often trade-offs and possible synergies in the use of water, energy and land for food production. The "water-energy-food nexus" approach is a useful concept when planning the use of these resources in agrifood chains (FAO, 2014b).

Carbon and nitrogen management options

The Earth's carbon and nitrogen cycles are affected by the types of soil, nutrient and water management practices farmers adopt, by the extent of agro-forestry practised, and by the expansion of agriculture onto non-agricultural land (see also Chapter 4). Smallholders, in particular, can benefit from practices that help restore soil productivity in areas where unsustainable land management has depleted soil organic carbon, natural soil fertility and soil quality, resulting in reduced productivity and increased vulnerability to climate hazards such as drought, flooding, and conditions that favour pests and diseases (Stocking, 2003; Lal, 2004; Cassman, 1999; FAO, 2007).

On cropland, levels of soil organic carbon (SOC) and plant-useable soil nitrogen can be improved through the adoption of practices such as agroforestry, improved fallows, green manuring, nitrogen-fixing cover crops, integrated nutrient management, minimum soil disturbance and the retention of crop residues. On grazing lands, improved pasture management, reducing or eliminating the occurrence of fires, and introducing improved fodder grasses or legumes are important means of improving carbon management. Mixed farming systems enhance resilience and reverse soil degradation by controlling erosion, providing nitrogen-rich residues and increasing soil organic matter. For example, drought-tolerant mixed farming systems practised in Ethiopia and the United Republic of Tanzania include a multipurpose legume, such as pigeon pea (*Cajanus cajan*), and *Faidherbia albida*, an indigenous nitrogen-fixing leguminous tree which provides pods palatable to livestock and leaves used as organic fertilizer. Higher production of pulses helps to diversify diets and provides extra protein during periods of seasonal food insecurity.

Context-specific climatic conditions will influence smallholders' choice of the carbon and nitrogen management options that are the most effective in improving their livelihood. For example, the application of mineral fertilizer may generate higher yields under average climatic conditions, but lower yields under conditions of high rainfall variability or the delayed onset of rainfall. Conversely, crop rotation may produce lower yields under average climatic conditions, but higher yields and a lower probability of yield loss under conditions of high rainfall variability (Table 8).

Improvements in the use of nitrogen fertilizer are critical to the sustainability of many smallholder farming systems. Indicators of nitrogen fertilizer use show that application rates and cereal yields are much higher in East Asia, but the additional amount of production obtained from fertilizer input is significantly higher in sub-Saharan Africa (Table 9). Also significantly higher is the partial nutrient balance – in sub-Saharan Africa, more nutrients are removed with the harvested crop than applied in fertilizer or manure, indicating unsustainable soil nutrient depletion. In East Asia, the opposite is the case.

Overuse of mineral fertilizer is clearly a problem in East Asia, where the excess input provides no »

BOX 10

BENEFITS OF WATER SAVING IN CHINA

China's Huang-Huai-Hai Plain is critical to the country's agricultural economy and national food security. Productivity is threatened by climate changes, including a significant overall increase in temperature and declining levels of humidity and precipitation over the past half-century (Yang *et al.*, 2015; Hijioka *et al.*, 2014).

In five of the region's provinces, a World Bank-financed project has promoted water-saving technologies and other improved practices – such as the use of drought-resistant crop varieties – with the goal of improving water management on some 500 000 ha of farmland. Irrigation facilities constructed as part of the project were transferred to 1 000 water users' associations, which were formed with government support and participate in all water management decisions. The associations also provide platforms for training in new water management techniques.

The project helped establish 220 farmer associations and cooperatives and undertook a variety of research, experimental and demonstration activities. The focus was on adaptation measures and water-saving technologies, which were subsequently put into practice by farmers. Some 1.3 million farm families saw benefits in the form of reduced irrigation costs, less groundwater depletion and higher water productivity.

SOURCE: Adapted from FAO and World Bank (2011).

TABLE 8

IMPACTS ON CROP YIELDS UNDER DIFFERENT CLIMATE EFFECTS IN ZAMBIA

	Higher yields	Lower yields	Reduced probability of yield loss
Average climatic conditions	Legume intercropping Inorganic fertilizer Improved seed	Crop rotation	Crop rotation Improved seed Timely fertilizer access
Increased rainfall variability	Crop rotation Timely fertilizer access	Inorganic fertilizer	Crop rotation
Delayed onset of rainfall	Improved seed Timely fertilizer access	Inorganic fertilizer	Inorganic fertilizer
Increased seasonal temperature	Timely fertilizer access	Improved seed	Improved seed

SOURCES: Based on Arslan *et al.* (2015), Tables 6, 7 and 8.

TABLE 9

DIFFERENCES IN NITROGEN USE IN SMALLHOLDER FARMING IN EAST ASIA AND SUB-SAHARAN AFRICA

	East Asia	Sub-Saharan Africa
Average nitrogen applied in cereal crop production (kg/ha)	155.0	9.0
Average cereal crop yield (tonnes/ha)	4.8	1.1
Partial factor productivity of nitrogen (kg grain/kg N)	31.0	122.0
Partial nutrient balance (kg N in grain/kg N applied)	0.5	1.8

SOURCES: Based on Fixen *et al.* (2015), Table 3.

» benefit; on the contrary, it is causing severe environmental harm, in the form of ground and surface water contamination, and greenhouse gas emissions. In East Asia, therefore, reducing mineral fertilizer use and ensuring the correct amount, timing and placement is an important part of sustainable intensification.

In sub-Saharan Africa, on the other hand, increasing the level of mineral fertilizer use, up to appropriate amounts, has considerable potential for boosting smallholder crop yields. However, given the generally poor condition of soils in much of the region, smallholders need support in improving soil quality and soil ecosystem services, as a complement to judicious fertilizer application.

Improved carbon and nitrogen management are also important for fishery and forestry systems. Box 11 presents an example from Viet Nam, where carbon management measures were introduced as part of an integrated climate-smart aquaculture system.

Food security benefits of improved farming practices

Significant improvements in food security can be achieved with the introduction of improved agricultural practices. Simulations using IFPRI's IMPACT model show that the adoption of heat-tolerant crop varieties produces the highest projected global yield increase for maize in 2050. Varieties that use nitrogen more efficiently produce the highest global yield increase for rice, while zero-tillage is the best option for wheat (Rosegrant *et al.*, 2014; De Pinto, Thomas and Wiebe, 2016).

Adopting these technologies would have significant positive impacts on food security by increasing the availability of food energy, enhancing smallholders' incomes and lowering food prices. The number of people at risk of undernourishment in developing countries would be reduced in 2050[5] by 12 percent (or almost 124 million people) if nitrogen-efficient crop varieties were widely used, by 9 percent (or 91 million people) if zero-tillage were more widely adopted, and by 8 percent (80 million people) if heat-tolerant crop varieties or precision agriculture were adopted (Figure 14).

The results assume standalone introduction of the indicated practices, and that the practices are adapted to the specific socio-economic and agro-ecological contexts where adoption is projected to occur. Under the climate-smart agriculture approach, an evidence base is developed to identify practices that are actually adapted to the local context. They are not determined *a priori* but based on a process of building evidence and dialogue. There is no standard list of climate smart agriculture practices that can be universally applied: in some cases zero-till agriculture does provide significant adaptation benefits, while in others it does not (Arslan *et al.*, 2015). It is also important to recognize that there is a wide range of combinations of practices that farmers may adopt to suit their specific needs.

In many contexts, it makes sense to combine the set of improved practices by "stacking" one on top of the other in the same order as crop production activities (i.e., first improvements in land preparation, planting and crop management, followed by irrigation, etc.). Model projections indicate that the benefits to food security are greater – up to three times greater than that which can be obtained from the improved use of nitrogen alone – when a combined set of improved practices is adopted, compared with the benefits of a single practice (Rosegrant *et. al.*, 2014).

Four strategies to build livelihood resilience

Diversification

Diversification is an important means of climate change adaptation because it helps to spread the risk of climatic variability damaging livelihoods. First, a distinction should be made between *agricultural* diversification and *livelihoods* »

5 The baseline scenario of IFPRI's IMPACT model used for these estimations projects a total of about 1 billion undernourished people by 2050, explaining why an impact of 12 percent on account of introducing nitrogen-efficient crop varieties would amount to a reduction in the number of people at risk of hunger by 124 million.

BOX 11

CLIMATE-SMART AQUACULTURE IN VIET NAM

Both climate change adaptation and mitigation measures are needed to protect coastal aquaculture production in Viet Nam's North Central Coast region. One feasible option is developing climate-smart aquaculture practices that integrate mono-sex tilapia into traditional mariculture systems.

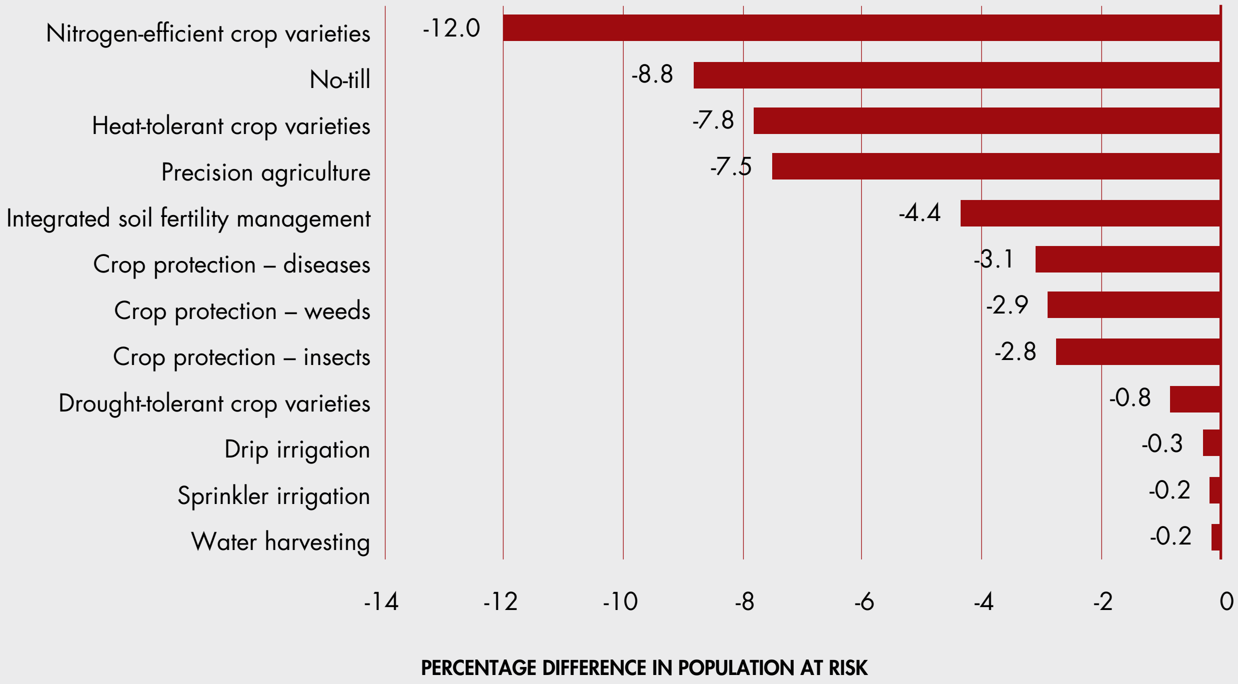
The results of trials in Thanh Hoa province show that incorporating tilapia is a good adaptation strategy, which addresses all three objectives of climate-smart agriculture: sustainably increasing productivity, increasing adaptive capacity and reducing GHG emissions. The approach resulted in higher production efficiency and increases in household income of between 14 and 43 percent. The diversified product portfolio also boosted the resilience of the system. By using natural feed sources and excess nutrients in the tilapia ponds, farmers were able to reduce the need for pellet feed, which helped to lower GHG emissions.

The promotion and scaling-up of climate-smart aquaculture requires policy incentives, regulations and strong institutional frameworks. Because the introduction of tilapia increases overall production, efforts are needed to expand markets, especially export markets, for the fish. Obstacles to adoption, such as the low quality and high cost of feed, can be overcome by connecting farmer groups to feed and seed suppliers.

SOURCE: Trinh, Tran and Cao, 2016.

FIGURE 14

CHANGE IN 2050 IN THE NUMBER OF PEOPLE AT RISK OF HUNGER, RELATIVE TO THE BASELINE SCENARIO, AFTER ADOPTION OF IMPROVED AGRICULTURAL TECHNOLOGIES



SOURCE: Rosegrant *et al.* (2014), based on simulations with IFPRI's IMPACT model.

» diversification (Thornton and Lipper, 2014). Agricultural diversification means adding plant varieties and species, or animal breeds, to farms or farming communities. It may involve landscape diversification, with different crops and cropping systems being interspersed in space and time. Livelihood diversification means farming households engaging in multiple agricultural and non-agricultural activities – for example, by combining on-farm activities with seasonal agricultural work elsewhere, taking a job in the city, processing farm products or opening a shop. Both agricultural and livelihood diversification are ways of managing climate risk.

Since climate shocks affect different farming and non-farming activities differently, diversification can potentially reduce the impact of these shocks on income, and provide a broader range of options for managing future risks. When combined with risk-mitigating measures, such as crop insurance or social protection, diversification can lead to higher incomes and help accelerate poverty reduction. However, if farmers diversify to low-productivity activities, it may actually reduce average income, force households to sell off assets in the event of shocks, and trigger a vicious cycle of greater vulnerability and exposure to risk (Dercon, 1996). The scope of crop diversification as a means of mitigating climate risks may be limited where the risks affect equally different varieties of crops (Barrett, Reardon, and Webb, 2001). However, crop diversification may still be an option, where farm conditions are neither so marginal that they limit diversification nor sufficiently optimal for a single high-return crop (Kandulu *et al.*, 2012).

Faced with climate variability, farm households engage in different diversification strategies, depending on the nature of their exposure and the performance of institutions. For instance, when rainfall is more variable, farmers seek alternative sources of income and employment in Malawi, but diversify into livestock in Zambia (Box 12). Where weather risks are high, many households in sub-Saharan Africa favour mixed livestock-crop systems, using their livestock as an asset to smooth income fluctuations (Herrero *et al.*, 2010 and 2013; Baudron *et al.*, 2013). Mixed farming systems provide, via manure amendments, about 15 percent of the nitrogen inputs used in crop production, which reduces input costs and achieves an emission intensity substantially lower than that of many grazing systems (Liu *et al.*, 2010; Herrero *et al.*, 2013). In addition, diversified farms can play an important role in maintaining and increasing the provision of ecosystem services, which helps to increase overall resilience (Ricketts, 2001; Kremen and Miles, 2012).

Support to risk management

Social protection programmes, which are a critical tool for poverty alleviation, may also play an important role in helping smallholders to manage risk under climate change. Social protection takes various forms, from cash transfers to school meals and public works. Agricultural input subsidies may also have a social protection function by helping to reduce the vulnerability of smallholders to price volatility. Evidence from Latin America and sub-Saharan Africa shows the clear benefits of social protection in terms of food security, human capital development, and economic and productive capacity, even among the poorest and most marginalized.

By ensuring predictability and regularity, social protection instruments enable households to better manage risks and engage in more profitable livelihood and agricultural activities. When directed towards women, they are not only empowering, but improve households' overall welfare thanks to women's priorities of food and nutrition security and children's wellbeing. Social protection programmes also have an important impact on the agricultural investment decisions of rural households and thus have a longer-term positive impact on access to food (FAO, 2015c).

In Zambia, households in areas that experienced lower than average rainfall had lower levels of daily caloric intake as well as lower food and non-food expenditures. This effect was most pronounced in the poorest households. Thanks to a cash transfer programme aimed at 20 000 ultra-poor households, they suffered much less from weather shocks. However, while participation in »

BOX 12

CLIMATE RISK, DIVERSIFICATION AND SMALL FARMER WELFARE IN MALAWI AND ZAMBIA

Malawi and Zambia are among the 15 countries most vulnerable to the adverse effects of climate change (Wheeler, 2011), particularly in agriculture. The sector employs a significant share of the population, which depends primarily on rainfed subsistence production and is, therefore, vulnerable to various shocks.

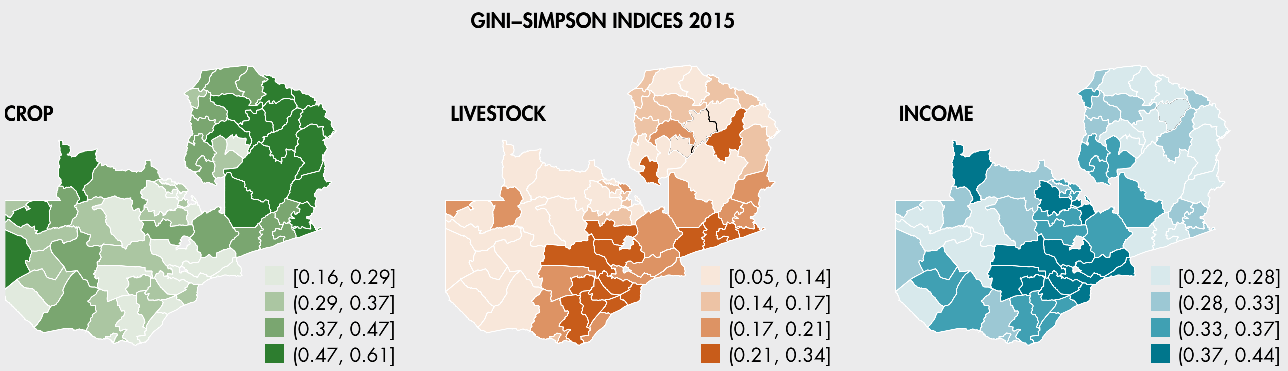
To what degree is diversification an effective climate change adaptation strategy for these countries? Recent FAO studies document various types of diversification in the farm sector – diversification into different crops, livestock, and natural resource- related activities or working on other farms – as well as in the non-farm sector, through activities such as wage employment, self-employment, transfers and rents.

The studies found that rates of crop, labour and income diversification in Malawi, and livestock diversification in Zambia, are higher where climate variability is greater, indicating that exposure to climate risk induces different types of diversification. In Zambia (see Figure), patterns of diversification vary: households diversify their crops more in areas with higher long-term average seasonal rainfall; livestock diversification is higher in areas where the long-term variation in rainfall is higher; and income diversification shows no clear pattern correlated with weather variables.

In general, access to extension led to greater crop, labour and income diversification in both countries. Households that received fertilizer subsidies in Malawi were more likely to have diversified crops and incomes, while in Zambia such households had lower levels of income diversification. This underlines the importance, when designing policies for diversification, of understanding how local institutions interact with incentives to diversify.

With the exception of crop diversification in Zambia, each type of diversification is associated with higher consumption or income per capita in both countries. In Malawi, income diversification reduces the variability in farm household consumption levels – an important indicator of food security. In Zambia, households engaging in any of the three types of diversification were found to be less likely to fall below the poverty line. The combined findings on diversification and incomes suggest policy entry points to improve institutions that facilitate the types of diversification needed to build resilience to shocks.

DIVERSIFICATION INDICES IN RURAL ZAMBIA BY DISTRICT



SOURCES: Based on FAO (2015b) and Arslan *et al.* (2016b).

» the cash grants programme helped mitigate the negative effects of climate shocks on food security, it was not sufficient to fully overcome them. It is important to ensure, therefore, that social protection programmes are aligned with other forms of climate risk management, including disaster risk reduction (Asfaw *et al.*, 2016b).

Existing social protection programmes rarely take climate risk into account. In order to fill this gap, several humanitarian and development stakeholders, including FAO, are helping national governments set up risk-informed and shock-responsive social protection systems, which provide support ahead of a crisis, based on economic and climate risk-related criteria (UNEP, 2016; Winder Rossi *et al.*, 2016). If effectively linked to early warning systems and informed by agricultural, food security and nutritional parameters, social protection systems can also be used to plan a timely response to emergencies (FAO, 2016a).

Implementation of the approach outlined above is achieved through the scaling-up of interventions that provide cash and short-cycle productive assets, accompanied by technical training. Where markets function and currency is stable, cash transfers have the advantages of cost-effectiveness, impact and flexibility, and give beneficiary households greater choice. Nevertheless, in 2015, cash transfers and vouchers accounted for only 6 percent of humanitarian aid (ODI, 2015). Enhancing the potential of cash-based interventions requires integrating cash in preparedness and contingency planning, strengthening partnerships with the private sector, using e-payments and digital transfers, and – when possible – leveraging cash transfers to build medium and long-term social assistance structures that can be used in recurrent emergencies.

Entry points and operational linkages between social protection and climate change policies are multiple. *Public works programmes*, including productive safety nets, can be designed to simultaneously contribute to increasing household incomes, engaging communities in climate-smart agriculture, and generating "green jobs" in areas such as waste management, reforestation and soil conservation (Asfaw and Lipper, 2016). *Index-based insurance*, which pays out benefits on the basis of indices such as rainfall, area-average yields and vegetation conditions measured by satellites, is being tested as a risk-mitigation tool in several countries. When an index exceeds a predetermined threshold, farmers receive a quick pay-out, delivered in some cases via mobile phones. However, index-based insurance by itself does not provide a full solution to climate-related risk. For example, India's Weather-Based Crop Insurance Scheme may have prompted a shift among participants towards more profitable but higher risk farm production systems, thanks to subsidized premiums (Cole *et al.*, 2013). Uptake of index-based insurance has been generally limited because it usually involves high transaction costs. Another problem is a lack of trust in insurance institutions.

Better information about weather conditions would help small-scale producers to adapt to foreseeable variations in climate by, for example, adjusting planting dates or timely sheltering of livestock. Surveys have found that farmers in Eastern and Southern Africa who were able to access seasonal forecasts changed at least some management decisions, which helped them to reduce harvest losses (O'Brien *et al.*, 2000; Ngugi, Mureithi and Kamande, 2011; Phillips, Makaudze, and Unganai, 2001, 2002; Klopper and Bartman, 2003; Mudombi and Nhamo, 2014). Access to climate-forecast information helped farmers in Kenya to avoid losses equivalent to as much as a quarter of their average net income (Erickson *et al.*, 2011). Farmers with access to information and communications technology tend to routinely use available climate information (Ramussen *et al.*, 2014). Investing in institutions that share seasonal forecasts, a key area of climate information, can increase farmers' capacity to reduce their exposure to risks (Hansen *et al.*, 2011). Likewise, for disaster relief agencies, overcoming institutional barriers to the use of seasonal forecasts has proved critical to saving lives during climate crises (Tall *et al.*, 2012).

Reducing gender inequalities

Because men and women have different priorities and capacities in responding to climate change, policy-makers and institutions need to explicitly recognize gender differentials in designing interventions that strengthen the resilience of rural livelihoods (Acosta *et al.*, 2015; Gumucio and Tafur-Rueda, 2015). Social norms often impose agricultural responsibilities and limit women's choices, which determine the type of information they need and the information channels they can access (Archer and Yamashita, 2003; McOmber *et al.*, 2013; Jost *et al.*, 2015). For example, information about the timing of rainfall onset is important for male farmers in Senegal because men have priority access to animals for field preparation; women lack the capacity to act on the information, and prefer forecasts of rainfall cessation and dry periods (Tall *et al.*, 2014).

The Kenya Agricultural Carbon Project, implemented by Vi Agroforestry and the World Bank, highlights several strategies that address gender disparities in land and tree tenure, labour, knowledge, benefit sharing, participation and leadership. Examples include: contracts signed by groups, including women even though they do not own land; investments in training designed to reach women (e.g. hiring female community facilitators); the provision of seedlings of tree species usually desired by women (e.g. species that provide fuelwood, fodder, shade and fruit); rotating leadership systems and rules; and improvements in women's access to loans and insurance (World Bank, 2010a; Vi Agroforestry 2015; Shames *et al.*, 2012). A participatory project in the water-stressed Kumbharwadi community, in Maharashtra state, India, reduced the amount of time women spent collecting drinking water and fuelwood by installing sources for both nearer to their homes, and helped to increase women's participation in village decision-making processes. The project resulted in an increase in the incomes of poor households (Gray and Srinidhi, 2013; World Bank, FAO and IFAD, 2015).

Migration

Environmental and climate stresses on livelihoods – such as droughts, floods and unpredictable weather patterns – push rural people to migrate. As land is farmed more intensively, soil degradation increases, production declines, and incomes fall. Likewise, water scarcity caused by prolonged drought and conflicts over water use may induce poorer farmers to abandon the land. Temporary, seasonal and permanent migration can be a form of livelihood diversification, which provides significant benefits to many rural households. It is a key source of income diversification that boosts household resilience and provides the means for productivity-enhancing investments. On the downside, migrants often face multiple hardships, risks and dangers.

One study projects that hundreds of millions of people might need to flee their homes as a result of climatic and environmental pressures between now and 2050 (IIED, 2010). Such forecasts have helped to place migration as an issue to be addressed in climate change adaptation. In their adaptation strategies, governments tend to take one of two approaches (KNOMAD, 2014). The first, and most common, sees adaptation as a way of reducing migration pressures and allowing people to remain where they are by improving agricultural practices and infrastructure. In the second view, migration is itself an adaptation strategy, which alleviates population pressure on fragile areas. Of particular interest to development policy-makers is the potential of migrants already living outside of vulnerable areas to help their home communities adapt and respond to climate change.

Social protection and active labour market policies can play important roles in mitigating many of the risks associated with migration. Better quality education and training would enhance the employment prospects of rural people who decide to migrate, especially youth, and of those who seek more skill-intensive employment in sustainable agriculture. Provision of suitable transport and communications infrastructure, either directly by the public sector or by promoting private investment, will be important in bringing down the costs associated with both travel and sending remittances, as well as facilitating flows of information on employment and business opportunities. ■

HOW MUCH WILL ADAPTATION COST?

How much will it actually cost to build the capacity of smallholder producers to adapt to climate change? That question arises often, particularly in the context of developing new sources of climate finance. A review of literature on the costs and benefits (to the entire economy) of adaptation to climate change identified more than 500 papers on the topic (Watkiss, 2015). Estimates vary for many reasons, including differences in regional coverage, climate change scenarios, methods and models, as well as in the time period, adaptation measures and sectors that were considered. Various global studies suggest that the costs of inaction far outweigh the costs of adaptation to climate change (Stern, 2007; OECD, 2012; Stern 2014; OECD, 2015). Some country-level analyses provide estimates of the costs of inaction side by side with costs of adaptation. Here we consider two such studies in developing countries, where a large share of farmers are smallholders, as well as a study initiated by FAO focusing specifically on smallholders in four countries (Box 13).

A study from Uganda estimates the economic impacts of climate change on agriculture, water, energy and infrastructure as ranging from a cumulative US$273 billion to US$437 billion between 2010 and 2050, depending on assumptions about socio-economic development and the severity of climate change (Markandya, Cabot-Venton and Beucher, 2015). Considering solely the agriculture sector, the costs of inaction, in terms of reduced crop and livestock production as well as reductions in exports, amount to between US$22 billion and US$38 billion in the same period. While the budget for adaptation, including more efficient irrigation systems, improved crop varieties, more adapted and productive livestock breeds, and credit facilities, could reach almost US$644 million annually by 2025, the cost of inaction would be up to 46 times higher.

A case study for Viet Nam likewise shows that the economic costs of climate change are likely to be far higher than the costs of adaptation (World Bank, 2010c). Although adaptation will not prevent economic losses as a result of climate change, it will significantly reduce their magnitude. Without adaptation, agricultural losses due to climate change are estimated at about US$2 billion per year. Even with adaptation, some losses are likely, but they will be limited to about US$500 million, thus reducing total losses by about US$1.5 billion dollars annually. Adaptation would include farmers' own adaptation strategies, such as changing planting dates and using drought-tolerant or salinity-resistant varieties, as well as government interventions, including investments in irrigation and increased spending on agricultural research and development. The costs of adaptation, estimated at about US$160 million annually over the period 2010–2050, would be a fraction of the savings from adaptation.

In short, while few systematic studies are as yet available on the cost of climate change adaptation in smallholder agriculture, the available evidence points to overwhelmingly positive benefit-cost balances. This is especially so when taken as the difference between the cost of non-action and the benefits of action, but also when weighing the cost of investments in climate-smart agricultural practices and the gains in terms of yield increases, livelihood improvements and reductions in the number of food insecure. The main issue, therefore, is how to manage the transition to sustainable agriculture and minimize the transaction costs for smallholder systems. ■

BOX 13

BENEFITS AND COSTS OF INVESTING IN SMALL FARMER ADAPTATION

Changes in agricultural practices will be an important means of building resilience and improving carbon and nitrogen management in smallholder production systems. However, the rates of adoption of these practices among farmers are fairly low.

The question is: how much will it cost to boost adoption rates to the level required to abate the negative effects of climate change? A modelling study that considers farmers' cropping decisions under climate change, combined with empirical estimates from household surveys in four countries, provides insights that help to answer this question (Cacho *et al.*, 2016). The study includes model results from four areas in four countries that are highly vulnerable to climate change impacts on agriculture: Bangladesh, India, Malawi and the United Republic of Tanzania.

The study projected the expected rates of adoption in 2050 of climate-smart agriculture, based on empirical evidence on adoption rates. The highest adoption rate is projected to be in Malawi with 96 percent, followed by United Republic of Tanzania (64 percent), India (62 percent) and Bangladesh (54 percent)*. However, projected levels of adoption, while relatively high, are unlikely in most cases to be sufficient to fully counterbalance climate change impacts on smallholders. This suggests that CSA practices alone will not be enough to achieve the transformational changes needed, without higher levels of investment in building enabling environments and in promoting technologies with high adaptation potential.

The study also looked into the costs and benefits of adaptation through investments in improved seed suited to projected changes in local conditions. In the absence of adaptation, the cost of climate change to smallholders is substantial under a scenario of severe climate change (Table A). Through the adoption of drought-resistant seed, and based on conservative yield assumptions, the losses due to climate change are reduced by between 34 percent and 51 percent, depending on the country. The net present value (NPV) of investments in improved seed adoption was estimated to range from an average of US$203 per ha in Malawi to US$766 per ha on rainfed land in India.

TABLE A

NET BENEFITS OF IMPROVED SEED ADOPTION IN SELECTED COUNTRIES FOR THE PERIOD 2020–2050 (net present value at a discount rate of 5%)

	Estimated cost of climate change damage (Present value in million US$)		Difference	Area considered	Net present value of seed adoption
	Baseline (no adaptation)	Improved seeds	%	(Million ha)	(US$/ha)
Bangladesh	221	125	43	0.2	454
India	13 595	6 626	51	9.1	766
Malawi	981	516	47	2.3	203
United Republic of Tanzania	8 567	5 622	34	9.7	303

Note: The base case under current conditions is compared to a case where improved seed is developed and reduces by 30% the damage under the most severe climate scenario (RCP 8.5). Assuming a policy in support of the adoption of improved seed, the cost per hectare is calculated as the sum of fertilizer and seed purchase and distribution costs, plus administration costs, divided by the total area covered by the policy. The net benefit over a period of 30 years is estimated, subtracting the costs of implementation of the policy.

SOURCE: Cacho *et al.*, 2016.

BOX 13

(CONTINUED)

The results suggest that well-designed, targeted adaptation initiatives can generate high returns to smallholders under the projected effects of climate change. In the case of improved seed, this requires interventions in the whole supply chain – from ensuring that sufficient quantities of seed are produced, to supporting the development of local enterprises needed to market inputs and buy outputs. Establishing systems that reduce the transaction costs of smallholder access to seed supply is also an important aspect of effective policies.
The analysis also looked at benefit-cost ratios of two other important climate adaptation measures: irrigation and water-saving technologies. The average benefits of irrigation under climate change were estimated at US$226 per ha in Bangladesh and US$494 per ha in India (Table B).
Benefits were calculated as the value of avoided damage per hectare, based on smallholders' crop revenues. The per hectare costs of irrigation improvements are lower for producers in small-scale systems, and consequently the benefit-cost ratios are considerably higher, which further supports the argument that investments made now in effective adaptation will provide high returns to smallholder agriculture.

TABLE B

BENEFITS AND COSTS OF IRRIGATION PER HECTARE IN 2050

	Benefits of irrigation (US$/ha)	Cost of irrigation infrastructure (US$/ha)		Benefit / Cost	
		Small scale	Large scale	Small scale	Large scale
Bangladesh	226	29	79	7.8	2.9
India	494	29	79	17.0	6.3

SOURCE: Cacho *et al.*, 2016.

* The LPJml-MAgPIE model framework (Popp *et al.*, 2016; Lotze-Campen *et al.*, 2008; Bondeau *et al.*, 2007) was used to estimate crop yields and prices under alternative climate scenarios. Crop yield projections were consistent with those of the IFPRI IMPACT model. Results for Bangladesh and India are not nationally representative. The survey used covered only a selection of villages.

MANAGING THE TRANSITION TO CLIMATE-SMART SMALLHOLDER SYSTEMS

Identifying barriers to adoption and assessing trade-offs

Climate-smart agriculture recognizes that there may be trade-offs, as well as synergies, among its three objectives of sustainably increasing productivity, increasing adaptive capacity and resilience to shocks, and reducing greenhouse gas emissions. This is particularly important when considering options for transforming smallholder agriculture for poverty reduction under climate change. The debate around possible trade-offs between mitigation and food security has been heated, owing to concerns that smallholder producers in developing countries might be forced to bear the costs of reducing greenhouse gas emissions in order to mitigate a climate change problem not of their making and from which they stand to suffer most (Lipper *et al.*, 2015).

The climate-smart approach addresses this issue explicitly by identifying the costs of mitigation actions through development of a site-specific evidence base. First, a proper assessment of the barriers smallholders face in transitioning to climate-smart, sustainable agricultural systems is undertaken (Box 14). The initial assessment is then the subject of dialogue among all stakeholders to decide what changes in policies and incentive structures are needed in order to create enabling conditions for the transition.

Explicit recognition of the costs of making changes is needed in order to adequately identify where trade-offs are possible. For example, the improvement of soil carbon stocks through improved land management and restoration carries investment costs in the form of fencing, seed and machinery, opportunity costs in the form of lost production, and operating costs in the form of annual labour inputs needed to maintain and enhance soil carbon. The costs of adopting practices that increase soil carbon can be quite significant for smallholders, particularly in the initial and transition phases. They can also outweigh the benefits to the farmers themselves, while generating benefits to others, by improving landscape and watershed functions.

Table 10 provides an example of these costs, indicating the number of years before a positive return could be obtained by yak herders in Qinghai Province, China, if they invested in restoring their highly degraded grazing lands. The smallest producers have the smallest returns in terms of the net present value (NPV)[6] per hectare of investment. They also face the longest wait for positive returns – it would take 10 years for their investment in restoration of degraded grazing lands to yield the same level of income they make with the current degraded system. While the restoration of highly degraded lands is considerably more expensive, the costs associated with the adoption of improved land management practices on good soils also represents a significant trade-off for farmers (FAO, 2009).

6 The NPV of an investment is the difference between the present value of cash inflows and outflows

The costs that agricultural producers face – and therefore also the trade-offs – are influenced by the policy and institutional environment. An important step in the transition to climate-smart agriculture, therefore, is assessing the need to modify existing policy measures, such as input subsidies, and the potential of social protection programmes to address risks imposed by climate change. For example, subsidies on mineral fertilizer generally do not provide incentives to use fertilizer efficiently; in fact, they may produce quite the opposite effect. Likewise, integrating exposure to climate risks as part of the targeting methodology for social protection programmes is a relatively easily implemented institutional shift in the direction of climate-smart agriculture. Re-orienting agricultural research to integrate climate change adaptation and mitigation is another important component of an enabling environment (Box 15).

The financing challenge

The sustainability of smallholder food production systems will depend upon the ability of smallholders to adopt climate-smart practices and technologies. To accomplish this goal, additional financial investments are needed. However, accessing finance for the agriculture sectors – let alone for climate-smart agriculture – is a challenge in many developing countries and has been for decades. Traditionally, agriculture's share in the portfolios of financial institutions has been small, and especially so when compared to agriculture's contribution to GDP. Because the agriculture sector is considered low-profit and high-risk, sources of finance in most countries limit their exposure, tighten lending criteria and impose onerous lending conditions. They often shy away from agriculture altogether, preferring to seek more stable returns from other sectors of the economy. The resulting shortfall in finance severely impacts agriculture, especially farmers and small and medium-sized agribusinesses.

»

BOX 14

FACTORS THAT HINDER ADAPTIVE CAPACITY

Insights into barriers smallholder farmers face in making the types of incremental changes needed for climate change adaptation are highlighted in a recent meta-analysis of the determinants of improved technology adoption in Africa (Arslan *et al.*, 2016a). The dataset is built on information from some 150 published papers and includes 87 improved practices in agroforestry, agronomy and livestock production.

The most prominent barriers to adoption of agroforestry are access to information, primarily from extension services, which is significant in around 40 percent of the studies where it is included. Other top determinants of adoption of improved agroforestry practices are distance to markets, membership of farmer groups and other social capital, and tenure security. For adoption of improved agronomic practices, the main barriers were related to information access, followed by tenure security, resource endowments and exposure to risks and shocks. The analysis also indicated a need for specifically targeting those with lower endowments, especially women farmers and female-headed households, as they typically have much more limited access to information and technologies. Male-headed farm households were far more likely to adopt improved agroforestry or agronomic practices.

AGROFORESTRY AND AGRONOMY: DETERMINANTS OF ADOPTION OF IMPROVED TECHNOLOGIES AND PRACTICES AND THEIR SIGNIFICANCE IN THE LITERATURE

Determinant	Agroforestry				Agronomy			
	1. Total	2. Negative (-)	3. Positive (+)	4. Not statistically significant	1. Total	2. Negative (-)	3. Positive (+)	4. Not statistically significant
	(No.)	(Percentage)			(No.)	(Percentage)		
Information	60	1.7	41.7	56.7	459	7.6	37	55.4
Resource endowments	75	14.7	28	57.3	991	12.9	29.2	57.9
Risk and shocks	16	0	18.8	81.3	106	8.5	29.2	62.3
Bio-physical factors	20	15	20	65	544	13.4	20	66.6
Distance to market/road	17	11.8	47.1	41.2	249	20.9	14.1	65
Socio-demographics	129	5.4	29.5	65.1	1 154	12.2	21.9	65.9
Groups/ social capital	29	10.3	44.8	44.8	288	9.7	26.7	63.6
Tenure security	19	10.5	42.1	47.4	116	8.6	36.2	55.2
Labour availability	18	5.6	38.9	55.6	96	14.6	24	61.4
Credit access	15	6.7	13.3	80	167	12.6	24.6	62.8
Total number of results	398	7.8	32.4	59.8	4 170	12.3	25.7	62

Note: Columns 2 to 4 show, for agroforestry and agronomy, the percentage of papers covering a specific determinant of adoption having a negative impact on adoption, a positive impact, or no statistically significant impact.
SOURCE: Arslan *et al.*, 2016a.

TABLE 10

OPPORTUNITY COSTS OF IMPLEMENTING IMPROVED GRAZING MANAGEMENT, QINGHAI PROVINCE, CHINA

Size of herd	Baseline net income	Net present value per ha over 20 years	Number of years to positive cash flow	Number of years to positive incremental net income compared to baseline net income
	(US$/ha/year)	(US$/ha)	(Number of years)	(Number of years)
Small	14	118	5	10
Medium	25	191	1	4
Large	25	215	1	1

SOURCE: McCarthy, Lipper and Branca, 2011.

BOX 15

RE-ORIENTING RESEARCH FOR CLIMATE CHALLENGE

Most crop research has focused on annual crops rather than perennials. As the impacts of climate change on agricultural productivity and production potential are felt, research must take a far broader, integrated approach, one that incorporates perennial crops, livestock and aquaculture, and has a better understanding of the implications of climate change for pests and diseases.

The development of new varieties and supporting technologies is especially urgent, owing to the lag – typically more than a decade – between initial research on a new variety and its release to producers (Challinor *et al.*, 2016). Particular attention needs to be paid to developing heat- and drought-tolerant varieties, not only for tropical countries, but also for temperate countries with already high temperatures during their growing seasons. Some developed countries, for example, are projected to experience significant maize yield declines under climate change. While developed countries generally have greater capacity in both public and private sectors to develop new varieties, poorer countries are dependent upon the CGIAR and national agricultural research institutes to develop high-yielding, climate-smart varieties. This implies a need for increased and sustained investment in these institutions.

» Smallholder farmers face the highest barriers to accessing finance. They usually have limited financial literacy, little or no collateral and credit history, and few other sources of income. Being highly disaggregated and located in areas far from urban centres, smallholders are difficult for lenders to even reach. Their isolation results in transaction costs that are sometimes greater than the size of the loan that farmers require. Access to finance is particularly difficult for women, owing to socio-economic, political and legal barriers.

Moreover, even where formal financial services are accessible, they frequently do not meet the needs; nor do they consider the circumstances of smallholders. Financial institutions tend to offer short-term working capital rather than the investment capital needed for investment in value addition and higher productivity. Moreover, financiers often set rigid repayment schedules and short maturities which, owing to the seasonality of agricultural cycles, do not match the seasonal cash flows of smallholder farmers.

As a result, the vast majority of farmers in developing countries are effectively disenfranchised from the financial system and denied opportunities for economic growth. By one estimate, the total smallholder financing needs in Latin America, sub-Saharan Africa and South and Southeast Asia are some US$210 billion per year (Rural and Agricultural Finance Learning Lab., 2016). Moreover, this financing gap is likely to substantially widen in the future, owing to the need for longer-term loans to fund climate change adaptation and mitigation activities.

Small and medium-sized enterprises (SMEs) also face challenges in accessing finance, in particular longer-term loans. SMEs are critical for agricultural development, as they play a major role in increasing smallholder income and productivity and improving the efficiency of value chains, which generate rural jobs. When SMEs lack the finance to grow to their full potential, they generate fewer jobs and employ fewer workers. The gap in financing for agricultural SMEs thus exacerbates unemployment and poverty in rural areas across the globe. Many SMEs require funds that are too large to be met by microfinance institutions, but not large enough – and perceived as too risky – to secure commercial loans. This is especially problematic when producers and enterprises wish to invest in value-adding infrastructure that could significantly raise their productivity and incomes. ■

CONCLUSIONS

This chapter has explored the vulnerability of smallholder farming systems to climate change risks, and examined entry points to addressing those vulnerabilities. Several key elements emerge from the analyses undertaken by FAO and from the literature. First, although climate change is a "catch-all" term, its manifestations will be complex and diverse. The binding constraints in terms of productivity vary considerably between farming systems and regions. Furthermore, there is no knowing whether average values, variability or extremes in rainfall or temperature will have the greatest impact on yields. As the world's climate changes, some of these impacts will be direct and others indirect through, for example, the propagation of pests and diseases. Understanding the key weather constraints and how they are affected by climate change is an important first step in determining the type of support that smallholder farmers will need. Much remains to be done in terms of improving our understanding and communicating it appropriately to stakeholders.

The second important point that emerges from this chapter is that sustainable intensification, improved agricultural technologies and diversification can abate the impacts of climate change, and even reduce considerably the number of people at risk of hunger. However, the widespread adoption of improved technologies may face policy and institutional constraints, which will need to be overcome. Diversification is typically adopted, and found to be more effective, in areas where weather variability is greater, as reported in case studies for Malawi and Zambia. This underscores the importance of addressing specific constraints, as opposed to imposing blanket policies across agro-ecological regions and farming systems.

The third point is that adaptation makes economic sense: the benefits outweigh costs by typically large margins. But that fact alone will not make adaptation happen. It is particularly difficult for smallholders to overcome barriers to adoption of new technologies and practices because of the challenges they face in accessing finance. The same applies to small and medium-sized enterprises that generate income for smallholders and rural jobs that allow for off-farm income diversification.

GICUMBI, RWANDA
A view of terraced hills.
©FAO/Giulio Napolitano

CHAPTER 4

FOOD AND AGRICULTURE SYSTEMS IN CLIMATE CHANGE MITIGATION

PERU
Farm workers restoring traditional terraces.
©FAO/A. Odoul

SACRED INCA VALLEY, PERU
The three-tier agro-ecological system (maize, potatoes and grazing).
©FAO/A. Proto

KEY MESSAGES

1 **THE AGRICULTURE SECTORS FACE A UNIQUE CHALLENGE**: to produce more food while reducing greenhouse gas emissions caused by food production.

2 **AGRICULTURE COULD REDUCE ITS EMISSION INTENSITY**, but not enough to counterbalance projected increases in its total emissions.

3 **ADDRESSING EMISSIONS FROM LAND USE CHANGE DRIVEN BY AGRICULTURAL EXPANSION IS ESSENTIAL**, but sustainable agricultural development will determine its success.

4 **ALTHOUGH IMPROVEMENTS IN CARBON AND NITROGEN MANAGEMENT ALSO REDUCE EMISSIONS**, they are likely to be driven by adaptation and food security objectives, rather than mitigation goals.

5 **REDUCING EMISSIONS FROM AGRICULTURE** also hinges on action to minimize food losses and waste and to promote sustainable diets.

CHAPTER 4

FOOD AND AGRICULTURE SYSTEMS IN CLIMATE CHANGE MITIGATION

Having examined in Chapter 3 measures that build the resilience of smallholders and vulnerable rural populations to climate change, we take a broader view of agriculture and food systems in order to assess their potential contribution to climate change mitigation. The agriculture sectors will be called upon to play their part in mitigation, because they will generate an increasingly large share of what will become, hopefully, declining levels of global emissions, and because they can, under certain conditions, sequester carbon dioxide.

Agricultural emissions are expected to grow along with food demand, which is being driven by population and income growth and associated changes in diets towards more animal-source products. Agriculture can contribute to mitigation by decoupling its production increases from its emissions increases through reductions in emission intensity, which is the quantity of GHGs generated per unit of output. This, in turn, can be complemented by actions that reduce food losses and waste and foster changes in food consumption patterns.

The agriculture sectors, particularly forestry, have a unique potential to act as carbon sinks by absorbing CO_2 and sequestering carbon in biomass and soil. At present, however, deforestation is a major source of emissions, and unsustainable farming practices continue to deplete the Earth's stock of soil organic carbon. Tapping into the carbon sequestration potential of forests and agricultural lands will depend on biophysical conditions, technical options and policies.

Since agricultural emissions, as well as sinks, are part of the global carbon (C) and nitrogen (N) cycles, optimizing agriculture's mitigation potential requires first an understanding of these cycles and how agricultural activities interact with them. This understanding will permit a fuller appreciation of the difficulties inherent in reducing agricultural emissions, which involve complex biophysical processes and are more difficult to monitor and control than emissions from most other anthropogenic sources of greenhouse gases. Improving the efficiency with which natural resources are used in agriculture will be a central element of mitigation strategies.

It is important to recall that in the agriculture sectors it is impossible to separate the objectives of food security, adaptation and mitigation, because there are synergies and trade-offs among them. Growing experience has shown that integrated packages of technologies and practices, tailored to the specific agroecological conditions of producers, are required to deliver mitigation and adaptation in a cost-effective manner. ■

THE TECHNICAL POTENTIAL FOR MITIGATION WITH ADAPTATION

Agriculture, forestry and land use (AFOLU) are responsible for about 21 percent of total greenhouse gas emissions. All carbon dioxide emissions from AFOLU are attributable to forestry and land use change, such as conversion of forests to pasture or crop production. The bulk of emissions of methane and nitrous oxide are attributable to agricultural practices (Table 5). Improved management of carbon and nitrogen in agriculture, therefore, will be crucial to its contribution to climate change mitigation (Box 16). »

BOX 16

CARBON AND NITROGEN IN THE AGRICULTURE SECTORS

The terms carbon cycle and nitrogen cycle are used to describe the flow of those two chemical elements, in various forms, through the Earth's atmosphere, oceans, terrestrial biosphere and lithosphere.

It is estimated that up to 80 percent of the total organic carbon in the terrestrial biosphere, excluding fossil fuels, is stored in soils, while about 20 percent is stored in vegetation.

Plant growth produces an estimated 54 Gt of carbon (or GtC), a year. The human appropriation of this net primary production – i.e. the quantity of carbon in biomass that is harvested, grazed, burned or lost as a result of human-induced land-use change – has been estimated in the range of 15–20 GtC a year (Running, 2012; Krausmann *et al.*, 2013).

Oceans and coastal margins play a significant role in the carbon cycle. It is estimated that more than 90 percent of global carbon is stored in aquatic systems. Furthermore, around 25 percent of annual GHG emissions are sequestered in aquatic environments, primarily mangroves, seagrasses, floodplain forests and coastal sediments (Nellemann, Hain and Alder, 2008; Khatiwala *et al.*, 2013). Aquatic systems could, therefore, contribute considerably to climate change mitigation.

Nitrogen is a major component of amino acids, the building blocks of plant growth. The use in agriculture of nitrogen, in plant-useable forms, has increased rapidly with the growing demand for food. In 2005, farmers applied to crops an estimated 230 million tonnes of nitrogen in the form of mineral fertilizer and manure. Global leakages of nitrous oxide into the environment may have already exceeded biophysical thresholds, or planetary boundaries (Rockström *et al.*, 2009; Steffen *et al.*, 2015).

Soil carbon sequestration to offset emissions

There is great concern about the magnitude of past and present losses of carbon as a result of human activity. Estimates of losses over the past 150 to 300 years from land use and land-use change, mainly the conversion of forests to agricultural land, range between 100 and 200 billion tonnes (Houghton, 2012). The importance of soils as a terrestrial regulator of the C and N cycles is increasingly recognized, especially following the new climate regime established by the Paris Agreement of December 2015, which calls for action to conserve and enhance sinks and reservoirs of greenhouse gases.

Soils represent the Earth's second largest carbon pool, after oceans, and small changes in the stock of soil organic carbon may result in large changes in levels of atmospheric CO_2 (Chappell, Baldock and Sanderman, 2016). Up to one metre in depth, the world's soils – excluding permafrost – contain a total of about 500±230 Gt of carbon (GtC), equivalent to twice the amount of carbon as CO_2 in the atmosphere (Scharlemann *et al.*, 2014). Soils carry a large potential for carbon sequestration, and this is especially so for degraded soils through restoration measures (Lal, 2010).

The capacity of soil to sequester carbon can be maintained and improved through farming practices that also restore soil health and fertility for agricultural production. Promoting sustainable soil management provides, therefore, multiple benefits: increasing productivity, fostering climate change adaptation, sequestering carbon and reducing emissions of GHG (FAO and ITPS, 2015). While the role of soils as potential sinks and reservoirs is recognized, knowledge of current soil carbon stocks and the soil's real sequestration potential is still limited, owing to a lack of adequate information and monitoring systems.

In order to tap the potential for soil carbon sequestration, sustainable soil management needs to be promoted as a system, with a range of functions that provide multiple ecosystem services (FAO and ITPS, 2015). The technical potential for SOC sequestration appears to be in a range of 0.37 to 1.15 GtC per year (Sommer and Bossio, 2014; Smith *et al.*, 2008; Paustian *et al.*, 2004). Those are technical potentials and it is implicitly assumed that all agricultural land would be managed to sequester carbon. However, soil C sequestration rates on land in agricultural use vary in the order of 0.1 to 1 tC per hectare per year (Paustian *et al.*, 2016). Therefore, billions of hectares would have to be managed to sequester carbon optimally in order to reach an annual sequestration rate of 1 GtC. Furthermore, levels of sequestration would be relatively low at first, would peak after 20 years, and would then slowly decline (Sommer and Bossio, 2014).

Reducing emissions in livestock supply chains

There is also great potential to reduce the livestock sector's GHG emission intensity. The precise potential is difficult to estimate as emission intensities vary greatly even within similar production systems, owing to differences in agro-ecological conditions, farming practices and supply chain management. Gerber *et al.* (2013a) estimate that emissions generated by livestock production could be reduced by between 18 and 30 percent if, in each system, the practices used by the 25 percent of producers with the lowest GHG emission intensity were widely adopted.

Based on six regional case studies and using a lifecycle assessment model, Mottet *et al.* (2016) estimate that sustainable practices would lead to reductions of between 14 and 41 percent in livestock GHG emissions. In five of the case studies, mitigation resulted in increased production as well as reduced emissions, a double-win for food security and climate change mitigation. Comparably high mitigation potential has been found for ruminant and pig production systems in Africa, Asia and Latin America. Significant emission reductions in countries of the Organisation for Economic Co-operation and Development (OECD) can also be attained in dairy systems with already high levels of productivity (Gerber *et al.*, 2013b).

The practices with highest technical potential for reducing enteric methane emissions and for sequestering soil carbon in grazing lands could reduce GHG emissions by an amount equal to 11 percent of annual global ruminant emissions. In a modelling study by Henderson *et al.* (2015), improved grazing management and the sowing of legumes were the most affordable practices – and, therefore, had the greatest economic potential. Grazing management was particularly effective in Latin America and sub-Saharan Africa, while sowing legumes appeared to work best in Western Europe. Urea treatment of straw tended to be an economically less attractive option at low carbon price levels, but very cost-effective at a high carbon price of US$100 per tonne of carbon dioxide equivalent (tCO_2-eq).

Mitigating nitrous oxide emissions

Together with water, nitrogen is the most important determinant of crop yields (Mueller *et al.*, 2012). Nearly 50 percent of world food production depends on nitrogen fertilizer, while the other 50 percent depends on nitrogen found in soil, animal manure, the tissues of nitrogen-fixing plants, crop residues, wastes and compost (Erisman *et al.*, 2008). Nitrogen is easily lost from agriculture to the environment, through volatilization and leaching, causing environmental damage which has been estimated at about equal to the monetary benefits of using nitrogen fertilizer in food production (Sutton *et al.*, 2011). Emissions of nitrous oxide from applied fertilizer have direct negative impacts: N_2O is the third most important greenhouse gas and the most significant cause of ozone depletion in the stratosphere. At the same time, thanks to its key role in photosynthesis and biomass production, nitrogen influences positively the biospheric carbon dioxide sink and carbon sequestration.

Sustainable nitrogen management in agriculture aims at simultaneously achieving agronomic objectives, such as high crop and animal productivity, and the environmental objectives of minimizing N losses. Because the nitrogen cycle is very “leaky”, its management is not easy. Under conditions of climate change and adaptation, it is even more complex because of its close interactions with the carbon and water cycles – utilization and losses of nitrogen in agriculture are strongly influenced by water and carbon availability.

The potential for reductions in nitrous oxide emissions in the global food system by 2030 and by 2050, through the use of improved practices, is illustrated by Table 11. Estimates are based on the potential for increasing N-use efficiency and/or lowering emission intensity (Oenema *et al.*, 2014). Assumptions, based on a literature review and expert views, include improvements in crop and animal production, manure management and food utilization, and lower levels of animal protein in diets. In the results of five scenarios analysed, effects include both direct and indirect N_2O emissions. (For comparison purposes, the global warming potential of 1 million tonnes of N_2O is equivalent to 265 million tonnes of carbon dioxide.)

In the business-as-usual scenario, annual nitrous oxide emissions from agriculture increase from an estimated 4.1 million tonnes in 2010 to 6.4 million tonnes in 2030, and 7.5 million tonnes in 2050. Reduction strategies could potentially hold emissions at 4.1 million tonnes in 2030 and cut them to 3.3 million tonnes by 2050. Improvements in crop production, notably fertilizer use, appear to have the greatest potential. However, offsetting the projected increases in emissions under the business-as-usual scenario for the year 2030 would require the adoption of all five of the emission reduction strategies presented in Table 11, including behavioural changes such as reducing animal protein in diets, making the reduction estimates uncertain. The strategies appear to be technically feasible, but there are many hurdles on the road to implementation. Large investments in education, training, demonstration and the

» development of site-specific technologies will be needed to achieve the projected N_2O emission reductions.

Achieving reductions in nitrous oxide emissions will depend on management practices that address their underlying root causes. The biophysical processes linked to emissions vary according to climatic and agroecological conditions and farming systems. Nuclear and isotopic techniques can help to understand these processes better, and to improve the monitoring of nitrous oxide emissions (Box 17). ■

MITIGATION AND ADAPTATION CO-BENEFITS THAT ENHANCE FOOD SECURITY

Better management of the carbon and nitrogen cycles is central to both the mitigation of net GHG emissions from the agriculture, forestry and land use sector and to increasing the efficiency of the global food system. Since mitigation and adaptation measures both contribute to food security and environmental sustainability, they can be implemented jointly and at the same time when there is potential for establishing strong synergies between them. Improving efficiency in the carbon and nitrogen cycles can strengthen resilience to climatic variability, reduce GHG emissions and contribute to food security through higher food output. The key to reaching these objectives is sustainable intensification (see Chapter 3), which seeks to increase food production per unit of input in ways that reduce both pressure on the environment and GHG emissions, without compromising the ability of future generations to meet their own needs (Garnett *et al.*, 2013; Smith *et al.*, 2013).

Many countries see the agriculture sectors as providing the most opportunity for creating synergies between climate change adaptation and mitigation, as well as significant socio-economic and environmental co-benefits. For example, increasing carbon and nitrogen efficiency in food systems reduces GHG emissions and increases carbon sequestration while, at the same time, improving food security and increasing resilience to climate change and climate shocks. More efficient production systems make fewer demands on natural resources and are, therefore, less vulnerable to scarcity and climate events that would further reduce the availability of land, water and nutrients.

By helping to reduce yield gaps and increase biological efficiencies, especially in developing countries, the sustainable intensification of agriculture would prevent deforestation and the further expansion of agriculture into carbon-rich ecosystems, thus simultaneously enhancing food security and contributing to climate change mitigation. In the livestock sector, improving pasture productivity can limit the expansion of pasture into tropical forests and enhance the conservation and sustainable development of carbon rich landscapes (De Oliveira-Silva *et al.*, 2016).

The following section outlines two complementary goals that should be considered in policies aimed at capturing adaptation and mitigation co-benefits: improving production efficiency and minimizing GHG emissions in food systems, and conserving and developing carbon-rich landscapes in agriculture and forestry.

Higher production efficiency, lower emission intensity

Investing in yield improvements

Since the 1960s, the intensification of crop and livestock systems has limited the expansion of farmland and improved the efficiency of food supply chains (Tilman *et al.*, 2011; Gerber *et al.*, 2013a; Herrero *et al.*, 2013). Through higher yields, agricultural intensification avoided GHG emissions between 1961 and 2005 that are »

TABLE 11

POTENTIAL FOR N_2O MITIGATION OF ANNUAL EMISSIONS UNDER FIVE SCENARIOS OF IMPROVED PRACTICES, 2030 AND 2050 (CUMULATIVE EFFECTS)

Emission reduction strategies	Nitrogen sources	2030			2050		
		N input (Tg)	EF (%)	N_2O emissions (Tg N_2O-N)	N input (Tg)	EF (%)	N_2O emissions (Tg N_2O-N)
Business as usual (BAU)	Fertilizer	132	2.37	3.1	150	2.37	3.6
	Manure	193	1.71	3.3	230	1.71	3.9
Total				**6.4**			**7.5**
Improved crop production	Fertilizer	118	2.02	2.4	128	1.9	2.4
	Manure	193	1.71	3.3	230	1.71	3.9
Total				**5.7**			**6.3**
Improved animal production	Fertilizer	118	2.02	2.4	128	1.9	2.4
	Manure	174	1.71	3.0	184	1.71	3.2
Total				**5.4**			**5.6**
Improved manure management	Fertilizer	108	2.02	2.2	103	1.9	2.0
	Manure	174	1.62	2.8	184	1.54	2.8
Total				**5.0**			**4.8**
Improved food utilization	Fertilizer	103	2.02	2.1	93	1.9	1.8
	Manure	156	1.62	2.5	147	1.54	2.3
Total				**4.6**			**4.1**
Less animal protein in diets	Fertilizer	98	2.02	2.0	84	1.9	1.6
	Manure	133	1.62	2.2	110	1.54	1.7
Total				**4.1**			**3.3**

Notes: Reduction in emissions are cumulative across the five scenarios. Inputs refer to fertilizer N use and manure N excretions measured in teragrams (Tg). N_2O emission factors (EF) and total N_2O emissions are projections for the total food system by 2030 and 2050.
SOURCE: Oenema *et al.*, 2014.

BOX 17

NUCLEAR AND ISOTOPIC TECHNIQUES FOR MITIGATION

Nuclear techniques can help to identify soil and water management factors that reduce the release of GHG from soil and thus contribute to climate change mitigation. For example, using a variety of isotopes, scientists can determine the extent of carbon and nitrogen accumulation and their interactions in soil organic matter as a result of recently added organic manure, crop residues or wastewater. The 15N stable isotopic technique can help to identify the source of nitrous oxide production from farmlands, which assists in targeting appropriate N_2O mitigation tools, such as liming to modify the degree of soil acidity, or adding nitrification inhibitors to nitrogen fertilizers to reduce the conversion of excess N into nitrate, a mobile form, which is readily converted into N_2O under anaerobic conditions. Isotopic and nuclear-based techniques used by FAO jointly with the International Atomic Energy Agency (IAEA) are at the forefront of innovative practices to address the food needs of the future, as well as contributing to a reduction in the impacts of climate change.

» estimated to total up to 161 GtC. Investments in productivity compare favourably, therefore, with other commonly proposed mitigation strategies because they limit agricultural land expansion and the large carbon losses associated with deforestation (Burney, Davis and Lobell, 2010).

As agricultural and forestry efficiency have improved over the past few decades, the GHG emission intensity of many products has declined. Between 1960 and 2000, global average intensities fell by an estimated 38 percent for milk, 50 percent for rice, 45 percent for pork, 76 percent for chicken meat and 57 percent for eggs (Smith *et al.*, 2014). Much of the reduction in ruminant emission intensity has been due to reduced output of methane for a given amount of milk and meat (Opio *et al.*, 2013; and Box 18). In both ruminants and monogastrics, improvements in feed conversion efficiency and husbandry, and the selection of highly efficient animal breeds, have played key roles. Reducing the number of animals required to produce a fixed level of output can yield significant efficiency gains. For example, a 28 percent overall reduction in annual methane emissions in the United Kingdom between 1990 and 1999 can be attributed largely to reductions in cattle numbers and the increased productivity of dairy cows (DEFRA, 2001). Strong disparities in resource-use efficiency and GHG emission intensity still exist between animal farming systems and across regions (Herrero *et al.*, 2013), suggesting significant potential for gains.

As well as reducing yield gaps and increasing herd productivity, improved long-term, farm-scale efficiency strategies would conserve and restore soils, water, biodiversity and critical ecosystem services such as pollination (Garibaldi, *et al.* 2016). For example, in both temperate and tropical regions, farming system diversification and crop-livestock-tree integration would increase farm-scale efficiency and reduce GHG emission intensity (Soussana, Dumont and Lecomte, 2015). A number of technologies can help raise production efficiency and generate co-benefits. They include the use of adapted varieties that harness genetic resources and advanced breeding, adjustments to planting dates and cropping periods, precision farming, judicious use of inorganic fertilizer in combination with organic nutrient sources and legumes, and the design of more diversified, sustainable cropping systems that also consider agro-forestry approaches.

Reducing resource-use intensity in aquaculture and fisheries

The fisheries and aquaculture sector can contribute to climate change mitigation by increasing its sequestration of carbon and reducing emissions from its value chain. It is of primary importance to halt habitat destruction and inappropriate management practices in fisheries and aquaculture, which disrupt the carbon sequestration functions of aquatic systems. There may be great scope for enhancing sequestration through the rehabilitation of mangroves and floodplain forests, even if this comes at an advanced cost for restoration.

In terms of GHG reduction, there is considerable potential for lowering emissions by reducing fuel and energy use. This can be achieved either directly – e.g. through more efficient fishing methods or energy use in processing – or indirectly, through a variety of actions, including energy savings along the supply and value chain and strategic waste reduction. Across the sector, the transition to more energy-efficient technologies is slow, although incentive mechanisms associated with carbon markets have shown some potential (FAO, 2013a).

Energy use in processing, storage and transport is the main source of GHG emissions in fisheries and aquaculture. Processing ranges from simple drying and smoking of fish in artisanal systems to highly controlled seafood preparation using high-specification packaging and labelling. There are wide variations in emissions, depending on local practices, inputs (species, sourcing, quantity and quality) and operating efficiency. As the most widely traded global food products, aquatic foods may travel considerable distances in a range of forms and in various states of perishability. Greenhouse gas outputs are usually directly related to fuel use in transport and to energy use in handling and storage. The most perishable fresh products require fast transport and energy- »

BOX 18

METHANE ABATEMENT IN LIVESTOCK AND PADDY RICE PRODUCTION

Numerous studies have investigated potentials for reducing methane emissions from livestock and flooded rice systems.

Enteric fermentation. Most available studies concern changes in animal diets and adding supplements to animal feed (Veneman, Saetnan and Newbold, 2014; Gerber *et al.*, 2013a). Improving the overall digestibility of feed rations and balancing their nutritional quality is the first level intervention, which yields most mitigation benefits (Garg *et al.*, 2013; Gerber *et al.*, 2011). Secondary plant metabolites, such as tannins, are also available in the diets of ruminants grazing and browsing natural vegetation, especially in Mediterranean and tropical regions (INRA, CIRAD and FAO, 2016), and are likely to reduce their methane emissions. A number of other mitigation strategies have been tested, including the use of chemical inhibitors, ionophores, antibiotics, hydrogen sinks, essential oils, enzymes, probiotics, defaunation and vaccination (Hristov *et al.*, 2013). However, some of these options are illegal in some countries, while others are restricted or not commercially available. In addition, since animal production gains from methane mitigation are modest or non-existent, incentives will be needed to promote adoption of expensive additives that cut emissions (Newbold, 2015).

Stored manure. Reducing methane emissions from stored manure requires management practices that avoid storing it under anaerobic and/or warm conditions. Emissions from manure are lower in dry lot and solid storage manure systems, which are found in parts of Africa and Latin America. In liquid manure systems, typical of Western Europe and North America, methane emissions are high, particularly when animals are confined. Frequent removal of slurry from livestock housing has thus been suggested as a way of reducing methane emissions (Sommer *et al.*, 2009). Anaerobic digestion of manure has large potential for reducing emissions and substituting fossil fuel with renewable methane, which can be used in heating and power generation and as a vehicle fuel. However, the unknown levels of methane leakage from digesters and gas storage raises doubts about the actual mitigation effect of this technology. All options for the reduction of methane emissions need to take into consideration the entire production system, to avoid leakage from one compartment to the next and increases in nitrous oxide emissions.

Flooded rice. A range of traditional and improved practices mitigate methane emissions from rice paddies, including water, straw and fertilizer management. Stopping flooding for a few weeks saves water, as well as reducing methane and GHG emissions by between 45 and 90 percent, without considering soil carbon stock increases. However, this practice can have negative impacts on yields, partly through increased weed competition. Drying early in the growing season, and then flooding, reduces emissions by 45 percent and produces yields similar to those of fully flooded rice (Linquist *et al.*, 2015).

» intensive storage. The choice of refrigerants is also important – the leakage of refrigerant gases from old or poorly maintained equipment depletes the ozone layer in the atmosphere and has significant global warming potential. More stable dried, smoked and salted products processed in artisanal supply chains require methods of transport that are not time-sensitive and produce lower levels of GHGs (FAO, 2013b).

The "Blue Growth" initiative launched by FAO seeks to reconcile economic objectives with the need to manage aquatic resources more sustainably. Fisheries and aquaculture value chains that adopt blue growth have been shown to reap considerable gains in productivity and income, while managing aquatic resources in a way that helps to restore their long-term productive potential. Healthier oceans and wetlands are also more resilient to climate-related shocks, which improves the adaptive capacity of those who earn their livelihood from fisheries and aquaculture.

For example, an FAO project worked with fishing communities in Grand Cess, Liberia, to process and smoke fish products more efficiently. It involved more than 240 fish processors in the construction of fish-smoking ovens and insulated containers for fresh fish storage, which allowed them to smoke fish and sell it on lucrative markets in nearby Côte d'Ivoire. The predominantly female fish processors benefited from substantial increases in their income, while also significantly reducing the amount of wood needed to smoke fish. This further increased their profits while generating important climate change mitigation co-benefits (FAO, 2011a).

Reducing on-farm losses

In developing countries, food losses occur throughout the production chain and hit small farmers the hardest. FAO estimates that between 30 and 40 percent of total food production may be lost before it reaches the market, owing to problems ranging from improper use of inputs to lack of adequate post-harvest storage, processing and transportation facilities. Reducing on-farm losses increases the efficiency of production systems. This can be achieved by improving soil health, reducing the sensitivity of crops and animals to pests and diseases, increasing feed use efficiency in livestock, restoring pollinators and reducing weed competition. Restoration of ecosystem services provided by diversified landscapes can also help to maintain crop and livestock health, and minimize production losses, while investments in roads, logistics, storage and primary processing infrastructure can reduce post-harvest losses.

On-farm diversification and integrated farming systems

As well as reducing yield gaps and increasing herd productivity, improved long-term farm-scale efficiency strategies should conserve soils, water, biodiversity and critical ecosystem services such as pollination (Garibaldi, *et al.*, 2016). For example, in both temperate and tropical regions, farming system diversification and crop-livestock-tree integration would increase resource-use efficiency and reduce GHG emission intensity (Soussana, Dumont and Lecomte, 2015). A number of technologies can help to raise production efficiency and harness co-benefits, including precision-farming, advanced breeding, judicious use of organic and inorganic fertilizers, and better use of legumes, genetic resources and landscape biodiversity.

Carbon-rich landscapes in agriculture and forestry

Since agriculture and forests occupy most of Earth's land surface, they are vital to the conservation and restoration of soil carbon and the enhancement of carbon sinks. Agroforestry, forest regeneration, plantations, conservation agriculture, organic farming and grazing management can all contribute to those goals, although options will not apply equally across all farming systems and regions.

Forest landscapes

Each year, forests absorb an estimated 2.6 billion tonnes of carbon dioxide (CIFOR, 2010), equivalent to about one-third of the carbon dioxide released from the burning of fossil fuels.

However, this immense storage system, once disrupted by deforestation, becomes a major source of emissions. According to the IPCC's Fifth Assessment Report, deforestation and forest degradation account for nearly 11 percent of all GHG emissions: more than the world's entire transport sector. As forests are lost, their capacity to sequester carbon is reduced.

During the 1990s, deforestation in the tropics was largely responsible for carbon dioxide emissions, while forest regrowth in the temperate zone and parts of the boreal zone accounted for carbon dioxide removals. However, the extent to which the carbon loss due to tropical deforestation is offset by expanding forest areas and accumulating woody biomass in the boreal and temperate zones is disputed. FAO estimates that during the first decade of this century, total emissions as a result of deforestation were 3.8 Gt of carbon dioxide equivalent (CO_2-eq) a year, while the net impact of forest degradation and forest management resulted in the sequestration of 1.8 GtCO_2-eq (FAO, 2016a). Also relevant are biomass fires, including peatland fires and drained peatlands, which account for emissions of 0.3 and 0.9 GtCO_2-eq a year respectively).

The carbon mitigation potential of reduced deforestation, improved forest management, afforestation and agroforestry differ greatly by activity, region, system boundaries and the time horizon over which mitigation options are compared. Reductions in deforestation dominate the forestry mitigation potential in Latin America and Africa, while forest management, followed by afforestation, dominate in OECD countries, economies in transition, and Asia. Afforestation's potential contribution to mitigation ranges between 20 and 35 percent of total forestry-related potential (Smith 2014: figure 11.18).

Climate change mitigation actions in the forest sector fall into two broad categories: reducing the emission of GHGs and increasing removals of GHGs from the atmosphere. The options can be grouped into four general categories:

- **Reducing or avoiding deforestation.** Maintaining the area under forest provides considerable socio-economic and environmental benefits (FAO, 2012). It retains biodiversity and ecosystem functions and, in large land areas, influences local weather patterns, which can have impacts on food production (Siikamäki and Newbold, 2012). Reduction of forest fires improves local air quality which has health benefits for communities living in and around forests Mery et al.
- **Increasing the area under forest.** The forest area can be increased through planting, seeding and assisted natural regeneration, and through natural succession. Afforestation leads to increases in the carbon pools held in above-ground and below-ground biomass and in dead organic matter. It is generally undertaken in rural areas and benefits the rural economy by generating income and employment. There is some concern that afforestation and reforestation may diminish food security, if they are carried out primarily on productive agricultural land, and that monoculture plantations reduce biodiversity and are at greater risk of diseases (FAO, 2011b). Careful planning, across all agriculture sectors, is needed when implementing this option.
- **Maintaining or increasing carbon density.** Activities which maintain or increase carbon stocks in forest stands include reduced-impact logging and sustained-yield management in timber production; maintaining partial forest cover; and minimizing the loss of the dead organic matter and soil carbon pools by reducing high-emission activities such as slash-and-burn cultivation (CIFOR, 2015; Putz and Romero, 2015). Replanting after harvesting or natural disturbances accelerates growth and thus the rate of carbon sequestration relative to natural regeneration.
- **Increasing off-site carbon stocks in harvested wood products.** When wood is transformed into long-lived products, such as buildings and furniture, it can act as a reservoir of carbon for decades or even centuries.

The benefits of mitigation through forestry can be amplified through education, training and the participation of rural communities in forestry planning and decision-making. Participatory approaches to forest management can be more successful than traditional, hierarchical programmes and may help to strengthen civil society and democratization processes (FAO, 2016b). They also create social capital, networks and social relations which allow communities to cope better with climate change.

The challenge posed by most forest-related mitigation activities is the need for substantial investment before benefits and co-benefits accrue, typically over many years if not decades. The substantial mitigation potential of forestry will not materialize without appropriate financing and enabling frameworks that create effective incentives.

Another issue is energy production and product substitution, which have social, economic and cultural implications (EEA, 2016). For example, policies in the European Union to increase the use of biofuels, including wood fuels, for energy generation are affecting how foresters in the region manage their forests, and how land in developing regions is used (EC, 2013). There are several reported cases of land grabs for biomass production, which has implications for food security.

Agricultural landscapes

Many current agricultural practices contribute to losses of soil organic carbon and to the reduction of SOC returns to soils (Table 12). Losses can be lowered or SOC returns to the soil increased by reducing fires, overgrazing and soil erosion, or by recycling crop residues and manure. Another option is to change the balance between photosynthesis and ecosystem respiration by increasing crop photosynthesis, through the use of cover crops, intercropping and agroforestry, and by minimizing soil disturbance through conservation agriculture. Large gains in crop carbon balances can also be achieved with improved crop varieties, nitrogen-fixing legumes and organic and inorganic fertilizers, which boost the amount of crop residues available for returning to the soil. Improved water management is also a strong driver of primary productivity, and complements all of those practices.

Practices optimized to sequester soil organic carbon also strengthen food security and facilitate climate change adaptation. As levels of SOC increase, important yield co-benefits could also be achieved year after year in developing countries (Lal, 2006).[7] By facilitating improvements in soil structure, water infiltration and water holding capacity, soil organic carbon also helps build resilience to drought and flooding, two climate change impacts that affect particularly tropical regions (Pan, Smith and Pan, 2009; Herrick, Sala and Jason, 2013). However, the impacts on yields are dependent on local conditions and the combination of practices adopted by farmers, and yield losses have been observed (Pittelkow *et al.*, 2015).

Carbon sequestration in agricultural soils may not be lasting. The extra soil carbon stored through improved agricultural practices is partly in unprotected forms, such that a fraction would decompose if the practices ceased. In addition, soil carbon sequestration may increase nitrous oxide emissions in the short term, and deficiencies in soil phosphorus and nitrogen may impede SOC storage (Penuelas *et al.*, 2013).

Action aimed at reaping the climate mitigation benefits of soil organic carbon needs to take a long-term view and be applied at landscape rather than at field scale. It requires an understanding that adoption of soil carbon sequestration measures will take time, and that SOC will increase only over a finite period, up to the point when a new equilibrium is reached. The additional stock will need to be monitored and conserved using appropriate land management practices. All of these factors were considered in an FAO-supported initiative on the restoration of degraded grasslands in the Qinghai region of China (Box 19).

Finally, agroforestry – the integration of trees and shrubs into crop and livestock systems – prevents soil erosion, facilitates water infiltration and reduces the impacts of extreme weather events. It also helps to diversify income sources »

7 Lal *et al.* (2004) estimate these co-benefits at a ratio of 0.07 unit of dry matter (DM) per soil organic carbon unit (≈ 0.07 t DM/t SOC).

TABLE 12

EXAMPLES OF AGRICULTURAL PRACTICES LEADING TO REDUCTIONS IN SOIL CARBON STOCKS

Temperate regions	Semi-arid and arid regions	Tropical regions
Drainage and cultivation of organic soils	Grazing pressure amid erratic rainfall contributing to desertification	Slash-and-burn agriculture lack of crop organic fertilization
Breeding on the harvest index	Lack of trees and lack of water conservation measures	Deep ploughing
Lack of cover crops		Lack of cover crops
Lack of crop-livestock integrated systems and agroforestry		Drainage and fires of tropical peatlands
Decline in permanent grasslands area		
Limited reuse of urban and industrial organic wastes		

Note: The harvest index refers to the weight of the harvested part of a plant as a share of total above ground biomass in the plant.
SOURCE: FAO and ITPS, 2015.

BOX 19

RESTORATION OF DEGRADED GRASSLANDS IN CHINA

Too much livestock can lead to overgrazing and land degradation. This is the hard lesson learned by herders in Qinghai region, China, where some 38 percent of grasslands have been degraded. Together with the Chinese Academy of Agricultural Sciences (CAAS), the World Agroforestry Centre and the Northwest Institute of Plateau Biology, FAO recently developed a methodology that gives farmers the tools to manage their animals and grasslands more sustainably for years to come.

Restoring degraded grazing lands and increasing stocks of soil carbon can simultaneously increase productivity, build resilience by improving soil moisture and nutrient retention, and improve livelihoods in small-scale herder communities. However, until now, carbon sequestration projects in grasslands have been hampered by high measurement costs. This problem was overcome in Qinghai with the development of a methodology certified by the Verified Carbon Standard, which focuses on monitoring practices. It allows farmers to access new sources of finance through carbon credits, which cover the costs of changing their management practices before productivity gains make it profitable to restore grasslands.

SOURCE: FAO, 2013a.

» and provides fodder for livestock. The use of nitrogen-fixing leguminous trees, such as *Faidherbia albida*, improves soil fertility and yields. Although there is clear and abundant evidence of the positive impacts of agroforestry practices on productivity, adaptive capacity and carbon storage, a wide variety of systems and tree species need to be considered in different contexts. ■

MITIGATION COSTS, INCENTIVES AND BARRIERS

There are many feasible and promising approaches to climate change mitigation in the AFOLU sector, and the technical potential is considerable. But what are the costs and thus the economic potential of mitigation? In other words, what is the hypothetical price of carbon that would induce farmers, fisherfolk and foresters to apply appropriate practices for sequestering carbon and reducing emissions?

Based on the combined mitigation potential of forestry and agriculture, estimated in the IPCC's Fourth Assessment Report, the IPCC suggests an economic potential in 2030 of between ≈3 and ≈7.2 Gt of carbon dioxide equivalent a year at carbon prices of US$20 and US$100 per tonne, respectively (Smith *et al.*, 2014).[8] Among regions, the largest mitigation potential for agriculture, forestry and land use is found in Asia, at all levels of carbon values (Figure 15, based on Smith *et al.*, 2014).

Forestry could make a significant contribution to mitigation at all levels of carbon prices. At low prices, the contribution of forestry is close to 50 percent of the total from the AFOLU sector; at higher prices the share of forestry is lower.

Forestry represents the bulk of mitigation potential in Latin America, at all levels of carbon prices. However, different forestry options have different economic mitigation potentials in different regions. Reduced deforestation dominates the forestry mitigation potential in Latin America and in the Middle East and Africa. Forest management, followed by afforestation, are the major options in OECD countries, Eastern Europe and Asia.

Among other mitigation options, cropland management has the highest potential at lower carbon prices of US$20 per tonne. At US$100, the restoration of organic soils has the greatest potential. Also, the potential of grazing land management and the restoration of degraded lands increases at higher carbon prices (Smith *et al.*, 2014).

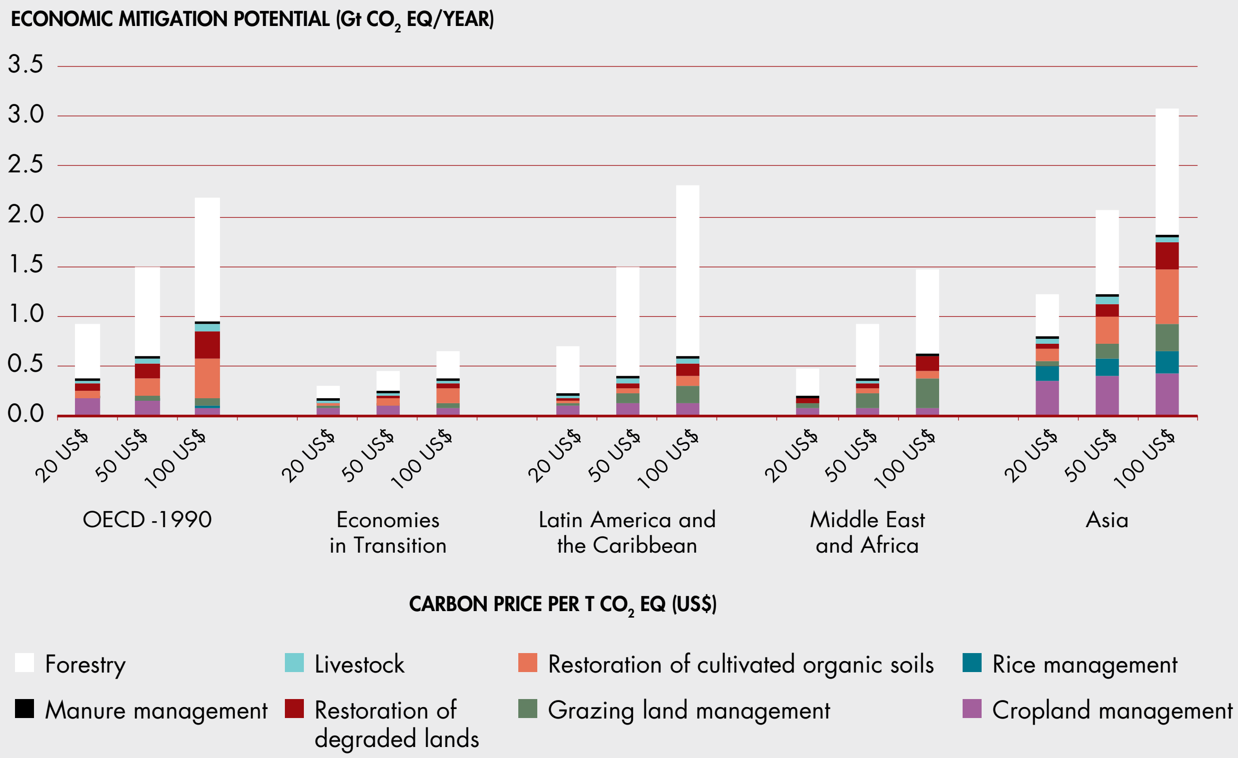
These estimates of economic mitigation potential provide broad indications of how to target interventions in the most cost-effective way. However, more detailed assessments are needed in order to properly assess AFOLU's mitigation potential, the impacts on vulnerable production systems and groups, and the costs of implementation. It is a pre-requisite that practices optimized to reduce GHG emissions or sequester carbon should also protect the land tenure rights of small-scale producers and contribute to food security and climate change adaptation, particularly for the most vulnerable groups.

A range of institutional and economic approaches can facilitate the implementation of agricultural emission reductions. On the institutional side, these would include providing information to farmers about agricultural practices that create adaptation/mitigation synergies and, if needed, access to credit to implement them. On the economic side, options include positive incentives for farmers to provide and maintain carbon sinks; taxation of nitrogen fertilizer in countries where it is being overutilized, a measure which is already applied in some OECD countries to reduce nitrate pollution; and supply-chain initiatives that market food products with a low carbon footprint (Paustian *et al.*, 2016). ■

8 A range of global estimates of sequestration potential at different levels of costs has been published since the IPCC's Fourth Assessment Report of 2007. The estimates differ widely. For carbon values up to US$20 a tonne, they range from 0.12 to 3.03 $GtCO_2$-eq per year. For values up US$100 per tonne, they range from 0.49 to 10.6 $GtCO_2$-eq (Smith *et al.*, 2014).

FIGURE 15

ECONOMIC MITIGATION POTENTIAL IN THE AFOLU SECTOR IN 2030, BY REGION



SOURCE: Smith *et al.*, 2014, Figure 11.17.

BOX 20

FOOD SYSTEM EMISSIONS: ENERGY USE ALONG SUPPLY CHAINS

The modernization of food supply chains has been associated with higher GHG emissions from both pre-chain inputs (fertilizers, machinery, pesticides, veterinary products, transport) and post farm-gate activities (transportation, processing and retailing). It has been estimated, using previous calculations and data from Bellarby *et al.* (2008) and Lal (2004), that the production of fertilizers, herbicides and pesticides, along with emissions from fossil fuels used in the field, represented in 2005 approximately 2 percent of global GHG emissions (HLPE, 2012).

Lifecycle analysis methods are needed to calculate emissions resulting from the consumption of food products. These approaches generally account for emissions from pre-chain inputs through to post-farm gate processing by including methane, nitrous oxide and CO_2 emissions, and fossil fuel use in food systems (e.g. Steinfeld *et al.*, 2006; FAO, 2013b). Including post-harvest stages, around 3.4 $GtCO_2$-eq of emissions are caused by direct and indirect energy use in the agrifood chain (FAO, 2011d). This can be compared with around 5.2 $GtCO_2$-eq generated by agriculture and around 4.9 $GtCO_2$-eq by forestry and land use change. Food systems currently consume an estimated 30 percent of the world's available energy, with more than 70 percent of that share being consumed beyond the farm gate.

Although they are heavily dependent on fossil fuels, modern food systems have contributed substantially to improving food security. If those systems are to contribute to climate change mitigation, however, they will need to decouple future development from dependence on fossil fuel. FAO's Energy-Smart Food for People and Climate (ESF) Programme uses a water-energy-food nexus approach to help developing countries to ensure adequate access to modern energy services at all stages of agrifood chains, improve energy efficiency and increase the share of renewable energy (FAO, 2014).

A FOOD SYSTEM PERSPECTIVE: MINIMIZING LOSSES AND WASTE, PROMOTING SUSTAINABLE DIETS

Reducing food losses and waste, and promoting a transition to more sustainable diets, can also deliver emissions reductions and contribute to global food security (Bajželj *et al.*, 2014). FAO has estimated that every year roughly one-third of the edible parts of food produced for human consumption is lost (FAO, 2011c), representing an enormous waste of the land, water, energy and inputs used to produce it and unnecessary emissions of millions of tonnes of greenhouse gases. Reducing food losses and waste by increasing the overall efficiency of food chains could contribute to reducing GHG emissions, as well as enhancing access to food and improving the resilience of food systems to climate change.

In low-income countries, food losses occur throughout food value chains, and result from managerial and technical limitations in harvesting, storage, transportation, processing, packaging and marketing (HLPE, 2014). The heaviest losses are in the small and medium-scale agricultural and fisheries production and processing sectors. Social and cultural conditions – such as the different roles that men and women play at different stages in the value chain – are frequently the underlying causes of food losses. The difficulties that women face in obtaining access to, and benefits from, resources, services, jobs and income-generating activities affect their productivity and efficiency in food production, which exacerbates food losses.

Food waste in middle and high-income countries is caused mainly by consumer behaviour and by policies and regulations that address other sectoral priorities. For example, agricultural subsidies may encourage the production of surplus food crops, which reduces both prices and the attention that is paid – along the value chain and by consumers – to food losses and waste. Furthermore, food safety and quality standards may remove from the supply chain food that is still safe for human consumption. At the consumer level, inadequate planning of purchases and failure to use food before its expiry date also lead to food waste.

Dietary patterns strongly influence some of the factors that are driving climate change. In countries where food consumption is increasing, diets generally include more livestock products, vegetable oils and sugar. This trend is expected to continue as a result of growth in incomes. A number of studies have looked at the environmental consequences of consumption of animal-source food, usually focusing on GHG emissions and land use (INRA and CIRAD, 2009; Erb *et al.*, 2009; Tilman and Clark, 2014; Tukker *et al.*, 2011; Van Dooren *et al.*, 2014). Using life cycle assessments, they generally conclude that alternative diet scenarios with less animal-source food could contribute to reducing global GHG emissions, and have positive impacts on human health.

There is increasing evidence that dietary patterns with low environmental impacts are also healthier. Common features of such diets are the diversity of foods eaten, a balance between energy intake and energy expenditure; the inclusion of minimally processed tubers and whole grains along with legumes, fruit and vegetables, and meat, if eaten, in moderate quantities. Healthy diets also feature dairy products in moderation, unsalted seeds and nuts, small quantities of fish and aquatic products, and very limited intake of processed foods that are high in fat, sugar or salt and low in micronutrients (FAO and FCRN, 2016).

Another critical factor that needs to be considered is the energy used in modern food systems to process food and bring it to consumers (Box 20). In high-income countries, perishable products require significant energy use, and corresponding levels of GHG emissions, in the storage, distribution and consumption stages. Fischbeck, Tom and Hendrickson (2016) have shown that following United States dietary guidelines for healthy weights would increase energy use by 38 percent, water use by 10 percent and GHG emissions by 6 percent. This is due to the bigger share in the diet of fruits and vegetables, which have a high energy, GHG and water footprint in the United States. This illustrates the importance of taking into account the specific characteristics of production systems in determining environmental footprints. It also indicates that there can also be trade-offs between reduced environmental impacts and healthier diets.

Bearing in mind the very large diversity at global level, rebalancing diets to reach nutritional targets could nevertheless bring very large co-benefits, through GHG mitigation and improvements in the overall efficiency of food systems (Tilman and Clark, 2014). Further examination of demographic and social differences, including fast-growing food consumption in developing countries, is needed to inform strategies for promoting optimal diets with improved health outcomes and reduced levels of nitrate pollution and greenhouse gas emissions. Multidimensional life cycle assessments at regional and global levels are needed to estimate the adaptation and mitigation effects of different dietary transitions, including the possible trade-offs. ■

CONCLUSIONS

Agriculture, forestry and land use are primary drivers of the terrestrial carbon and nitrogen cycles. Better management of these cycles in agriculture, forestry and aquaculture can provide multiple benefits in terms of food security and climate change adaptation and mitigation. Policies need to pursue three complementary goals:

- to increase agricultural production efficiency and minimize farm-level GHG emission intensity;
- to conserve and restore, through agricultural and forestry management, carbon-rich soils and carbon-rich landscapes; and
- To guide food systems towards reduced food losses and waste, and towards healthier diets.

Pursuing these goals simultaneously would help tap into the potential for co-benefits of adaptation and mitigation. Priorities in food and agricultural policies will need to be re-set – from a narrow focus on reducing yield gaps to a much broader focus on other, equally important, objectives: soil conservation and restoration to enhance the capacity of soils to sequester carbon dioxide; improvements in nitrogen management to reduce emissions and enhance productivity; practices that simultaneously increase farm level production efficiency and minimize GHG emission intensity; measures to minimize losses and waste within food systems and to promote sustainable diets; and diversification strategies that increase the resilience of production systems to climate change and climatic variability.

Having focused, in this chapter, on the mitigation side of the adaptation-mitigation nexus in agriculture and food systems, Chapter 5 will examine an agricultural response to climate change, in terms of policies and institutions.

CHAPTER 5

THE WAY FORWARD: REALIGNING POLICIES, BUILDING INSTITUTIONAL CAPACITY

KIROKA, UNITED REPUBLIC OF TANZANIA
A farmer who has adopted the System of Rice Intensification (SRI) method examines her rice paddy.
©FAO/D. Hayduk

RUSUMO, UNITED REPUBLIC OF TANZANIA
Mulching – dry leaves cover the ground at a primary school's banana farm.
©FAO/M. Longari

KEY MESSAGES

1 **THE AGRICULTURE SECTORS FEATURE** prominently in nearly all the Intended Nationally Determined Contributions submitted by countries in preparation for the United Nations Climate Change Conference in Paris (COP21).

2 **IN THEIR INDCS, COUNTRIES HAVE MADE STRONG COMMITMENTS** to both adaptation and mitigation efforts in agriculture.

3 **FOLLOW-UP ACTION PLANS CAN ONLY BE EFFECTIVE IF THEY ARE PART OF BROADER**, transformative policies on agriculture, rural development, food security and nutrition.

4 **THE INTERNATIONAL COMMUNITY MUST SUPPORT DEVELOPING COUNTRIES** in strengthening their capacity to design and implement integrated policies that address agriculture and climate change.

CHAPTER 5

THE WAY FORWARD: REALIGNING POLICIES, BUILDING INSTITUTIONAL CAPACITY

Chapters 3 and 4 presented the economic and technical options for building resilience to climate change and contributing to climate change mitigation. Those options will need to be enabled and supported by appropriate policies, institutional frameworks and investment finance mechanisms. Many of these are important for agricultural development in general, but become even more necessary when addressing climate change. Existing policy frameworks need to be modified to integrate climate change concerns. As well as addressing agriculture and food security *sensu stricto*, they will need to encompass land and water management, disaster risk management, social protection, and research and development.

Many countries have designed broad climate change policies and strategies, which establish overall objectives and targets that reflect the relative importance of various sectors in their economies, as well as their national priorities. However, as yet, few have spelled out detailed action plans to achieve climate targets. This chapter provides an overview of policy actions proposed by countries in relation to agriculture and land use, and land-use change and forestry (LULUCF) in their Intended Nationally Determined Contributions (INDCs) under the United Nations Framework Convention on Climate Change (UNFCCC). It then discusses how these national commitments need to be linked to policies and institutions in order to ensure an effective response to the climate challenges facing agriculture. ■

AGRICULTURE NOW CENTRAL TO "INTENDED CONTRIBUTIONS"

At the Paris Climate Conference (COP21) in December 2015, countries' Intended Nationally Determined Contributions served as the basis for negotiations and helped to produce the Paris Agreement on climate change. However, while countries committed themselves to defined mitigation targets, those targets – if reached – would result in aggregate greenhouse gas emission levels in 2030 some 28 percent higher than those required to keep the global temperature increase below 2 °C.

Even though ambitions fall short of what is needed, and despite an apparent resistance to undertaking binding international commitments, many countries have taken steps to define their climate change actions. Under the Paris Agreement, each party to the UNFCCC is to prepare and maintain a Nationally Determined Contribution (NDC), to be renewed every five years and recorded in a public registry. If a country has previously submitted an INDC, it will become an NDC once the country ratifies the agreement. While not binding, the NDCs are meant to guide country-level climate action in the coming years. They include not only targets, but also concrete strategies for addressing the causes of climate change and responding to its effects.

While all the INDCs prepared for Paris were meant to cover mitigation, parties were also invited to consider including an adaptation component, or communicating their undertakings in adaptation planning. As of 31 March 2016, INDCs had been submitted to the UNFCCC by 188 countries.[9] All of them contain mitigation commitments, and about 70 percent of them also include a section on adaptation.

An FAO analysis of the INDCs submitted before COP21 shows that the agriculture sectors do feature prominently (FAO, 2016). More than 90 percent of countries include the agriculture sectors in their mitigation and/or adaptation contributions. In addition, developing countries – particularly the least-developed countries (LDCs) – put a strong emphasis on the agriculture sectors in terms of both mitigation and adaptation:

- **Mitigation.** Agriculture[10] and land use, land-use change and forestry are among the most referenced sectors in mitigation contributions, which set out targets and/or actions for mitigation efforts. This holds, in particular, for the INDCs submitted by developing countries. Most countries, however, have not specified agriculture and LULUCF-specific mitigation targets, but have subsumed these under economy-wide targets for GHG emission reduction.
- **Adaptation.** More than 90 percent of developing countries included in their INDCs a section on adaptation to climate change in their agriculture sectors, and consider it an issue of major concern. Adaptation features in all INDCs submitted by countries in sub-Saharan Africa and Eastern and Southeast Asia. Most LDCs also highlight extreme events as their main adaptation challenge, and more than 80 percent of them mention droughts and floods as immediate threats.

Synergies among actions aimed at climate change adaptation and mitigation in the agriculture sectors are highlighted in many INDCs, as much as co-benefits foreseen in terms of improved social and economic outcomes and environmental protection. About one-third of all countries mention such co-benefits. Thirty-one countries explicitly mention climate-smart agriculture Specific reference is made to joint benefits in terms of rural development, improved health, poverty reduction and job creation, on the one hand, and conservation of ecosystems and biodiversity, on the other. Likewise, the importance of reducing gender inequalities and promoting women's empowerment in order to improve agricultural production, while reducing vulnerability to the impacts of climate change, is underlined in many of the INDCs.

The INDCs were not prepared according to a standard format. Therefore, they are heterogeneous in length, coverage and level of detail. Because of this heterogeneity, caution is needed when comparing country priorities and actions beyond broad patterns. However, the INDCs submitted do provide a clear indication of the importance attached to the agriculture sectors, by the vast majority of countries, in terms of both adaptation and mitigation. At the same time, however, it is clear that much better tools are needed to tailor climate actions to the specific characteristics and circumstances of the agriculture sectors (Box 21). »

9 A total of 161 INDCs were submitted to the UNFCCC, corresponding to 188 countries (the European Union INDC corresponds to 28 countries). Libya, the Democratic People's Republic of Korea, Nicaragua, Palestine, the Syrian Arab Republic, Timor-Leste and Uzbekistan have not yet submitted INDCs. On 19 April 2016, Panama submitted its NDC, which is not included in this analysis.

10 In the context of mitigation, emissions from the "agriculture sector" – in accordance with IPCC terminology – includes emissions from enteric fermentation, manure management, rice cultivation, prescribed burning of savannas and grassland, and from soils (i.e. agricultural emissions). Emissions related to forest and other land uses are covered under LULUCF.

BOX 21

THE AGRICULTURE SECTORS AND UNFCCC

How the agriculture sectors are taken into consideration in UNFCCC discussions is often misunderstood, with frequent statements that agriculture was not included, or was even excluded, from the negotiations. The United Nations Framework Convention on Climate Change embraces *all* anthropogenic sources of GHG emissions, as well as *all* impacts of climate change. The question, therefore, is not whether the agriculture sectors are integrated in the scope of the Convention, but how their specificities are accounted for.

There are several points that enable the specific consideration of issues related to agriculture and food security. The first one is the UNFCCC's recognition of the importance of food production – Article 2 of the Convention, which states its objective, says that this objective should be achieved while ensuring that "food production is not threatened". The Paris Agreement, adopted in COP21, further recognizes "the fundamental priority of safeguarding food security and ending hunger, and the particular vulnerabilities of food production systems to the adverse effects of climate change".

The second point is the recognition, reaffirmed in the Paris Agreement, of the important role of land use, land-use change and forestry in addressing climate change. This has prompted diverse work streams, under the climate convention, on how to take into account the specificities of sources and sinks in accounting rules and financial mechanisms. Among the principal issues considered are the distinction between natural and anthropogenic causes of sources and sinks, and how to deal with the non-permanence of emission reductions through sinks. It has also led to an initiative, launched in 2008, to reduce deforestation and forest degradation (REDD+) by providing payments to developing countries. Forests are quite prominent in the Paris Agreement. Article 5 recognizes the central role of forests in achieving the 2 °C goal through mitigation options covered by REDD+. It also acknowledges the potential of forests for joint mitigation and adaptation approaches, and their important role in yielding non-carbon benefits.

Third, since the Bali Conference (COP13) in 2007, a specific work stream on agriculture, intended in this context as crop and livestock production, has been developed. It has advanced through four thematic workshops in the UNFCCC's Subsidiary Body for Scientific and Technological Advice, on early warning systems, vulnerability, adaptation and productivity. The results will be discussed in COP22, in Marrakech.

Finally, the need for mechanisms and tools that recognize and are adapted to the specificities of the agriculture sectors emerges as a cross-cutting theme, both in the above-mentioned work streams, and in all the activities under the Convention. Emissions and emission reductions, including sources and sinks, are more difficult to assess and monitor in agriculture than in most other sectors. The sheer number and small size of actors in the agriculture sectors are also a major source of difficulties and transaction costs for the implementation and monitoring of mechanisms that have been conceived, generally, for the energy and industrial sectors. Moreover, the fact that mitigation and adaptation are treated separately in the UNFCCC impedes a proper valuation of the synergies, as well as the trade-offs, between adaptation and mitigation actions, which are particularly important in the agriculture sectors. As underlined in the INDCs, actions in the agriculture sectors are particularly significant in terms of potential co-benefits or trade-offs with environmental, economic and social issues. These issues are important to the agriculture sectors, but are not taken into account in most UNFCCC discussions and mechanisms.

» The INDCs also highlight how adaptation and mitigation actions in the agriculture sectors are particularly rich in potential co-benefits. As countries move from intentions to implementation, many have expressed concern about the adequacy of available financial resources and about their own institutional capacity. Countries of sub-Saharan Africa express such concerns most often, and their INDCs are also among the most detailed and exhaustive when it comes to agriculture. ■

FROM INTENTIONS TO ACTION: AGRICULTURE IN CLIMATE STRATEGIES

Since the Nationally Determined Contributions are general, non-binding commitments, and not action plans, the commitments undertaken need to be translated into action at the national level. This directly concerns agriculture and food security policy-making. However, it also entails the mainstreaming of climate change considerations into a range of other policies and action areas that are highly relevant to agriculture and food security, such as land and water management, but also disaster risk management and social protection. The challenge is to incorporate the agriculture sectors into national climate change strategies, which are themselves linked to UNFCCC mechanisms (Figure 16).

A series of instruments have been designed under the UNFCCC for linking international climate change commitments to concrete action for mitigation and adaptation at the country level:

- **National Adaptation Programmes of Action (NAPAs)** were originally established by the UNFCCC as a dedicated, harmonized, country-led instrument for least developed countries. The programmes identify priority activities responding to "urgent and immediate needs" – for which further delay could increase vulnerability or lead to increased costs at a later stage – for climate change adaptation. To date, 50 countries have submitted NAPAs to the UNFCCC Secretariat (UNFCCC, 2016a). Agriculture and natural resource management issues are particularly prominent in them. The great majority of priority projects are related to the agriculture sectors and food security (Meybeck *et al.*, 2012), and most belong to one of five main categories: cross-sectoral (including early warning systems, disaster management, education and capacity building), management of ecosystems, water management, plant production and livestock, and diversification and income. All NAPAs are eligible for funding under the LDC Fund, which is managed by the Global Environment Facility (GEF) for their implementation.
- **National Adaptation Plans (NAPs)** focus on addressing medium and long-term adaptation needs and provide a significant opportunity to integrate the concerns and needs of the agriculture sectors and actors in broad national strategies and policies. Three countries – Brazil, Burkina Faso and Cameroon – have each completed a NAP, and all give importance to adaptation in agriculture.
- **Nationally Appropriate Mitigation Actions (NAMAs)**, as defined by the UNFCCC, are prepared by national governments in the context of sustainable development and provide for nationally appropriate actions that reduce emissions in developing countries (UNFCCC, 2016b). They typically include more detailed actions than INDCs and can be project-based, programmatic, sector-wide, or focused at the policy level (Wilkes, Tennigkeit and Solymosi, 2013). Sectoral policies need to be defined or revised and aligned with climate policies and priorities. Baseline scenarios have to be constructed and the mitigation potential of different options estimated. The barriers to implementation of these options need to be identified. Institutional arrangements for coordination and financing, as well as for measuring, reporting and verification, must be established. Some 13 percent of the NAMAs in the convention's NAMA registry are in the AFOLU sector (UNFCCC, 2015). ■

INTEGRATED APPROACHES THAT ALIGN CLIMATE AND DEVELOPMENT GOALS

The NAPAs, NAPs and NAMAs focus on actions that address climate change, either through adaptation or mitigation. However, as discussed in Chapters 3 and 4, to be effective and to ensure that co-benefits are achieved, these actions need to be an integral part of broader agriculture, food and nutrition policies.

Restoration of forests and degraded soils, climate-smart agricultural practices, agroecology and better management of water resources can all contribute to the productivity improvements needed to respond to the growing demand for food, improve the resilience of farming systems and reduce the emission intensity of crops, livestock, fisheries and forestry, while increasing carbon sequestration in soils and forests. However, as indicated in Chapters 3 and 4, a shift towards sustainable practices in the agriculture sectors may not be enough to place food systems on a sustainable pathway and to eradicate hunger. For that, further efforts are needed to improve the resilience and livelihoods of the food insecure and, across all economic sectors, to ensure a reduction in GHG emissions in order to prevent the global temperature from increasing by more than 2 °C. Agricultural and rural development policies that help diversify income and employment opportunities for the poor and food insecure need to be complemented by policies that address the carbon footprint of entire food systems – for example, through measures that align dietary preferences with environmental objectives.

From the perspective of agriculture, such an integrated approach needs to start from an understanding of the drivers of agricultural production and natural resource management choices, of their impacts on farmers' livelihoods and of the consequences for the environment. Doing so is complex, and win-win solutions may not always be possible. Policies, market forces and environmental constraints drive the use of inputs and other resources in agriculture, the levels of productivity, and the degree of conservation or depletion of natural resources. These drivers vary significantly among countries. Subsistence farmers in Africa and smallholders in Asia face different constraints and do not have the same ability to respond to policy and market signals as global agri-businesses. As shown throughout this report, climate impacts vary widely by region, and will have to be addressed according to local circumstances. Despite those differences, there are a number of common areas where trade-offs between climate and food security objectives can be addressed and where different policy domains should come together.

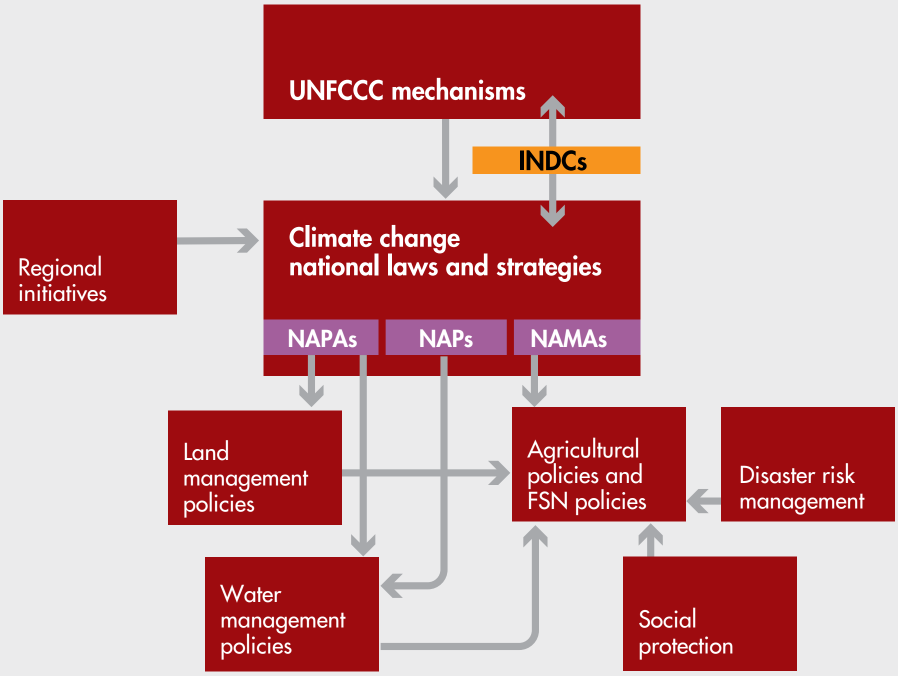
Undoing environmentally harmful subsidies and support measures

The OECD countries spent US$211 billion in agricultural production support in 2015. In the non-OECD countries for which data are available, this support reached US$352 billion in the same year.[11] Governments support farmers and agri-businesses to provide direct stimulus to agricultural production, influence input costs, supplement farm incomes, and achieve other social, economic and environmental objectives, such as landscape preservation, water conservation, poverty reduction, and climate change mitigation and adaptation. Much of the existing production support in both developed and developing countries involves subsidies on inputs, such as fertilizer and energy, particularly fossil fuels, or direct payments to farmers. In OECD countries, support measures have been declining since the 1980s, both in real and »

11 Agricultural production support estimates (PSE) are taken from the Producer and Consumer Support Estimates database of the OECD (2016). The database includes estimates for nine non-OECD countries: Brazil, China, Colombia, Indonesia, Kazakhstan, Russian Federation, South Africa, Ukraine, and Viet Nam.

FIGURE 16

FROM INTERNATIONAL COMMITMENTS AND MECHANISMS TO NATIONAL POLICIES AND INSTITUTIONS



SOURCE: FAO.

BOX 22

THE NEED FOR POLICY COHERENCE BETWEEN AGRICULTURE AND ENERGY

Lower taxes on fuel used in agricultural production and support to the development of biofuels are two prime examples of the need for better alignment of agricultural, energy and climate change policies.

The argument for ***lower taxes on fuel*** used in the agriculture sectors is the importance of transportation fuels as an input to production, and the fact that they are mostly used off-road. However, when it comes to GHG emissions, diesel combustion contributes equally to CO_2 emissions, irrespective of where it takes place. An agricultural policy allowing full exemption would not, therefore, be consistent with mitigating climate change.

Biofuels are another energy-related area where policy coherence is problematic. Biofuel development is shaped by several policy domains – agriculture, energy, transport, environment and trade – and often there is no clear coordination and policy coherence among them (FAO, 2008). Only if the role of biofuels is considered in relation to these policy domains can it be ensured that objectives are not in conflict with each other.

Producing biofuel feedstock competes with conventional agriculture for land and other productive resources, which can affect food security and nutrition through higher and more volatile food prices. As the economic viability of biofuel production depends on oil prices, volatility in energy markets is transmitted to agricultural markets and on to food prices (see Enciso *et al.*, 2016).

Biofuel policy measures are commonly implemented through tax credits, quantitative targets (blending or use mandates), and trade restrictions (Sorda, Banse and Kemfert, 2010). These have different effects on volatility in agricultural markets. Tax credits provide a stronger link to energy markets, through relative prices, rather than quantitative targets; hence the latter are more predictable in terms of demand for biofuels.

Biofuel policies link markets for agricultural commodities and energy, and must be considered within the wider context of climate change policy. If biofuel support policies are put in place, then mandates could be preferable to tax credits, from a food security perspective, because they are less prone to market volatility. However, much depends on the magnitude of the mandate and the size of the tax credit. Particular care needs to be taken in managing the interactions between tax credits and mandates, further complicating policy coherence (De Gorter and Just, 2009).

» relative terms. Relative to the value of production at the farm gate, support dropped significantly, from 46 percent in 1986 to 20 percent in 2014. In contrast, in most non-OECD countries for which data are available, agricultural production support is increasing.

Support measures may have unintended impacts on the environment, if misaligned with efforts to address climate change and environmental concerns. For example, input subsidies may induce inefficient use of synthetic fertilizers and pesticides and increase the emission intensity of production. Almost half of all agricultural subsidies provided by governments of OECD countries in 2010–12 were "potentially most harmful to the environment" by inducing greater demand for chemical fertilizers and fossil fuels and leading to more greenhouse gas emissions (OECD, 2015). The share of environmentally damaging subsidies has fallen from 75 percent in 1995, while the share of subsidies and payments subject to compliance with environmental regulations has increased. While that is a promising trend, OECD countries still have some way to go to align overall agricultural price policies with incentives to adopt environmentally sustainable production practices.

In developing countries, trends are towards increasing use of producer price support and input subsidies. Input subsidies are often motivated by the belief that, by reducing input costs, yields will increase and food security will improve. As discussed in Chapter 3, in some contexts, particularly in parts of sub-Saharan Africa, incentives to increase the use of nitrogen fertilizer can indeed have the co-benefit of enhancing productivity and improving the resilience of smallholder producers. However, benign impacts do not apply in all contexts, such as in East Asia, where excessive use of fertilizer has no production benefit and instead causes severe environmental harm (Fixen *et al.*, 2015). Hence, careful assessment and policy design are needed to avoid creating incentives that counteract environmental goals.

One way of aligning agricultural development and climate goals would be by making agricultural support measures conditional upon the adoption of agricultural practices that lower emissions and conserve natural resources. As subsidy levels are significant, there is scope for a re-alignment and a re-direction of incentives. However, none of this will suffice without concerted efforts to align policies on climate change and agriculture with policies in other domains, particularly the energy sector (Box 22).

Managing natural resources

Another key domain for policy synergy is sustainable natural resource management. Optimizing the sustainable use of land and water requires appropriate governance and mechanisms to manage synergies and trade-offs between different objectives, interests and time scales. To achieve multiple objectives in agriculture, energy and forestry, large-scale land-use planning is needed in order to identify priority areas for REDD+, agricultural production and forests for other uses, such as biomass energy production.

Crops and livestock are the most important sectors driving deforestation and forest degradation. The energy sector is also closely linked to forests in most developing countries, through the widespread dependence on wood fuels, especially in Africa and Asia, and the expansion onto forest land of biofuel feedstock production, mainly in Asia and Latin America. The success of climate change mitigation and adaptation actions will be heavily dependent, therefore, on the harmonization of objectives across the agriculture and energy sectors. To ensure national ownership and political sustainability, REDD+ will also need to contribute to realizing the objectives of other key economic sectors.

Supporting and facilitating collective action

Climate change gives rise to new and increasing demands for collective action and, consequently, coordination among stakeholders. These demands should be met through policies and institutions that facilitate and support coordinated design and implementation of actions, either in a specific area – e.g. a watershed or forest – or in a sector, such as an entire food chain. Promoting inclusiveness and transparency in decision-making, and providing incentives to actions that aim to induce long-term public and collective adaptation benefits, are particularly important for the management of natural resources (Place and Meybeck, 2013).

In order to support landscape restoration, for example, cross-sectoral coordination is essential. Agencies often work in relative isolation, and even at cross-purposes. This is at least partially due to how institutions are structured and the lack of capacity of institutions to cooperate closely in land-use planning and management. There is a need – and a real scope – for institutions dealing with ecosystem and land-use issues to integrate the management of natural resources, especially forests, trees, soil and water, through improved, multisectoral land use (Braatz, 2012).

To support improved governance of land and water tenure systems under climate change, multistakeholder dialogue, taking into account the interests of women, the poor and marginalized groups, is a promising option. For instance, experience over past decades has shown that forests can be managed well and degradation can be reversed by involving local communities, with support from legitimate decentralized institutional arrangements developed through consultative processes (FAO, 2013). There are many examples of forest farmer groups (FAO and AgriCord, 2012) and community forestry groups (e.g. Nepal's Community Forest User Groups). The same holds for community fisheries groups and organizations.

Social networks are also important components of local governance and can help to provide for effective responses to climate change. Traditional forms of reciprocal and mutual labour – for example, in soil and water conservation work and in shifting cultivation systems – have been partly or totally abandoned in many areas, owing to socio-economic changes (FAO, 2013). Supporting or reactivating these forms of cooperation for restoration work, where appropriate, may be beneficial. Encouraging informal social networks to share information and experience on adaptation options may also help to build social resilience to climate change. Such networks can play a key role in establishing surveillance, monitoring and early warning systems.

Managing risks

Climate change is bringing new risks and changing existing ones (FAO and OECD, 2012). Better management of actual risks has been highlighted by the IPCC as a key adaptation action. This requires appropriate institutions and policies, which are mostly sector- and/or risk-specific. Weather stations, weather and climate projection tools, yield response models, environmental monitoring tools and vulnerability assessments can help to determine how local climate conditions will change in the future, and to estimate their impact on production. They are essential for reliable early warning systems and for assessing adaptation options.

Comprehensive risk management strategies require a clear understanding of the robustness of different risk management instruments under climate uncertainty (Antón *et al.*, 2013). They also require coordination of actions by public, private and civil society sectors, from the global to local levels (World Bank, 2013). National governments could provide mechanisms for proactive and integrated risk management – such as a national board that coordinates risk management strategies with institutions for risk monitoring, prevention, control and response at the local and global levels – and provide incentives for private sector participation in risk coping. As highlighted in Chapter 3, social protection programmes that guarantee minimum incomes or access to food have an important role, but need to be well linked with other forms of climate and disaster risk management (Box 23).

Policies are also needed to reduce financial risks, lower transaction costs, facilitate financial transactions, enable access to financial services, and facilitate long-term investments, through safe savings deposits, low-priced credit and insurance. The financial needs of smallholders and family farmers for both working capital – for example, to buy fertilizer and seed – and for medium and long-term investments must be addressed and supported.

Last but not least, policies and institutions must actively support the diversification of livelihood strategies. Livelihood diversification is among the most effective risk management strategies for smallholders and family farmers facing climate change. Depending on the specific context, it might include land-use diversification as well as income or labour diversification. Agricultural and rural development policies thus need to integrate diversification as a key component, and local institutions need to facilitate it by providing incentives through improved access to credit, insurance, information and training.

Building institutions and policies for more resilient systems with lower emissions

Given the emphasis countries have placed in their INDCs on both mitigation and adaptation, supporting food producers in their efforts to adapt to climate change, while keeping GHG emissions in check, must become a priority. To adopt new and more resilient livelihoods, farmers, herders, fisherfolk and foresters need an institutional environment which supports that change. At present, however, this type of enabling policy and institutional environment is often lacking, especially for smallholder producers.

Institutional arrangements that support increased and stabilized returns from agricultural production are essential. Agricultural input and output markets play a central role here, but other institutions – such as rural credit and insurance programmes, agricultural extension, land and water tenure arrangements, and input subsidy programmes – have all been found to play important roles in supporting, or hindering, smallholders in the transition to systems with higher resilience (see Chapter 3 as well as: McCarthy, Best and Betts, 2010; Asfaw, Coromaldi and Lipper, 2015; Asfaw *et al.*, 2015; Asfaw, DiBattista and Lipper, 2014; Arslan *et al.*, 2014; 2015; Arslan, Belotti and Lipper, 2015).

In order for food producers to access the inputs and know-how needed for climate change adaptation, and to be able to sell the products of their diversification activities, it will be even more important, under climate change, to create solid links between smallholders and local, national and regional markets. Developing market linkages also requires investment in small- and medium-size food processors, and in small-scale traders at the retail and wholesale levels. Government intervention may be needed to reduce transaction costs in accessing markets and to establish regulatory instruments that bridge the gaps in economic and political power that divide smallholders and their organizations from other contracting organizations. ■

STRENGTHENING REGIONAL AND INTERNATIONAL COOPERATION

Transboundary issues

Addressing climate change often requires collective management of natural resources, which may, in turn, require transboundary »

BOX 23

DISASTER RISK REDUCTION FOR FOOD SECURITY AND NUTRITION

Building resilience requires a change in the conventional approach to disaster risk reduction (DRR) – from simply reacting to extreme events to prioritizing the reduction and active management of risks. On a yearly average, less than 5 percent of all humanitarian funding has gone to disaster preparedness and prevention; and less than 1 percent to those countries most in need. Investment in DRR from official development aid (ODA) disbursements was in the range of 0.4 percent in 2010 and 2011 across all sectors (UNISDR/OECD, 2013).

The Food and Agriculture Organization has conceptualized and implements DRR action in many countries recurrently exposed to extreme climate and other events (for several examples, see FAO, 2016). The approach is based on four mutually supportive pillars, which correspond to the Sendai Framework for Disaster Risk Reduction. They aim at:

- creating an enabling environment through strengthened capacities and enhanced legal and planning frameworks for disaster risk and crisis governance;
- understanding the risk and informing decision-making through sector-specific risk monitoring and early warning;
- promoting location-specific practices that prevent and mitigate the impacts of natural hazards and disasters; and
- enhancing capacities, coordination and planning for preparedness, emergency response and building back better than before during rehabilitation.

BOX 24

KNOWLEDGE GAPS AND DATA CHALLENGES

Climate change also changes the risk environment and adds an additional layer of uncertainty to risks already faced by food producers. Gaps in important information and knowledge, such as intra-seasonal weather forecasts, need to be addressed. Investment is required in infrastructure to measure, record, store and disseminate data on weather variables, and to provide weather and seasonal climate forecasts at desired spatial and temporal scales. Climate forecasts need to be made more useful and more user-friendly through partnerships among agencies dealing with meteorological and hydrological services, agricultural research, and extension.

In the context of the need for more coordinated action, the Agricultural Model Inter-comparison and Improvement Project is an important initiative linking modelling efforts around the world, focusing on climate, crops, livestock and economics, and helping to highlight remaining knowledge gaps and how to address them. For example, despite recent literature on climate change effects on plant pests and pathogens (Bebber, Ramotowski and Gurr, 2013; Gregory *et al.*, 2009) and their antagonists (Thomson, Macfadyen and Hoffmann, 2010), they are not incorporated in projections of climate impacts on agriculture; they have been identified as important for further model development (Rosenzweig *et al.*,2014).

To underpin both forecasting and monitoring of the actual impacts of climate change, and actions to counteract these impacts, statistics will need to provide better information on a range of processes, including: socio-economic drivers of emissions; emissions; Earth observations; impacts on ecosystems and economic activities; adaptation actions; and mitigation actions. Major data gaps still exist in all these areas, particularly for developing countries that lack the capacity to analyse time-series data, estimate emissions in key sectors and make full use of Earth observations. Countries need support in improving their national statistical systems, and especially in developing their capacity to evaluate climate change risks using socio-economic, geo-referenced data and integrated economic models.

International and regional collaboration will be key in addressing these knowledge gaps and delivering information to stakeholders. The FAO statistical database, FAOSTAT, provides yearly updates of emissions estimates by country for agriculture, land use, land-use change and forestry. FAO also publishes geo-spatial information through a number of portals and specialized products, such as GeoNetwork, the Harmonized World Soil Database, and Collect Earth — a new tool which enables forest data collection through Google Earth.

» action. Moreover, climate change will increase the potential for movements of pests and diseases, as well as movements of products, from one country to another. This calls for strengthened regional and international cooperation to facilitate exchanges of knowledge, manage common resources, and exchange and value plant and animal genetic resources.

Many resources upon which the agriculture sectors depend – such as water, fish stocks and ecosystems – are transboundary in nature. Changes in the environment will lead to changes in the availability of these resources and to the migration of species, people and human activities as they seek to adjust to these changes. In addition, extreme events, such as forest fires, species invasions, and pests and diseases, reach across national boundaries. Policies and institutions dedicated to the prevention and management of specific risks and vulnerabilities that are being affected by climate change are mainly local and national, but they can be effectively supported by international cooperation and tools.

Multicountry and regional action to monitor and manage changes in natural resources, as well as risks to the agriculture sectors and food security, is thus crucial to addressing climate change. Important examples of transboundary cooperation in the agriculture sectors include:

- **Regional fisheries bodies**, institutions and networks, which work together in the adaptive regional management of transboundary fisheries stocks and the regional control of fish diseases. For example, the management of industrial fisheries for skipjack and yellowfin tuna in the equatorial waters of the western Pacific Ocean keeps catches within sustainable bounds and optimizes the distribution of economic benefits.
- **Regional forestry commissions**, which coordinate actions that have transnational implications and which benefit from collaboration among countries in the regions. Examples of joint action include regional initiatives on forest fires and invasive species, as well as regional collaboration on forest resource assessments.
- **Institutions for transboundary water resource management**, such as the Nile Basin Initiative and the Mekong River Commission, which help develop a shared vision of demands on water resources within regional water basins.
- **Regional projects**, such as the Great Green Wall initiative to combat desertification in Africa.
- **Regional and global early warning systems**, such as FAO's Global Information and Early Warning System and its Emergency Prevention System for Animal Health.
- **The FAO Desert Locust Control Committee**, which consists of 64 countries, and strengthens national capacities in desert locust monitoring, control, contingency planning, training and environmental safety in nearly 30 countries.

The role of trade in adaptation and mitigation

An efficient international trading system is important for both climate change adaptation and mitigation. Climate change may have far-reaching impacts on global production patterns and patterns of international trade in food and agricultural products. Trade may be part of adaptation strategies for regions adversely affected by climate change. Trade restrictions, such as tariff and non-tariff barriers, which limit the response of global agricultural production to changes in demand and supply under climate change, should be minimized. However, since impacts are expected to be worse in low-latitude regions (see Chapter 2), climate change is likely to exacerbate existing imbalances between the developed and developing world. Climate change underscores the need to help developing countries deal with food and energy price increases, as well as volatility in food supplies.

Existing trade policy frameworks are far from being "climate-compatible". For instance, the role of trade measures in international negotiations on climate change stabilization is unclear. There is no consensus as to whether current World Trade Organization (WTO) trade rules can promote adherence to climate goals, or are a threat to mutually agreed climate solutions (Early, 2009). In fact, various forms of climate change mitigation policies could be challenged under WTO rules if they were deemed to be trade distorting. This could apply, for example to: payments for environmental services, such as forest and soil carbon sequestration; policies implemented as unilateral measures, such as carbon taxes or cap-and-trade regimes; and related border adjustment measures that place duties on imports from countries not undertaking comparable mitigation efforts based on the carbon-content of products or production methods.

A key step towards reaching an international agreement on the harmonization of trade rules with climate objectives will be to tackle concerns that climate measures may distort trade, or that trade rules could stand in the way of greater progress on climate change (Wu and Salzman, 2014). ■

CONCLUSIONS

In the Intended Nationally Determined Contributions submitted in preparation for COP21, a large number of developed and developing countries clearly expressed their determination to ensure an effective response by the agriculture sectors to climate change, in terms of both adaptation and mitigation. This determination needs to be translated into concrete action with the support of an enabling policy and an institutional environment, as well as regional and international cooperation. Action plans should now build on a recognition that there are important synergies and trade-offs between mitigation, adaptation, food security and the conservation of natural resources. Creating co-benefits requires coordination across all relevant domains.

Unfortunately, there is a general lack of coordination and alignment of agricultural development plans and actions that address climate change and other environmental problems. This is leading to the inefficient use of resources and is preventing the integrated management required to address climate change threats, ensure productivity improvement in food production and enhance the resilience of vulnerable households. At the same time, it should be recognized that assessments of the impacts of climate change are surrounded by uncertainty and hampered by large knowledge gaps. To better inform policy action, much greater efforts are needed to improve assessment tools and close knowledge gaps, for example by strengthening statistical systems and climate forecasting and monitoring capacity (Box 24).

Breaking down the silos between policies on adaptation, mitigation, food security, nutrition and natural resources is essential also when determining the financing needed to support the transition towards sustainable, climate-smart food systems. The next chapter turns to the issue of linking climate change action and agricultural finance.

CHAPTER 6

FINANCING THE WAY FORWARD

DLBISSI, BURKINA FASO
Sacks of animal feed provided through an FAO distribution centre in a drought-stricken area.
©FAO/I. Sanogo

DJIBO, BURKINA FASO
Soon after heavy rain in the desert between Djibo and Dori.
©FAO/G. Napolitano

KEY MESSAGES

1 **INTERNATIONAL PUBLIC FINANCE FOR CLIMATE CHANGE ADAPTATION AND MITIGATION** is a growing, but still relatively small, part of overall finance for the agriculture sectors.

2 **MORE CLIMATE FINANCE IS NEEDED** to fund developing countries' planned actions on climate change in agriculture.

3 **PROVIDED POLICIES AND INSTITUTIONAL FRAMEWORKS THAT PROMOTE TRANSFORMATIVE CHANGE ARE IN PLACE**, international public climate finance can act as a catalyst to leverage larger flows of public and private funding for sustainable agriculture.

4 **CAPACITY CONSTRAINTS CURRENTLY HAMPER DEVELOPING COUNTRIES'** access to and effective use of climate finance for agriculture.

5 **INNOVATIVE FINANCIAL MECHANISMS** can strengthen the capacity of financial service providers to manage risks related to climate change, helping to leverage investments for climate-smart agriculture.

CHAPTER 6

FINANCING THE WAY FORWARD

The previous chapters of this report highlighted the benefits of climate change mitigation and adaptation interventions in the agriculture sectors. Most of the adaptation interventions needed are similar to interventions that promote general rural development, but they should be designed with a focus on changing climatic conditions and related risks, constraints and opportunities. Many of the agricultural practices proposed are relatively low-cost and have both mitigation and adaptation benefits, which increases their cost-effectiveness.

Chapter 3 showed that the costs of adaptation actions in smallholder agriculture would be a fraction of the benefits and, hence, would justify generous allocations of climate finance. The case for funding increases becomes even stronger when considering the mitigation co-benefits of climate-smart development, illustrated in Chapter 4, and the emphasis that countries have placed on adaptation and mitigation in agriculture in their Intended Nationally Determined Contributions (INDCs), as discussed in Chapter 5. This chapter examines the role of finance in climate change adaptation and mitigation in the agriculture sectors, and how public finance – both international and domestic – can be used more effectively to support adaptation and mitigation efforts. ■

CLIMATE FINANCE FOR AGRICULTURE

Still relatively small, but with catalytic potential

There is no single definition of "climate finance". It may be loosely defined as all finance that, regardless of origin, contributes to climate change adaptation and/or mitigation objectives. It is useful, however, to distinguish between public and private sector financing since they can play complementary roles in mobilizing resources for climate change adaptation and mitigation.

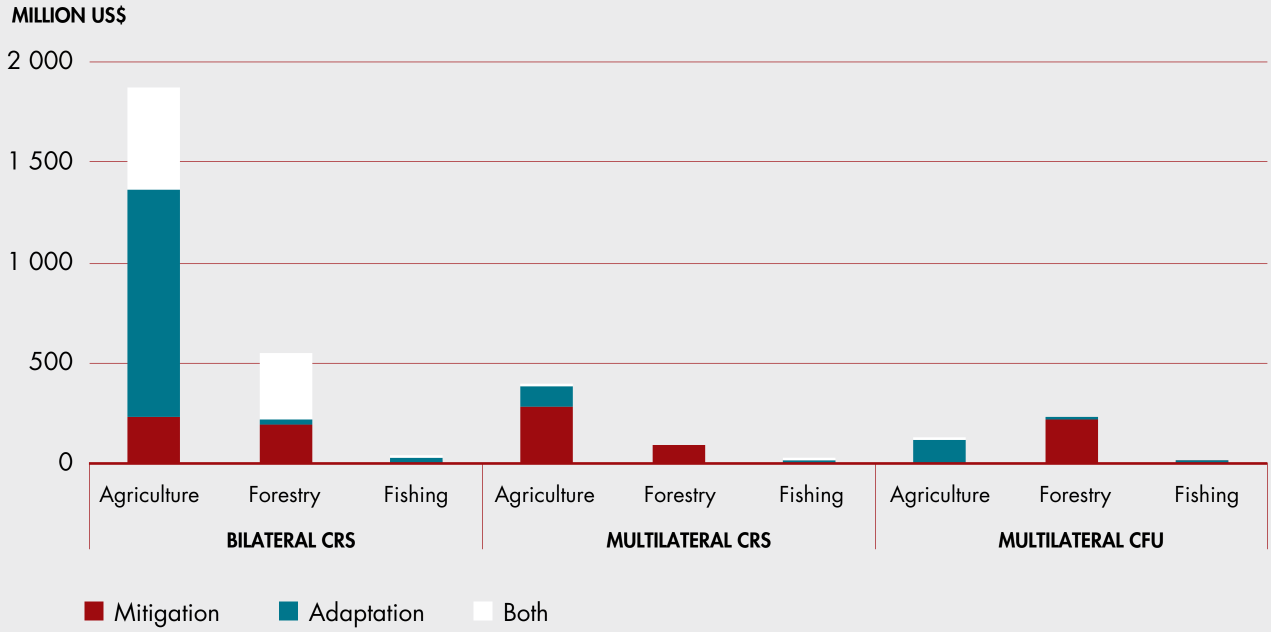
While difficult to track, available estimates suggest that the private sector is by far the largest source of finance for climate change adaptation and mitigation efforts, contributing approximately 62 percent of the US$391 billion invested in addressing climate change in 2014 (Buchner *et al.*, 2015). Farmers, from small to large, are the biggest investors in agriculture, providing many times what governments provide for rural infrastructure and agricultural research and development. Most agricultural investments are financed from domestic resources – whether public or private – and only a small share of the funding comes from international sources (FAO, 2012). However, while small in magnitude, international public financing can act as a catalyst, leveraging private financing and investments in agriculture, including climate-related investments.

Starting from low levels, international public finance for climate change mitigation and adaptation in agriculture, forestry and fisheries has increased substantially since 2002. By the end of 2014, it had reached nearly US$4 billion Norman & Hedger, 2016. and around 12 percent of overall official development assistance (ODA) was committed for climate-related investments (OECD, 2015a). This is only a fraction of overall domestic government spending on agriculture by developing countries, which totalled approximately US$252 billion in 2012.[12] However, when used properly, climate-related

12 Estimate for about 100 developing countries using IFPRI (2015) and adjusted from constant 2005 to constant 2012 dollars using United Nations (2013).

FIGURE 17

AVERAGE ANNUAL INTERNATIONAL PUBLIC FINANCE FOR MITIGATION AND/OR ADAPTATION BY SECTOR AND SOURCE, 2010–14



Notes: "CRS" is OECD's Creditor Reporting System; "CFU" is ODI's Climate Fund Update. To avoid double counting, some adjustments were made. See Annex to Chapter 6 for details.
SOURCES: Bilateral and multilateral CRS estimates are from OECD (2015a) and multilateral CFU are from ODI (2015).

finance can help redirect other sources of finance for agricultural development towards investments in enabling institutions, technologies, and practices that contribute to climate change adaptation and mitigation in the sector.

Trends in international public climate finance for agriculture[13]

International public climate finance has evolved in line with the incremental nature of commitments made in the UNFCCC process, as described in Chapter 5. The "architecture" may be seen as consisting of: on the one hand, funding from bilateral and multilateral development finance bodies destined for climate change mitigation and adaptation; and, on the other, dedicated multilateral climate funds, such as the Green Climate Fund (GCF), set up expressly to support climate action. The focus here is on the financing made available from each of these sources for addressing climate change adaptation and mitigation in agriculture (crop production and livestock), forestry and fisheries.

Data on the scale of commitments between 2010 and 2014 suggest that bilateral development assistance has been the dominant source of international public finance for climate change adaptation and mitigation in agriculture, forestry and fisheries. Average annual bilateral commitments were US$1.9 billion for agriculture, US$552.7 million for forest conservation and US$37.5 million for fisheries. Bilateral funding was far larger than climate finance commitments from multilaterals (Figure 17).

Globally, the level of international support for mitigation has far surpassed finance for adaptation (Norman and Nakhooda, 2014). However, in recent years, there has been a shift towards adaptation,

13 This section draws on Norman & Hedger (2016), a background paper prepared for *The State of Food and Agriculture 2016*.

particularly by bilateral donors. Although the focus is also shifting for multilateral funding, in the period 2010–14 it was still dominated by mitigation, which accounted for approximately 70 percent of funding in the agriculture, forestry and fisheries sectors. Forest conservation and REDD+ have been financed mainly as a mitigation opportunity, although bilateral donors are moving towards forest interventions that support both mitigation and adaptation objectives. Funds available for fisheries are predominantly for adaptation and building resilience.

There are differences in the regional allocation of adaptation and mitigation finance. Making precise estimates is difficult because the regional allocation of about one-fifth of bilateral finance tagged for climate change is either unspecified or unclear. Of the remainder, some 62 percent of finance from dedicated climate funds has been targeted at Latin America and the Caribbean, reflecting the significant opportunities seen for reducing emissions in the forest sector in that region. Adaptation funding has concentrated on sub-Saharan Africa, the region likely to be most impacted by climate change, with 54 percent of approved dedicated climate finance for the period 2010–14. Bilateral donors have also allocated almost half of their adaptation-tagged finance to sub-Saharan Africa. While bilateral donors have focused finance on countries vulnerable to food insecurity, finance currently misses the most vulnerable countries, a fact which reflects donor concerns about those countries' capacity to absorb and benefit from development assistance.

Bilateral donors and dedicated multilateral climate funds report a significant focus on capacity development, including policy and administrative management and institutional strengthening, across the agriculture sectors. That focus is most pronounced for the forestry sector, where 57 percent of bilateral and 75 percent of dedicated multilateral finance supports policy and administrative management, in particular for REDD+ readiness, which assists governments in developing national REDD+ plans and strategies. Similarly, in the fisheries sector, 43 percent of bilateral climate funding and more than 90 percent of multilateral climate funding were allocated to supporting policy and strengthening institutions.

Most bilateral and dedicated multilateral climate funding for agriculture supports both agricultural development and agricultural policy and administrative management objectives, although funding is spread across a wide range of sub-sectors. Some 40 percent of bilateral agricultural climate finance is tagged broadly for agricultural development, with donors focusing overwhelmingly on rural development. Bilateral donors have specifically sought to support smallholders moving from subsistence farming to producing a marketable surplus through improved irrigation and value-chains, as well as inclusive models for contract farming (Donor Tracker, 2014). Dedicated climate projects that support low-carbon and resilient crop and livestock production are few; they account for just 4 percent of total reported bilateral finance in the case of crop production and 0.1 percent in the case of livestock (see Box 25 for examples of uses of available funding).

In terms of multilateral funds, the GEF has been one of the largest funds financing climate change mitigation. The fund reported to COP21 that, since its creation in 1991, it has financed 839 projects for climate change mitigation, with more than US$5.2 billion in GEF financing in more than 167 countries, mobilizing US$32.5 billion in co-financing. The GEF has sought to develop long-term, sustainable approaches to maintaining forests. As of June 2016, the GEF had supported more than 430 forest-related projects, with US$2.7 billion in grants that leveraged an additional US$12.0 billion in co-finance. Funding for forests is steadily increasing. During the four years of the Fifth Replenishment (GEF-5), exactly US$700 million in grants was committed. In the first two years of GEF-6 (2014–18), grants of US$566 million have already been made available through 52 projects and programmes to enhance the economic, social and environmental value of all types of forests. In addition, the GEF has also launched a US$45 million integrated programme to take deforestation out of commodity supply chains.

»

BOX 25

DEDICATED CLIMATE FUNDS AND THE AGRICULTURE SECTORS

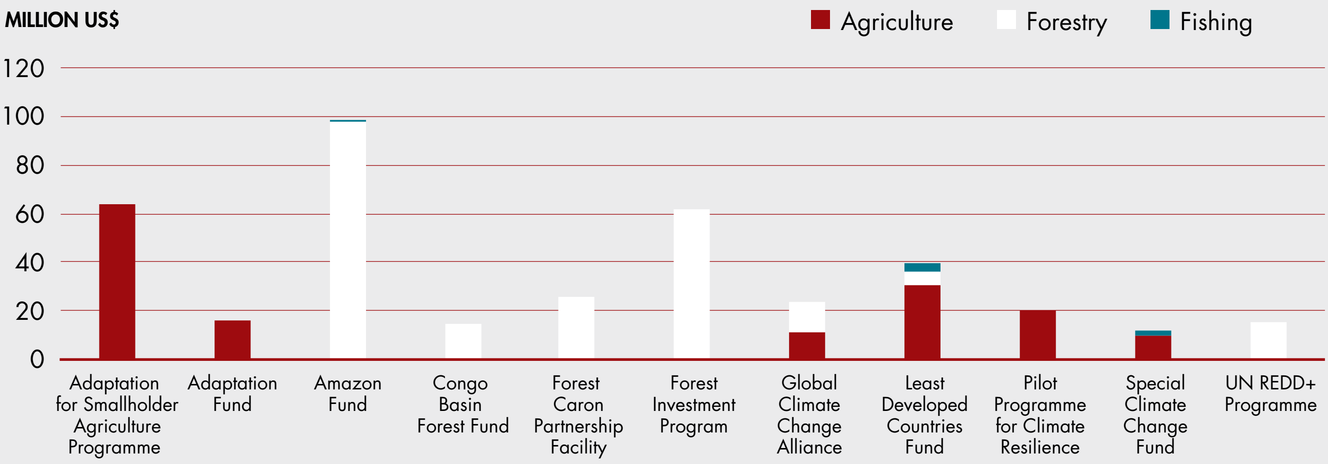
Dedicated multilateral funds, although smaller than bilateral funds in the volume of finance, focus on adaptation or mitigation outcomes as primary objectives, which is not necessarily the case with all bilateral funding. Multilateral funds support climate change mitigation and adaptation actions that are not covered by existing ODA-supported development programmes. At least 13 dedicated multilateral climate funds have invested in agricultural, forestry and fisheries projects or programmes since 2010. Their size varies notably (see Figure). Although bilateral and multilateral climate finance employs a range of financial instruments, grants predominate, particularly in the case of dedicated multilateral climate funds and bilateral donors.

For agriculture, the most significant funds are the Adaptation for Smallholder Agriculture Programme (ASAP) of the International Fund for Agricultural Development (IFAD), and the UNFCCC's Least Developed Countries Fund, which is managed by the Global Environment Facility (GEF). Launched in 2012 to mainstream climate change adaptation within IFAD investment programmes, ASAP focuses all of its approved finance on supporting the adaptation of low-income smallholder farming to climate change. When paired with IFAD investment operations, the impact is high. The ASAP experience has highlighted the need to co-design investments early on, rather than "retrofit" advanced pipeline projects, and to ensure that climate interventions are an integral part of the design, not the subject of a separate process or step.

The Least Developed Countries Fund specifically supports the least developed countries in adapting to climate change, by identifying key vulnerabilities and adaptation needs, as well as raising awareness and sharing knowledge. The Fund has programmed around 33 percent of its approved finance for agriculture, food security and sustainable land management outcomes.

The architecture supporting forest conservation has been designed largely to support the three phases of REDD+, from REDD+ Readiness to verified emission reductions, with payments based on results. The main international multilateral forestry funds include the Forest Investment Program, the Forest Carbon Partnership Facility (FCPF), the Global Environment Facility and the UN-REDD Programme. The UN-REDD Programme approved an average of US$15.6 million per year and the FCPF's Readiness Fund an average of US$26 million per year between 2010 and 2014. Both of these dedicated climate funds offer relatively small grants – of around US$5 million – to partner countries for capacity building and readiness activities. The Forest Investment Programme has approved on average US$61.6 million annually between 2010 and 2014, making it one of the most significant sources of finance for forests. The fund offers bridging finance between early policy and capacity building support and efforts to demonstrate successful programmes that will lead to verified emission reductions on the ground. Among the national and regional dedicated funds, the Amazon Fund is the largest source of public finance for forest conservation programmes in the Amazon biome.

DEDICATED MULTILATERAL CLIMATE FUNDS (AVERAGE ANNUAL FINANCE COMMITTED BY SECTOR), 2010–14



SOURCE: ODI, 2015.

» Financing needs and prospects

Figure 17 shows that international public finance for adaptation and mitigation in the agriculture sectors averaged US$3.3 billion a year between 2010 and 2014. Available estimates of the cost of adaptation in agriculture vary widely, but are generally much higher than available publicly sourced international climate finance for the agriculture sectors. The World Bank estimates adaptation costs for the agricultural sectors alone at more than US$7 billion per year. These resources would be needed for investments in agricultural research, irrigation efficiency and expansion, and roads, in order to counteract the effects of climate change on calorie availability and child malnutrition (Nelson *et al.*, 2010). The projected cost would be higher if the cost of improving agricultural extension services were factored in as part of responding to climate change. Factoring in the costs of GHG mitigation that is not obtained as a co-benefit of adaptation practices would add additional billions of US dollars per year in financing needs.[14] Clearly, the agriculture sectors will need an increase in the level of financing that is proportionate to the adaptation needs and the mitigation ambition of countries. Not all financing will need to be international public financing, if other existing funding sources can be leveraged (see section 6.2). Nonetheless, without adequate international public climate finance allocated to the agriculture sectors, such leveraging would be difficult to implement. Here the potential magnitude of such funds going forward is assessed.

The Green Climate Fund (GCF) is the largest international climate fund and aims at allocating resources evenly between mitigation and adaptation. It is referred to in several INDCs as a key funding source. As of May 2016, countries had pledged to the GCF some US$10.3 billion, of which US$9.9 billion has been signed over to the Fund. This sum is expected to rise to at least US$100 billion in annual climate finance to developing countries by 2020. Investments in the agricultural sectors are well aligned with the GCF's stated priorities – four of its eight strategic fund-level impacts are directly linked to the agriculture sectors. This is further reflected by the agriculture sectors being present in four out of the first eight projects approved by the GCF in November 2015, and five of the nine projects approved in June 2016.

Beyond the GCF, new pledges were announced at COP21 in Paris, in December 2015. At least US$5.6 billion has been pledged to new and existing initiatives or funds that could be at least partly eligible for use in support of agricultural, forestry and fisheries programmes. Another US$12.7 billion was pledged for other sectors, mainly energy and insurance, and US$126 billion was pledged without specifying the target sector. Information regarding the time period to which the pledges refer is, however, limited.

Recently, support has grown for cross-cutting forest and agricultural sector programmes. The GEF has announced new climate finance commitments of US$3 billion from across its focal areas, with at least US$300 million being dedicated to coastal and marine issues over the next four years. Another US$250 million will flow through the GEF's Sustainable Forest Management/REDD+ Incentive Mechanism, which will mobilize US$750 million in grants from other focal areas to tackle the drivers of deforestation and forest degradation, while supporting the role of forests in national and local sustainable development plans. Some US$45 million will address the key global drivers of deforestation by expanding the supply of sustainably managed commodities, while more than US$116 million will help to improve food security, strengthen resilience and enhance carbon sequestration in sub-Saharan Africa (Box 26). »

14 Based on IPCC's economic potential for mitigation, presented in Chapter 4, realizing 1 GtCO_2-eq reduction in annual emissions (which is just a fraction of the economic mitigation potential at the lower cost estimate of up to US$20 per tonne of CO_2-eq) would cost billions of dollars per year. Reducing emissions from deforestation, which is thought to be among the most cost-effective options, is still estimated to cost annually US$4–10 per tonne of CO_2-eq reduction, without accounting for transaction costs (Cattaneo *et al.*, 2010). If countries improve policy coherence with climate objectives, then financial costs may be lower, but some trade-offs will remain that require financing.

BOX 26

TOWARDS SUSTAINABILITY AND RESILIENCE IN SUB-SAHARAN AFRICA

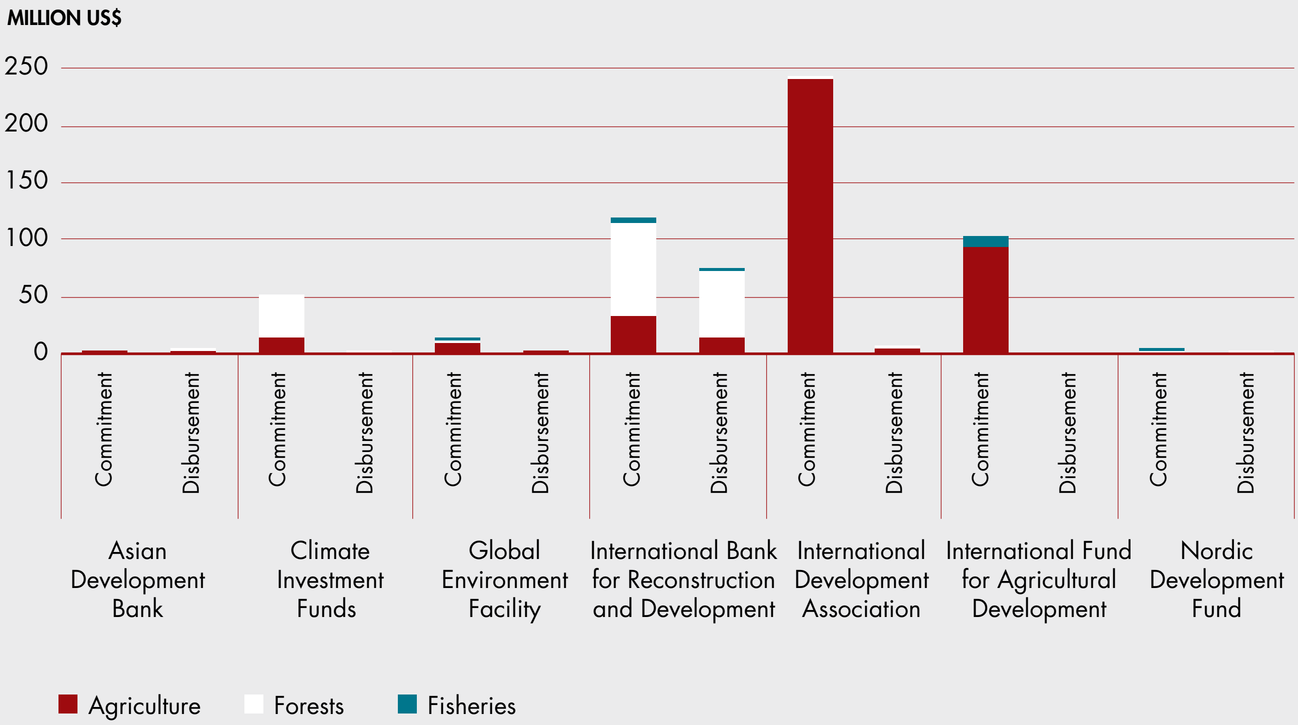
As part of its sixth replenishment, the Global Environment Facility has launched an Integrated Approach Pilot (IAP), which aims at fostering sustainability and resilience for food security in sub-Saharan Africa. The US$116 million programme seeks to safeguard ecosystem services by promoting the integrated management of natural resources through projects in 12 countries. The projects will help smallholders to become more resilient to climate change by improving soil health and access to drought-tolerant crop varieties, adjusting planting periods and cropping portfolios, and enhancing on-farm agrobiodiversity.

The projects will be supported by a regional hub, which will establish or strengthen multistakeholder frameworks that engage smallholder farmer groups, private sector entities, governments and scientific institutions, at national and regional levels. The hub project will identify, document and disseminate best management practices in order to inform regional and national policies and to upscale and out-scale viable approaches at the national level.

The IAP is led by IFAD, in close collaboration with FAO, the United Nations Environment Programme and the United Nations Development Programme (UNDP). Partner countries are Burkina Faso, Burundi, Ethiopia, Ghana, Kenya, Malawi, Niger, Nigeria, Senegal, Swaziland, the United Republic of Tanzania and Uganda.

FIGURE 18

AVERAGE ANNUAL MULTILATERAL COMMITMENTS AND DISBURSEMENTS BY SECTOR, 2010–14



SOURCE: OECD, 2015a.

» The capacity challenge: from commitment to action

Even though estimates are uncertain, there is clearly a wide gap between financing needs and available resources for addressing climate risks to agriculture. Availability of resources is not the only constraint many developing countries face, however. Many countries encounter difficulties in accessing funding and in effectively deploying the resources that they have obtained.

The OECD (2015b) notes six major challenges countries face in accessing climate change adaptation finance: (a) a low level of awareness of the need for adaptation and of relevant sources of funding; (b) difficulty in meeting funds' procedures and standards for accessing finance; (c) low level of capacity to design and develop projects/programmes and monitor and evaluate progress; (d) limited availability of and access to climate information; (e) a lack of coherent policies, legal and regulatory frameworks and budgets; and (f) a lack of clear priorities identified through transparent multistakeholder processes.

Problems may also arise after having accessed funds, during the implementation phase. For example, allocating and approving finance requires time, and many countries face capacity constraints in the effective management of funds. The constraints include the low absorptive capacity of low-income countries' public financial systems, which slows the rate of disbursement.

Reporting by all donor sources indicates that commitments to the agriculture sectors are significantly higher than disbursements. Disbursements or finance released to a recipient or implementing agent is usually structured to be released over the life cycle of the project and often lags behind commitment levels. Multilateral donors have a more protracted disbursement timeframe, the result of lengthy processes for programme approval and implementation, and equally lengthy processes for transferring funds. While a number of countries have been very successful in securing funds, for most of them disbursement constraints remain a challenge that also hinders the attainment of objectives and impacts (see Figure 18, and Norman and Nakhooda, 2014).

An example of the challenges posed by the approval process is provided by the Green Climate Fund. Its project approvals have been fewer than anticipated. Funding for the first eight projects approved in November 2015 amounted to only US$168 million, with total project costs of US$624 million. The GCF Board has set a target of committing US$2.5 billion in funding in 2016; in June 2015, nine projects with a value of US$257 million in GCF resources and total cost of US$585 million, were approved. The low approval level is indicative of the challenges the GCF is facing as a new institution, the capacity constraints of the direct access entities and at the national level, staffing constraints in the GCF Secretariat, and the rigorous project preparation requirements that did not distinguish between project type and size.

A number of decisions have been taken that should expedite the preparation and approval of GCF projects. A comprehensive readiness programme and preparatory support programme have been put in place to strengthen the capacities of national designated authorities and national entities, and steps have been taken to increase GCF staff from 45 to 100 by the end of 2016. At its June 2016 meeting, the GCF Board approved the operational guidelines for its Project Preparation Facility and a simplified procedure for micro-scale and small-scale funding proposals that are assessed as low risk or no risk. These new procedures should accelerate the project approval process.

Capacity constraints, which affect both providers and recipients of funds, will need to be addressed if agricultural climate finance is to have a truly catalytic effect in terms of enhancing resilience and the sustainability of agriculture, forestry and land use. ■

MAKING A LITTLE GO FAR: USING CLIMATE FINANCE STRATEGICALLY

International public finance tagged for climate change will probably remain a fraction of overall investment in agriculture. To achieve impact in increasing farming systems resilience or reducing greenhouse gas emissions, climate finance must focus on using strategic leverage points to direct broader financing volumes towards climate outcomes. In particular, public funds should be oriented towards:

- reinforcing the enabling environment needed to overcome barriers to the adoption of climate-smart agriculture;
- supporting the mainstreaming of climate change adaptation and mitigation efforts in domestic budgets; and
- unlocking private capital for climate-smart agricultural investment.

Financing the enabling environment for climate-smart agricultural development

International funding for the agriculture sectors has a significant focus on capacity development, including policy and administrative management and institutional strengthening across all the agriculture sectors. At the same time, capacity constraints are a major obstacle to the effectiveness of all climate finance mechanisms. This applies to funds such as the GEF and the GCF, where a major impediment to impact is the high cost of project development. However, even after projects are prepared and approved, disbursing funds and bringing projects to fruition can also be a challenge. Readiness funds and programmes may help strengthen the capacity of national and regional entities to receive and manage climate financing.

As highlighted in Chapter 5, there is a continued need to support the development of policies and institutions to facilitate and secure public and private investment for rural development. Climate change accentuates the need for strong institutions that support integrated management of natural resources and collective action. This also applies to policies and programmes dedicated to the prevention and management of specific climate risks and vulnerabilities, such as increased rainfall variability, extreme weather events and upsurges in plant pests and animal diseases. Early warning systems and mechanisms for sharing information along the food value chain will be critical to the success of climate-smart agricultural development.

Policies and institutions that provide appropriate information and incentives to food producers are often weak in responding to climate-related extreme events, or in overcoming barriers to the adoption of climate-smart farming practices. In the former case, carefully designed social protection programmes that guarantee a minimum income or access to food have an important role to play within a broader agricultural risk management strategy. As discussed in Chapter 3, improving smallholders' access to financial services will be important in supporting their efforts to address climate change.

With a better enabling environment, also limited international public finance can act as a catalyst to galvanize commitments from other public and private sector sources. The broad coalition of non-governmental organizations and private corporations which signed the New York Declaration on Forests, in 2014, is one example of the catalytic role public finance can play. The coalition seeks to reduce global emissions of greenhouse gases by between 4.5 and 8.8 Gt annually (Conway *et al.*, 2015). The public financing of efforts to reduce emissions from deforestation is likely to have played a role in catalysing this private sector participation by lowering risks linked to country participation, and improving country readiness in terms of the necessary institutional frameworks.

A core goal expressed by the private sector through the declaration is the elimination of deforestation associated with the production of agricultural commodities such as palm oil, soy, paper and beef products by 2020. Large institutional investors are also redirecting investments to align them with climate objectives, such as reducing emissions from deforestation. For example, the Norwegian Pension Fund has begun to divest shares in companies associated with unsustainable palm oil production, which can be viewed as an alignment of private financing with global climate change mitigation objectives.

Mainstreaming climate change in domestic budgets

Domestic government budgets are a key source of climate-relevant public finance. They constitute a much more significant source of public investment in agriculture than providers of international public climate finance. No comprehensive assessment is available to track climate finance from domestic budgets, and there is no agreed classification system for national climate budget tagging that permits international comparisons or aggregation. However, evidence from 11 countries indicates that domestic resources are a significant and, in some cases, even a dominant part of climate change expenditure (UNDP, 2015). Furthermore, there may be rural development funds that, strictly speaking, would not fall under climate financing but are "climate-relevant" in the sense that, through the pursuit of other policy objectives, they may influence climate change outcomes in areas such as resilience or levels of GHG emissions.

For climate-related policy goals to be achieved, domestic budgets for agricultural investments need to reflect the systematic integration of climate change considerations into policies and planning, as outlined in Chapter 5. In this respect, agricultural support policies need to be considered in the broader context of climate policy. For example, input subsidies may induce the inefficient use of synthetic fertilizers and pesticides, and increase the emission intensity of production.

A meta-analysis of climate-relevant public expenditure and institutional reviews in 20 countries in Africa, Asia and the Pacific, highlights the fact that agriculture is very prominent, second only to public works and transport, with water and irrigation being another prominent expenditure area. Significant shares of climate-relevant expenditures are channelled through local governments. The effective use of funds channelled this way requires adequate coordination with national policies and improved implementation capacities at the local level. The review showed that, while countries had made significant progress in establishing national climate policies, there had been limited integration with sector and sub-national policy, leading to a lack of coherence in how climate change is addressed. Mechanisms to ensure that policy priorities were reflected in public expenditure programmes were also lacking, as were (although some progress was noted) frameworks that assessed the performance of climate spending. As with international funding mechanisms, capacity – both technical and operational – remains an overarching challenge in many contexts (UNDP, 2015).

To ensure the full mainstreaming of climate change in public expenditure, the UNDP review recommends the adoption of a comprehensive climate financing or fiscal framework which includes: planning and costing climate change strategies and actions in the medium and longer term; employing a whole-of-government approach engaging all relevant stakeholders; bringing public sources of climate finance (domestic and international) into the national planning and budgeting system, to be delivered through country systems; and aligning private sources of climate finance with the overall policy framework. A number of countries have started making headway in strengthening their investment appraisal mechanisms to integrate climate change (Box 27).

Country-study evidence highlights the need for capacity development to allow governments to move towards the systematic integration of climate change action into their budgets (UNDP, 2015). Dedicated climate finance should support the strengthening of national systems and capacity for mainstreaming. This includes: »

BOX 27

INTEGRATING CLIMATE CHANGE INTO ECONOMIC APPRAISALS

Thailand's Ministry of Agriculture and Cooperatives has spearheaded the country's budget mainstreaming effort, moving from a qualitative assessment of the climate relevance of policies and programmes to a quantitative approach using cost-benefit analysis. The benefit-cost ratio (BCR) for a given policy is recalculated capturing the impact and associated costs of climate change. The difference between the BCR in a climate change and a "business–as-usual" scenario leads to a climate change relevance score, which provides an indication to policy-makers and managers of the change in importance of a particular programme if climate change is factored in. Pilot analysis suggests that the consideration of climate change increases the benefit of programmes managed by the Ministry by between 10 and 20 percent. The results also highlight opportunities to improve design (Government of Thailand, 2014). An assessment of a major new investment in improved water distribution and diversion resulted not only in enhanced budget justification for the project but also informed redesign of diversion canals and flood control systems (UNDP, 2015).

In Cambodia, piloting of a similar approach in the Ministry of Agriculture, Forestry and Fisheries suggests that the effectiveness of programmes managed by the Ministry could be substantially improved when climate change is taken into account. The analysis could support requests for funding from the Ministry of Economy and Finance, which introduced in 2016 a requirement in the national budget guidelines that climate-relevant programmes be identified (see Cambodia Climate Change Alliance, 2015 and Government of Cambodia, 2016).

BOX 28

MAINSTREAMING CLIMATE CHANGE IN INTERNATIONAL FINANCING INSTITUTIONS

As the importance of climate change and its cross-cutting nature has gained increasing recognition in the development community, international financing institutions have begun to develop specific approaches, tools and protocols to integrate climate change considerations into planning and implementation. Recent joint public commitments highlight convergence around key principles and greater ambition. In December 2015, a group of 26 major financial institutions adopted five voluntary "Principles to mainstream climate action within financial institutions" (World Bank, 2015):

- commit to climate strategies;
- manage climate risks;
- promote climate-smart objectives;
- improve climate performance; and
- account for climate action.

Specific implementation approaches are illustrated by the example of the World Bank. The International Development Association (IDA), the part of the Bank that helps the world's poorest countries, has committed to incorporating climate and disaster risk considerations into the analysis of countries' development challenges and priorities and into resulting programmes. All new operations are to be screened for short- and long term climate change and disaster risks and, where risks exist, they will be addressed with appropriate resilience measures. Screening tools have been developed for the national policy level, along with project-level tools and a specific sector tool for agriculture. The tools are designed to help increase the effectiveness and longevity of investments.

To complement screening and facilitate the development of appropriate solutions, the World Bank, in partnership with a wide range of organizations, has also enhanced the availability of datasets, tools and knowledge to support climate-smart development planning. Climate risk screening is now applied to all IDA projects, and will be extended to other World Bank operations in early 2017. The Bank's 2016 Climate Change Action Plan recognizes climate change as a threat to its core mission of poverty reduction, and makes a commitment to moving from early screening to *ex-ante* planning with a climate lens, in support of countries' INDC/NDC implementation (World Bank, 2016).

- reviewing planning and budgeting processes and related institutional roles, to identify and address bottlenecks – in policies, incentives and institutions – that impede an integrated approach to climate change;
- strengthening the capacity of relevant institutions and stakeholders at national and sub-national levels, particularly the technical and functional expertise needed to translate policies into programmes and budgets, and track and assess performance; and
- enhancing transparency frameworks to demonstrate results and ensure accountability.

Further work is needed to improve methodologies for climate-relevant public expenditure reviews and effectiveness assessments, and to develop practical guidelines and tools that countries can adapt to their specific circumstances, including the integration of climate change in cost-effectiveness analyses and investment appraisal. In defining nationally appropriate investment design and appraisal mechanisms, governments can also draw on the experience of international financing institutions that have already developed approaches and protocols to mainstream climate change in their portfolios (Box 28).

Efforts to enhance the integration of climate change into domestic budgets should always be aligned within ongoing efforts to strengthen public financial and expenditure management. Just as climate change should not be considered a stand-alone issue, climate change budget mainstreaming needs to be addressed in the context of a country's overall financial management systems.

Unlocking private capital for climate-smart agricultural investment[15]

Private investment is the most important source of agricultural investment (FAO, 2012). However, as discussed in Chapter 3, the lack of access to adequate and sufficient finance, which could unleash the full potential of private investment, remains a significant constraint for smallholder farmers and agricultural small and medium enterprises (SMEs). The main challenges are the transaction costs of lending to small-scale and dispersed customers with little or no financial literacy, information gaps and asymmetries regarding what constitutes viable funding propositions in agriculture, and the management of actual and perceived risks. A key challenge, and one which will be exacerbated by expected increases in climate variability, is the inability of both farmers and financiers to fully manage the impacts of seasonality on cash flows.

Adjusting food production systems to respond to climate change will require substantial upfront investments in increasing farmers' productivity and their capacity to adapt, while reducing the emission intensity of production. This requires not only a significant increase in the amount of capital available but also longer maturities (of 5 to 7 years) and more flexible repayment schedules that are adjusted to cash flows. That would allow farmers to undertake the necessary investments to maintain current yields, produce more food on less land, and adopt practices and technologies that would increase resilience while also reducing emissions.

Climate finance can help address the constraints that prevent financial service providers from offering the types of financial services that smallholders and SMEs require to undertake climate-smart investments. It can play a catalytic role by unlocking other sources of private capital and supporting the agriculture sector in becoming part of the solution to climate change. By filling the financing gap and catalysing investment that would not happen without the right enabling conditions, climate finance can strengthen risk management mechanisms, foster development of appropriate financial products, and address the capacity constraints of both lenders and borrowers. Through strategic support, climate finance can demonstrate the viability of climate-smart agricultural investments to private investors and banks that remain reluctant to expand their lending into agriculture.

15 Based on World Bank (2016).

In particular, climate finance can support the design of *innovative mechanisms* to leverage additional sources of capital, from both public and private sources, which can be directed towards climate-smart investments. These mechanisms include:

- fostering public-private partnerships to leverage the resources, expertise and capacities of different stakeholders. These partnerships can bridge the gap between potential investors and SMEs, or farmers who individually can neither approach investors nor make a strong case for their investment proposals;
- designing and piloting innovative investment vehicles that can help to attract additional capital by diversifying and managing the risk return profile of different investors (e.g. layered capital structures in which public finance can absorb risks related to climate change, or extend repayment rates to better match project cash flows); and
- supporting the development and bundling of a wider range of financial instruments to increase effectiveness and provide more holistic and comprehensive solutions. These include insurance products, warehouse receipts and value chain finance.

Climate finance could also fund the technical assistance that is critically needed by actors in the financial system to enhance their capacity to manage agricultural risks, and to address the specific requirements of smallholders and SMEs, whose business and financial management skills should also be strengthened so that they can take advantage of emerging financing options. Capacity support should focus on strengthening the skills of borrowers and lenders in identifying and implementing investments that enhance climate resilience and, where possible, contribute to emission reductions. Capacity support to lenders would focus on enhancing their understanding of risks in the agriculture sectors and developing customized agricultural financial products and services to support investments.

Transaction costs will continue to provide a challenge to agricultural finance for the foreseeable future. However, by taking advantage of the trend towards mobile financial services, climate finance can support and further strengthen the development and roll-out of those services that address the needs of smallholders and SMEs for climate-smart investments in remote areas. ■

CONCLUSIONS

Much more needs to be done to strengthen the enabling environment for climate-smart agricultural investments, mainstream climate change considerations in domestic budget allocations and implementation, and unlock private capital for climate-smart agricultural development. International climate finance can be used strategically to leverage domestic public funds and private sector financing, as well as additional international public resources.

It is still not clear what proportion of new pledges to climate financing will be directed to supporting adaptation and mitigation action in the agriculture sectors, but the amounts may be significant. The transition to sustainable, resilient, climate-smart food and agricultural systems requires adaptation to climate change and a commitment to climate change mitigation throughout the agriculture sectors. The transition will depend on action by policy-makers, civil society, farmers, herders, foresters and fisherfolk, as well as stakeholders along the food and agriculture value chains worldwide. It is vital to ensure that the climate finance available to the agriculture sectors is commensurate with the role the sector must play in ensuring food security and responding to the challenge of climate change today and in the future.

ANNEX

DATA ON INTERNATIONAL PUBLIC CLIMATE FINANCE FOR AGRICULTURE, FORESTRY AND FISHERIES

Data presented in Chapter 6 come from two datasets that are used to understand international public finance for climate change mitigation and adaptation in the agricultural sector. These are the OECD's Creditor Reporting System (CRS) and the Climate Fund Update (CFU) of the Overseas Development Institute (ODI), United Kingdom.

The CRS data cover some dedicated climate funds as well as bilateral and multilateral commitments directed at climate change adaptation and mitigation. The CFU data focus on dedicated multilateral climate funds, which have been expressly set up to address climate change. For climate finance directed towards the agricultural sector, the CRS include many, but not all, of the dedicated climate funds considered by the CFU. The CRS data also include the climate-related portion of general development funds from multilateral institutions, whereas the CFU data do not include any finance from general development funds (see Table). The CRS includes bilateral donors' funds; these are outside of the scope of the CFU.

As with any datasets, there are some clear limitations to using the CRS and CFU data to understand international public finance of climate change related projects in the agricultural sector. Both datasets consider some of the same climate funds. For figures and tables in this chapter, which include both CRS and CFU data, we have therefore adjusted each dataset accordingly (removing funds shown as greyed out text in the table from the respective dataset) so that as little double-counting as possible appears in the figures. It is not possible to identify and thus remove the ASAP funds from either the CRS or the CFU data.

Both the datasets are also lacking in terms of their comprehensiveness. For example, the OECD CRS dataset does not include all donor countries; it is limited to the assistance committed by OECD member states and thus exclude assistance from countries such as China. In addition, there is a lack of information on the extent to which projects and finance reported are entirely supporting climate outcomes. Numerous issues have been raised in terms of how projects are designated ("tagged") as supporting climate change adaptation and/or mitigation (Caravani, Nakhooda and Terpstra, 2014; Michaelowa and Michaelowa, 2011).

COVERAGE OF INTERNATIONAL PUBLIC CLIMATE FINANCE DATASETS INCLUDED IN CHAPTER 6

<table>
<tr><th></th><th>OECD Creditor Reporting System (CRS)</th><th>ODI Climate Funds Update (CFU)</th></tr>
<tr><td rowspan="4">Dedicated climate funds</td><td colspan="2">Adaptation for Smallholder Agriculture Programme (ASAP)</td></tr>
<tr><td></td><td>Adaptation Fund (AF)
Amazon Fund
Congo Basin Forest Fund (CBFF)
Forest Carbon Partnership Facility (FCPF)
Global Climate Change Alliance (GCCA)
UN-REDD Programme</td></tr>
<tr><td>Forest Investment Program (FIP)
Least Developed Countries Fund (LDCF)
Pilot Program for Climate Resilience (PPCR)
Special Climate Change Fund (SCCF)</td><td>Forest Investment Program (FIP)
Least Developed Countries Fund (LDCF)
Pilot Program for Climate Resilience (PPCR)
Special Climate Change Fund (SCCF)</td></tr>
<tr><td>Global Environment Facility – all focal areas</td><td>Global Environment Facility climate change focal area</td></tr>
<tr><td>Other multilateral development assistance</td><td>International Fund for Agricultural Development (IFAD)
International Bank for Reconstruction and Development (IBRD)
International Development Association (IDA)
Asian Development Bank
Nordic Development Fund</td><td>Not applicable</td></tr>
<tr><td>Bilateral development assistance</td><td>Commitments made by OECD DAC members and non-DAC members</td><td>Not applicable</td></tr>
</table>

SOURCES: OECD (2015a) and ODI (2015).

STATISTICAL ANNEX

AMBUQUÃŒ, ECUADOR
Vegetation and irrigated crops in the Chota Valley.

STATISTICAL ANNEX

NOTES ON THE ANNEX TABLES

KEY

The following conventions are used in the tables:

.. = data not available

0 or 0.0 = nil or negligible

blank cell = not applicable

Numbers presented in the tables may differ from the original data sources because of rounding or data processing. To separate decimals from whole numbers a full point (.) is used.

TECHNICAL NOTES

TABLE A.1

Projected changes in crop yields due to climate change for all locations worldwide

Source: Data are the same as those used in Porter *et al.* (2014) and Challinor *et al.* (2014). An updated version of the data is available at http://www.ag-impacts.org

Notes: Studies came from a broad survey of the literature, which included process-based and statistical models. There are wide methodological variations among the studies, which are based on different climate models, emissions levels and crop models. Some studies include adaptation, whereas others do not.

Reference provides the author(s) and year of the study containing estimate(s) of change in crop yields. The full citations are provided in the References to the main report.

Geographical location is the province, state, country or region to which the estimate of change in crop yield refers, using the wording and geographical classifications found in the original dataset. Some estimates are for the global level. The following notation is used: (1) the estimate is considered to be for a location in a developed region; (2) estimate for a location in a developing region; and (3) the location is global or unspecified.

Period refers to the mid-projection year – calculated from the starting year to the latest year in the simulation – and considers the time period to which it belongs. For instance, estimates from a study written in 2010 may be projections for 2050 and 2080; in this instance the midpoint is considered to be 2065 and the estimates are grouped accordingly in the bin 2050–69.

Crops (estimated yield change) reports the crops or groups of crops and, in parentheses, the estimates of the change(s) induced by climate change in the respective yield(s). Some studies report more than one estimate for a given location, time period and crop; this is due to the use of more than one combination of climate models, emissions levels, crop models, adaptation and/or no adaptation.

TABLE A.2

Net emissions and removals from agriculture, forests and other land use in carbon dioxide equivalent, 2014

Source: FAO, 2016.

Emissions from agriculture are expressed in carbon dioxide (CO_2) equivalent and consist of methane (CH_4) and nitrous oxide (N_2O), produced by aerobic and anaerobic decomposition processes in crop and livestock production and management activities. They are computed at Tier

1 following IPCC Guidelines for National GHG Inventories. The emissions are estimated as the product of an activity level (such as number of livestock, harvested area, application of fertilizer or other) and an emissions factor from the IPCC. They include the following sub-domains: burning crop residues (CH_4, N_2O); burning savanna (CH_4, N_2O); crop residues (N_2O); cultivation of organic soils (N_2O); enteric fermentation (CH_4); manure management (CH_4, N_2O); manure left on pastures (N_2O); manure applied to soils (N_2O); rice cultivation (CH_4); and synthetic fertilizers (N_2O).

Emissions/removals from forests consist of CO_2 emissions from the degradation of forest lands and carbon removals (carbon sink) by land that has remained forest land from year $t - 1$ to year t. At the country level, forest data are either positive (net emissions) or negative (net sinks).

Emissions from net forest conversion are CO_2 emissions resulting from deforestation, or the conversion of forest land to other uses.

Emissions from burning biomass consist of gases produced from the burning of biomass for the following items: humid tropical forest, other forests, and organic soils. They consist of methane (CH_4), nitrous oxide (N_2O) and, only in the case of organic soils, also carbon dioxide (CO_2).

Emissions from cropland organic soils are those associated with carbon losses from drained organic soils of croplands.

Emissions from grassland organic soils are those associated with carbon losses from drained organic soils of grasslands.

TABLE A.3

Agricultural emissions in CO_2 equivalent by source, 2014

Source: FAO, 2016.

Emissions from burning crop residues consist of methane (CH_4) and nitrous oxide (N_2O) gases produced by the combustion of a percentage of crop residues burned on-site. The mass of fuel available for burning should be estimated taking into account the fractions removed before burning due to animal consumption, decay in the field, and use in other sectors (e.g. biofuel, domestic livestock feed, building materials). Emissions are estimated as the product of an IPCC emissions factor and activity data (the amount of biomass burned, which is calculated from harvested area of wheat, maize, rice and sugarcane).

Emissions from burning of savanna consist of methane (CH_4) and nitrous oxide (N_2O) gases produced from the burning of vegetation biomass in the following five land cover types: savanna, woody savanna, open shrublands, closed shrublands and grasslands. Emissions are calculated as the IPCC emissions factor times activity data (total mass of fuel burned using the Global Fire Emission Database).

Emissions from crop residues consist of direct and indirect nitrous oxide (N_2O) emissions from nitrogen (N) in crop residues and forage/pasture renewal left on agricultural fields by farmers. Direct emissions are estimated as the product of activity level (crop yield and harvested area) and an emissions factor from the IPCC. Crops considered include barley, beans-dry, maize, millet, oats, potatoes, rice-paddy, rye, sorghum, soybeans and wheat. Indirect emissions are also estimated; they are the N in crop residues forage/pasture renewal that is lost through runoff and leaching.

Emissions from cultivation of organic soils are those associated with nitrous oxide gas from cultivated organic soils (both cropland and grassland organic soils). Emissions are estimated as the product of activity level (area of cultivated organic soils) and an emissions factor from the IPCC.

Emissions from enteric fermentation consist of methane gas (CH_4) produced in digestive systems of livestock (both ruminants and non-ruminants). The emissions are estimated as the product of activity level (number of livestock) and an emissions factor from the IPCC. Livestock considered include buffaloes, sheep, goats, camels, llamas, horses, mules, asses, pigs, dairy and non-dairy cattle and poultry.

Emissions from manure management consist of methane (CH_4) and nitrous oxide gases from aerobic and anaerobic decomposition processes. The emissions are estimated as the product of activity level (number of livestock) and an emissions factor from the IPCC. Livestock considered include buffaloes, sheep, goats, camels, llamas, horses, mules, asses, ducks, turkeys, dairy and non-dairy cattle, chickens (layers and broilers) and market and breeding swine.

Emissions from manure left on pastures consist of direct and indirect nitrous oxide (N_2O) emissions from manure nitrogen (N) left on pastures by grazing livestock. Livestock data cover the following animal categories: buffaloes, sheep, goats, camels, llamas, horses, mules, asses, ducks, turkeys, dairy and non-dairy cattle, chickens (layers and broilers) and market and breeding swine.

Emissions from manure applied to soils consist of direct and indirect nitrous oxide (N_2O) emissions from manure nitrogen (N) added to agricultural soils by farmers. Livestock data cover the following animal categories: buffaloes, sheep, goats, camels, llamas, horses, mules, asses, ducks, turkeys, dairy and non-dairy cattle, chickens (layers and broilers) and market and breeding swine.

Emissions from rice cultivation consist of methane gas (CH_4) emitted by anaerobic decomposition of organic matter in paddy fields. The emissions are estimated as the product of activity level (harvested area of rice paddy) and an emissions factor from the IPCC.

Emissions from synthetic fertilizers consist of direct and indirect nitrous oxide (N_2O) emissions from nitrogen (N) added to agricultural soils by farmers. The emissions are estimated as the product of activity level (application of nitrogen fertilizer) and an emissions factor from the IPCC.

COUNTRY GROUPS AND REGIONAL AGGREGATES

Tables A.2 and A.3 present country groups and regional aggregates for all indicators. They are calculated for the country groupings and regions as described below. World and regional totals may differ slightly from those available in FAOSTAT.

For Tables A.2 and A.3, as well as some figures and tables in the text, regional groupings and the designation of developing and developed regions follow a similar classification to the UNSD M49 classification of the United Nations Statistics Division, available at unstats.un.org/unsd/methods/m49/m49.htm.

The main difference is that "Countries and territories in developed regions", as used here, includes countries designated as being in developed regions by the UNSD M49, as well as countries in Central Asia (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan). Data for China, mainland exclude data for Hong Kong Special Administrative Region of China and Macao Special Administrative Region of China. ■

TABLE A.1

PROJECTED CHANGES IN CROP YIELDS DUE TO CLIMATE CHANGE FOR ALL LOCATIONS WORLDWIDE

REFERENCE	GEOGRAPHICAL LOCATION	PERIOD	CROPS (ESTIMATED YIELD CHANGE)
Abraha & Savage, 2006	KwaZulu-Natal, South Africa (2)	2030/49	Maize (−10.7, −10.7, −8.7,−8.7, −6.6, −6.6, 5.9, 6.0, 8.1, 8.1, 10.2, 10.3)
Alexandrov & Hoogenboom, 2000	Bulgaria (1)	2010/29	Maize (−12.0); wheat (11.0, 13.0)
		2050/69	Maize (−19.0, −1.0); wheat (25.0, 30.0)
		2070/89	Maize (−18.0); wheat (26.0)
Arndt *et al.*, 2011	Central Mozambique (2)	2030/49	Cassava (−6.2, −3.1); maize (−5.6, −3.0)
	North Mozambique (2)	2030/49	Cassava (−6.5, −0.1); maize (−2.9, −1.9)
	South Mozambique (2)	2030/49	Cassava (−3.2, 0.4); maize (−4.4, −3.9)
Berg *et al.*, 2013	Africa and India (2)	2030/49	Millet (−26.7, −24.1, −22.6, −14.6, −14.1, −13.2, −13.1, −12.4, −11.4, −10.5, −8.7, −7.3, −7.2, −6.8, −6.8, −6.7, −6.2, −6.2, −5.8, −5.6, −5.5, −4.9, −4.8, −4.7, −4.5, −4.4, −4.0, −3.7, −3.6, −3.6, −2.9, −2.8, −2.4, −2.3, −2.1, −1.8, −1.1, 0.0, 0.6, 0.8, 1.3, 2.1, 2.9, 4.1, 11.7, 17.1, 20.3, 30.5)
	Africa and India (2)	2070/89	Millet (−90.5,−44.3, −41.0, −25.8, −25.1, −24.6, −23.1, −23.0, −22.5, −22.5, −22.0, −21.5, −20.5, −20.0, −18.4, −18.0, −17.8, −17.4, −17.2, −16.9, −15.3, −14.6, −14.1, −13.6,−12.6, −12.5, −12.4, −11.2, −11.1, −11.0, −10.8, −10.2, −9.2, −8.2, −8.0, −5.7, −5.6, −4.8, −3.8, −3.6, −3.2, 7.9, 18.9, 23.0, 45.8, 48.6, 56.4, 62.2)
Brassard & Singh, 2007	Southern Quebec, Canada (1)	2050/69	Wheat (4.3, 10.7, 24.0); maize (9.4, 30.2, 31.3)
Brassard & Singh, 2008	Quebec, Canada (1)	2050/69	Maize (−6.8, −6.5, −0.6, 1.1, 4.0, 4.1); potato (−18.6, −16.2, −14.4, −12.0, −11.3, −10.8); soybean (−5.1, 15.1, 18.7, 39.3, 67.3, 84.8); wheat (−18.9, −3.2, 4.1, 4.2, 11.4, 14.8)
Butt *et al.*, 2005	Mali, 85 agroecological zones (2)	2030/49	Maize (−13.5, −11.2,−10.3, −8.6)
Calzadilla *et al.*, 2009	Sub-Saharan Africa (2)	2050/69	Wheat (−24.1); cereal Grains (1.1); rice (3.0)
Chhetri *et al.*, 2010	Southeastern USA (1)	2010/29	Maize (1.2, 2.0, 2.7, 3.6)
		2030/49	Maize (4.2, 4.4, 5.7, 6.1)
		2050/69	Maize (5.3, 5.3, 5.8, 6.0)
Ciscar *et al.*, 2011	British Isles (1)	2070/89	Wheat, Maize and soybean (−11.0, −9.0, 15.0, 19.0)
	Central Europe North (1)	2070/89	Wheat, maize and soybean (−8.0, −3.0, −1.0, 2.0)
	Central Southern Europe (1)	2070/89	Wheat, maize and soybean (−3.0, 3.0, 5.0, 5.0)
	Northern Europe (1)	2070/89	Wheat, maize and soybean (36.0, 37.0, 39.0, 52.0)
	Southern Europe (1)	2070/89	Wheat, maize and soybean (−27.0, −12.0, −4.0, 0.0)
Deryng *et al.*, 2011	Argentina (2)	2050/69	Maize (−30.3, −26.3, −17.7,−10.0, −9.8, −4.8, −4.6, −2.2); soybean (−39.3, −36.1, −24.6, −20.5, −20.5, −19.5, −19.3, −13.2)
	Brazil (2)	2050/69	Maize (−38.1, −34.6, −28.6, −26.3, −25.2, −23.2, −23.2, −19.2); Soybean (−32.6, −31.4, −24.2, −24.2, −23.5, −19.7, −19.0, −15.7)

TABLE A.1

(CONTINUED)

REFERENCE	GEOGRAPHICAL LOCATION	PERIOD	CROPS (ESTIMATED YIELD CHANGE)
Deryng *et al.*, 2011	Canada (1)	2050/69	Maize (−54.6, −45.2, −36.2, −27.1, 4.9, 5.3, 6.0, 21.6); soybean (−66.5, −60.9, −56.2, −46.8, −27.7, −16.9, −11.4, −4.9); wheat (−35.4, −34.5, −22.2, −21.2, −5.1, −3.3, −1.1, −0.7)
	China (2)	2050/69	Soybean (−45.9, −43.9, −33.6, −32.5, −13.9, −8.7, −6.7, −6.1); wheat(−29.3, −29.1, −19.2, −18.8, −5.6, −5.5, −4.3, −1.8)
	France (1)	2050/69	Maize (−59.7, −46.2, −43.9, −41.7, −30.3, −27.0, −21.6, −11.6); wheat (−49.1, −42.5, −32.8, −31.3, −25.5, −21.4, −13.7, −0.5)
	Germany (1)	2050/69	Wheat (−29.0, −26.7, −15.5, −12.6, −8.5, −3.8, 4.0, 8.9)
	India (2)	2050/69	Maize (−31.0, −28.2, −26.3, −22.9, −19.8, −18.6, −16.9, −14.6); soybean (−32.9, −27.8, −24.6, −24.5, −21.8, −20.0, −17.4, −15.5)
	Indonesia (2)	2050/69	Maize (−11.9, −10.4, −10.3, −8.6, −3.2, −2.8, 0.8, 1.0)
	Kazakhstan (1)	2050/69	Wheat (−38.0, −28.0, −22.4, −20.0, −12.3, −8.3, 0.9, 2.4)
	Mexico (2)	2050/69	Maize (−39.7, −37.0, −29.1, −27.0, −24.6, −23.9, −18.9, −16.0)
	Paraguay (2)	2050/69	Soybean (−43.3, −28.8, −28.0, −25.2, −18.0, −17.3, −16.5, −13.6)
	Poland (1)	2050/69	Wheat (−23.1, −19.6, −11.0, −11.0, 6.5, 8.2, 11.1, 17.6)
	Romania (1)	2050/69	Maize (−48.1, −45.7, −30.5, −25.9, −16.9, −13.9, 1.2, 2.5)
	Russia (1)	2050/69	Wheat (−29.6, −25.2, −24.7, −21.3, −8.5, −6.3, −6.0, 0.3)
	South Africa (2)	2050/69	Maize (−38.8, −31.4, −29.4, −27.9, −26.0, −22.6, −17.1, −14.6)
	UK (1)	2050/69	Wheat (−32.9, −31.9, −26.3, −20.1, −8.2, −0.3, 3.4, 4.2)
	Ukraine (1)	2050/69	Wheat (−28.8, −23.1, −21.4, −17.2, −3.5, −2.1, 7.1, 10.3)
	USA (1)	2050/69	Maize (−44.7, −30.6, −25.7, −22.8, −18.9, −14.2, −1.3, −0.5); soybean (−52.7, −39.3, −36.5, −33.2, −26.6, −24.9, −14.8, −13.1); wheat (−32.6, −23.2, −21.6, −21.0, −17.2, −11.9, −4.3, −2.8)
Giannakopoulos *et al.*, 2009	NE Mediterranean (Serbia, Greece and Turkey) (3)	2030/49	Cereals (4.4, 12.5); legumes (−7.2, −0.9); maize (−0.6, −0.2); potato (−9.3, 4.4); sunflower (−5.4, −0.9)
	NW Mediterranean (Portugal, Spain, France and Italy) (1)	2030/49	Cereals (−0.3, 4.7); legumes (−14.4, −4.9); maize (4.2, 8.8); potato (4.9, 7.5); sunflower (−12.4, −2.8)

TABLE A.1

(CONTINUED)

REFERENCE	GEOGRAPHICAL LOCATION	PERIOD	CROPS (ESTIMATED YIELD CHANGE)
Giannakopoulos *et al.*, 2009	SE Mediterranean (Jordan, Egypt and Libya) (2)	2030/49	Cereals (–10.1, –4.9); legumes (–30.1, –23.3); maize (–7.9, –6.7); potato (–5.7, –4.3); sunflower (–0.4, 3.7)
	SW Mediterranean (Tunisia, Algeria and Morocco) (2)	2030/49	Cereals (–3.8, –3.4); legumes (–23.9, –18.5); maize (–9.4, –6.4); potato (–13.3, –1.5); sunflower (–10.3, –4.3)
Hermans *et al.*, 2010	Europe (1)	2050/69	Wheat (34.0, 97.0)
Iqbal *et al.*, 2011	Faisalabad, Pakistan (2)	2010/29	Maize (–1.5, –1.3, –0.4, –0.3, –0.3, 0.7, 0.8, 1.7, 3.9)
		2010/29	Maize (–2.1, –1.1, –0.5, 0.0, 0.3, 0.7, 1.7, 2.7, 3.2)
		2050/69	Maize (–8.1, –5.4, –4.1, –3.6, –3.0, –1.4, –0.6, –0.5, 0.5)
Izaurralde *et al.*, 2001	USA, regional (1)	2010/29	Corn (4.3, 15.4)
		2030/49	Soybean (–9.4, 7.9); wheat (25.2, 37.1)
		2050/69	Wheat (0.1, 5.0, 15.3, 15.8)
		2090/2109	Maize (7.9, 17.1)
		2090/2109	Soybean (–8.7, 6.6); wheat (29.5, 40.5)
Kim *et al.*, 2010	Korea (2)	2010/29	Rice (–4.2, –1.1, 0.7)
		2050/69	Rice (–9.9, –2.6, 0.3)
		2070/89	Rice (–14.1, –3.0, 1.9)
Lal, 2011	Central India, South India, Sri Lanka (2)	2010/29	Rice (6.0, 18.0); wheat (22.0, 24.0)
		2050/69	Rice (–30.0, –21.0, –4.0, –1.0, 3.0); wheat (–23.0, –19.0, –8.0, 7.0, 9.0)
		2070/89	Rice (–8.0); wheat (–1.0)
	Central plains of India, Southern India, Sri Lanka (2)	2010/29	Rice (3.0, 18.0); wheat (23.0, 25.0)
		2050/69	Rice (–6.0, 1.0)
		2050/69	Wheat (–3.0, 9.0)
		2070/89	Rice (–5.0); wheat (–2.0)
	Pakistan, N, NE & NW India, Nepal, Bangladesh (2)	2010/29	Rice (4.0, 5.0, 15.0); wheat (21.0, 23.0, 26.0, 26.0)
		2010/29	Rice (17.0)
		2050/69	Rice (–31.0, –24.0, –7.0, –5.0, –1.0, 1.0, 2.0); wheat (–18.0, –11.0, –3.0, –1.0, 11.0, 12.0, 16.0)
		2070/89	Rice (–12.0, –8.0); wheat (1.0, 2.0)
Li *et al.*, 2011	China, mid latitude, central (2)	2030/49	Maize (10.7, 22.8)
	USA, mid-Western region (1)	2030/49	Maize (–7.4, 41.6)
Lobell *et al.*, 2008	Andean region (2)	2010/29	Barley (–2.1); cassava (1.5); maize (0.0); palm (2.9); potatoes (–2.6); rice (–0.5); soybean (–0.2); sugar cane (0.5); wheat (–2.5)
	Brazil (2)	2010/29	Cassava (–4.9); maize (–2.3); rice (–4.5); soybean (–4.1); sugarcane (0.6); wheat (–6.8)
	Central Africa (2)	2010/29	Cassava (–1.5); groundnuts (–2.2); millet (–4.9); maize (–0.5); palm (–2.4); rice (–2.9); sorghum (–3.9); wheat (–1.2)
	Central America (2)	2010/29	Cassava (2.3); maize (–1.0); rice (–0.5); sugar cane (7.4); wheat (–4.7)

TABLE A.1

(CONTINUED)

REFERENCE	GEOGRAPHICAL LOCATION	PERIOD	CROPS (ESTIMATED YIELD CHANGE)
Lobell *et al.*, 2008	China (2)	2010/29	Rice (–0.2); soybean (2.3); potatoes (2.1); groundnuts (2.0); maize (–2.3); wheat (2.0); sugar cane (1.5)
	East Africa (2)	2010/29	Barley (31.8); beans (4.0); cassava (1.7); cowpeas (–18.5); groundnuts (3.5); maize (–0.2); rice (7.6); sorghum (–1.1); sugarcane (–4.0); wheat (5.4)
	Sahel (2)	2010/29	Cowpeas (8.8); groundnuts (–0.5); maize (–3.6); millet (–2.3); rice (2.9); sorghum (–5.6); wheat (–8.0)
	South Asia (2)	2010/29	Groundnuts (1.2); millet (–2.1); maize (–4.8); rapeseed (–6.5); rice (–3.3); soybean (3.9); sugarcane (0.0); sorghum (0.1); wheat (–2.9)
	Southeast Asia (2)	2010/29	Soybean (–2.4); cassava (–0.7); wheat (–1.1); sugarcane (5.3); rice (–1.2); maize (–3.0); groundnuts (–1.2)
	Southern Africa (2)	2010/29	Cassava (0.8); groundnuts (1.2); rice (4.4); soybean (–8.3); sugarcane (–3.1); wheat (–9.0); sorghum (–8.2); maize (–22.5)
	West Africa (2)	2010/29	Cassava (0.7); groundnuts (–7.1); maize (–3.8); millet (–0.1); sorghum (–4.1); rice (0.5); wheat (–2.1); yams (–6.0)
	West Asia (2)	2010/29	Barley (1.2); maize (–1.1); potatoes (3.4); rice (–4.4); sorghum (0.7); sugarcane (–5.4); sunflower (–5.8); sugarbeet (0.1); soybean (–2.3); wheat (–0.5)
Moriondo *et al.*, 2010	Northern Europe (1)	2030/49	Soft wheat/sunflower (–5.0); spring wheat (7.0); soybean (–13.0, –4.0); sunflower (8.0)
Müller *et al.*, 2010	China & centrally planned Asia (2)	2050/69	Major crops (–3.7, –3.6, –3.4, –2.9, 11.8, 14.3, 15.4, 15.8)
	Europe (1)	2050/69	Major crops (–0.3, 0.8, 1.2, 3.7, 16.7, 16.7, 16.8, 17.5)
	Former Soviet Union (1)	2050/69	Major crops (–0.5, –0.2, 0.9, 4.3, 21.4, 21.4, 21.4, 22.3)
	Latin America & the Caribbean (2)	2050/69	Major crops (–11.3, –9.4, –8.2, –3.7, 9.5, 11.8, 12.2, 13.3)
	Middle-East & North Africa (2)	2050/69	Major crops (–16.6, –14.8, –14.5, –13.2, –3, –2.5, –2.1, –0.7)
	North America (1)	2050/69	Major crops (–10.3, –9.3, –7.1, –1.8, 10.6, 11.6, 12.2, 14.7)
	Pacific Asia (2)	2050/69	Major crops (–18.5, –18, –16, –11.7, 19.9, 21.9, 22.8, 23)
	Pacific OECD (3)	2050/69	Major crops (–15, –14.7, –13.5, –9.8, 3.3, 3.5, 3.6, 4.6)
	South Asia (2)	2050/69	Major crops (–18.9, –16.4, –15.3, –14.4, 14.6, 19.8, 21.3, 24.6)
	Sub-Saharan Africa (2)	2050/69	Major crops (–8.5, –8.2, –7.6, –5.9, 6.7, 7.5, 7.8, 8.4)
	World (3)	2050/69	Major crops (–8.2, –7.6, –6.5, –3.5, 12.4, 12.5, 12.6, 13.1)

TABLE A.1

(CONTINUED)

REFERENCE	GEOGRAPHICAL LOCATION	PERIOD	CROPS (ESTIMATED YIELD CHANGE)
Osborne, Rose & Wheeler, 2013	Global, and top 15 producing countries (3)	2030/49	Soybean (–48.4, –45.5, –43.0, –41.4, –39.5, –39.2, –36.5, –35.0, –35.0, –34.0, –33.9, –33.7, –33.6, –31.1, –29.6, –29.4, –28.8, –27.5, –26.3, –25.8, –22.6, –20.8, –20.6, –20.4, –20.4, –20.3, –19.9, –19.9, –19.3, –19.3, –18.2, –13.8, –12.0, –11.3, –5.1, –2.9, –2.4, 0.5, 1.0, 2.1, 2.2, 5.4, 8.8, 13.7, 48.3); spring wheat (–41.0, –36.5, –32.1, –29.4, –26.0, –25.0, –22.4, –21.6, –20.5, –18.5, –18.2, –17.3, –15.5, –14.5, –14.4, –13.5, –12.7, –12.5, –11.0, –10.1, –10.1, –8.9, –8.6, –7.1, –6.8, –6.8, –6.8, –6.8, –5.1, –5.1, –4.3, –3.3, 0.5, 0.6, 0.7, 4.2, 6.6, 6.6, 8.5, 15.2, 24.5, 25.3, 27.9, 39.5, 40.7)
Peltonen-Sainio, Jauhiainen, & Hakala, 2011	Finland (1)	2010/29	Spring wheat (–5.9); spring oats (–5.1); spring barley (–5.7); winter rye (3.0); winter wheat (2.4)
Piao *et al.*, 2010	Unspecified (3)	2010/29	Maize (–2.0, 10.0); rice (5.0); wheat (15.0, 17.0)
	Unspecified (3)	2050/69	Maize (–4.0, 20.0); rice (4.0, 8.0); wheat (21.0, 25.0)
	China, entire country (2)	2010/29	Rice (2.0)
Ringler *et al.*, 2010	Central sub-Saharan Africa (2)	2050/69	Cassava (–0.1); rice (–0.6); maize (–0.8); sugar cane (0.9); sweet potato and yam (–0.1)
	Eastern sub-Saharan Africa (2)	2050/69	Cassava (0.4); maize (–1.9); rice (0.2); sugar cane (0.4); sweet potato and yam (1.1)
	Gulf of Guinea (2)	2050/69	Cassava (–11.9); maize (0.2); rice (1.4); sugar cane (–0.5); sweet potato and yam (–15.1)
	Southern sub-Saharan Africa (2)	2050/69	Cassava (–0.8); maize (–0.9); rice (–2.3); sugarcane (1.1); sweet potato and yam (1.1)
	Sudano-Sahelian sub-Saharan Africa (2)	2050/69	Cassava (1.2); maize (3.3); rice (–0.8); sugarcane (0.3); sweet potato and yam (2.0)
Rowhanji *et al.*, 2011	Tanzania (2)	2050/69	Maize (–13.0); rice(–7.6); sorghum (–8.8)
Schlenker & Roberts, 2009	US (1)	2030/49	Cotton (–22.0); maize (–29.0); soybean (–21.0)
		2070/89	Cotton; (–65.0); maize (–72.0); soybean (–65.0)
Shuang-He *et al.*, 2011	Middle and lower Yangtze river, China (2)	2030/49	Rice (–15.2, –14.8, –4.1, –3.3)
Southworth *et al.*, 2000	United States, Illinois (1)	2050/69	Maize (–25.9,–17.1)
	United States, Indiana (1)	2050/69	Maize (–18.5, –11.2)
	United States, Michigan (1)	2050/69	Maize (15.4, 18.3)
	United States, Ohio (1)	2050/69	Maize (–9.5, –5.4)
	United States, Wisconsin (1)	2050/69	Maize (–0.2, 14.1)
Tan *et al.*, 2010	Ghana (2)	2090/2109	Maize (–19.0, –18.0, –18.0)
Tao *et al.*, 2009	North China Plain (Henan) (2)	2010/29	Maize (–9.7)
		2050/69	Maize (–15.7)
		2070/89	Maize (–24.7)
	North China Plain (Shandong) (2)	2010/29	Maize (–9.1)
		2050/69	Maize (–19.0)
		2070/89	Maize (–25.5)

TABLE A.1

(CONTINUED)

REFERENCE	GEOGRAPHICAL LOCATION	PERIOD	CROPS (ESTIMATED YIELD CHANGE)
Tao & Zhang, 2010	North China Plain (2)	2050/69	Maize (−21.5, −19.1, −16.8, −15.4, −14.7, −13.7, −13.2, −13.0, −9.7, −9.1, −9.1, −7.2, −3.3, 0.5, 15.6, 30.2)
Tao & Zhang, 2011	China (2)	2070/89	Maize (−19.6, −19.1, −14.0, −13.5, −6.5, −5.3, −5.0, −4.6, −3.4, −3.3, −2.0, −1.9)
Thornton *et al.*, 2009	East Africa (2)	2010/29	Maize (−15.0; −11.0; −3.0; −1.0)
Thornton *et al.*, 2010	Burundi (2)	2030/49	Maize (6.0, 8.6, 9.4, 11.7)
		2050/69	Maize (8.2, 8.6, 9.6, 9.9)
	East Africa (2)	2050/69	Maize (−58.0, −53.0, −51.0, −47.0, −44.0, −43.0, −42.0, −35.0)
	Kenya (2)	2030/49	Maize (11.7, 12.9, 15.4, 16.7)
		2050/69	Maize (15.8, 16.2, 17.6, 17.7)
	Rwanda (2)	2030/49	Maize (9.3, 10.9, 11.9, 12.8)
		2050/69	Maize (13.2, 14.9, 16.9, 17.0)
	Tanzania (2)	2030/49	Maize (−4.7, −3.1, −2.8, −1.5)
		2050/69	Maize (−13.0, −10.1, −5.7, −4.1)
	Uganda (2)	2030/49	Maize (−3.6,−2.5, −2.3, −1.3)
		2050/69	Maize (−15.6, −12.3, −5.1, −3.3)
Thornton *et al.*, 2011	Central sub-Saharan Africa (2)	2090/2109	Beans (−69.0); maize (−13.0)
	East sub-Saharan Africa (2)	2090/2109	Beans (−47.0); maize (−19.0)
	Southern sub-Saharan Africa (2)	2090/2109	Beans (−68.0); maize (−16.0)
	Sub-Saharan Africa (2)	2090/2109	Beans (−71).0; maize (−24.0)
	West sub-Saharan Africa (2)	2090/2109	Beans (−87.0); maize (−23.0)
Tingem & Rivington, 2009	Cameroon (2)	2010/29	Maize (7.4, 8.2, 61.0, 62.3)
		2070/89	Maize (−14.6, −5.6, 32.1, 45.0)
	Cameroon, four sites (2)	2010/29	Maize (−10.9, 9.9, 29.6, 31.8)
		2070/89	Maize (−7.5, −1.6, 8.5, 12.0)
Walker & Schulze, 2008	South Africa (2)	2070/89	Maize (−18.3, −8.0, −6.3, 3.0, 8.7, 9.7, 9.7, 16.7, 22.3)
Wang *et al.*, 2011	Baicheng county, China (2)	2010/29	Maize (−14.6)
		2050/69	Maize (−27.9)
		2070/89	Maize (−35.9)
	Baishan county, China (2)	2010/29	Maize (12.2)
		2050/69	Maize (32.3)
		2070/89	Maize (34.8)
	Chuangchun county, China (2)	2010/29	Maize (−10)
		2050/69	Maize (−26.2)
		2070/89	Maize (−34.6)

TABLE A.1

(CONTINUED)

REFERENCE	GEOGRAPHICAL LOCATION	PERIOD	CROPS (ESTIMATED YIELD CHANGE)
Wang *et al.*, 2011	Jilin district, China (2)	2010/29	Maize (–3.2)
		2050/69	Maize (–14.6)
		2070/89	Maize (–23.6)
	Liaoyuan county, China (2)	2010/29	Maize (–9.5)
		2050/69	Maize (–23.9)
		2070/89	Maize (–31.6)
	Siping county, China (2)	2010/29	Maize (–11)
		2050/69	Maize (–26.4)
		2070/89	Maize (–35)
	Songyuan county, China (2)	2010/29	Maize (–8.7)
		2050/69	Maize (–23.9)
		2070/89	Maize (–32.8)
	Tonghua county, China (2)	2010/29	Maize (–0.3)
		2050/69	Maize (–9.6)
		2070/89	Maize (–18.9)
	Yanji, China (2)	2010/29	Maize (11.1)
		2050/69	Maize (24.6)
		2070/89	Maize (23.9)
Xiong *et al.*, 2007	Irrigated rice, China, no adaptation (2)	2010/29	Rice (–0.4, 3.8)
		2050/69	Rice (–1.2, 6.2)
		2070/89	Rice (–4.9, 7.8)
	Rainfed maize, China, no adaptation (2)	2010/29	Maize (1.1, 9.8)
		2050/69	Maize (8.5, 18.4)
		2070/89	Maize (10.4, 20.3)
	Rainfed wheat, China, no adaptation (2)	2010/29	Wheat (4.5, 15.4)
		2050/69	Wheat (6.6, 20)
		2070/89	Wheat (12.7, 23.6)
Xiong *et al.*, 2009	China (2)	2010/29	Rice (–4.9, 3.4, 6.3, 15.8)
		2050/69	Rice (–12.6, –8.6, 0.0, 8.0)
		2070/89	Rice (–26.2, –18.4, –5.6, –0.9)

TABLE A.2

NET EMISSIONS AND REMOVALS FROM AGRICULTURE, FORESTS AND OTHER LAND USE IN CARBON DIOXIDE EQUIVALENT, 2014

		FORESTS		OTHER LAND USE		
	EMISSIONS FROM AGRICULTURE	EMISSIONS/ REMOVALS FROM FORESTS	EMISSIONS FROM NET FOREST CONVERSION	EMISSIONS FROM BURNING BIOMASS	EMISSIONS FROM CROPLANDS	EMISSIONS FROM GRASSLANDS
	(Thousand tonnes)					
WORLD	5 241 761	-1 845 936	2 913 158	1 302 674	756 075	25 705
COUNTRIES AND TERRITORIES IN DEVELOPING REGIONS	3 971 916	-617 225	2 786 785	1 047 486	504 550	17 946
Eastern and South-Eastern Asia	**1 200 079**	**-30 495**	**566 447**	**426 306**	**359 610**	**10 492**
Brunei Darussalam	147	0	0	169	380	0
Cambodia	19 354	1 310	21 424	1 045	0	0
China, Hong Kong SAR	81	..	..	0	0	0
China, Macao SAR	3	..	..	0	0	0
China, mainland	707 640	-313 720	0	1 422	1 052	164
Democratic People's Republic of Korea	4 542	-129	14 063	166	201	1
Indonesia	165 614	629 248	368 819	389 752	285 367	8 982
Lao People's Democratic Republic	8 097	16 199	0	1 867	0	0
Malaysia	14 276	-206 783	24 183	16 115	36 509	961
Mongolia	21 476	-14	15 962	529	7 796	331
Myanmar	66 510	-30 534	105 869	11 462	18 258	51
Philippines	53 173	-60 353	0	57	0	0
Republic of Korea	12 710	-43 408	3 808	11	0	0
Singapore	102	44	0	0	0	0
Thailand	63 040	12 467	0	2 357	1 142	1
Timor-Leste	784	1 938	4 161	14	0	0
Viet Nam	62 530	-36 760	8 160	1 340	8 906	1
Latin America and the Caribbean	**909 180**	**-456 940**	**1 158 474**	**33 366**	**15 309**	**1 748**
Anguilla	0	4	0	0	0	0
Antigua and Barbuda	22	7	0	0	0	0
Argentina	112 377	-32 733	121 466	4 125	994	756
Aruba	0	0	0	0	0	0
Bahamas	26	346	0	41	0	0
Barbados	53	3	1	0	0	0
Belize	318	-803	2 270	228	542	42
Bolivia (Plurinational State of)	23 183	-348	84 090	1 971	0	0
Brazil	441 905	-205 413	499 443	12 112	35	2
British Virgin Islands	8	2	1	0	0	0
Cayman Islands	4	9	0	0	0	0
Chile	9 839	-105 380	0	306	115	19
Colombia	53 628	-3 154	17 542	1 564	3 058	504
Costa Rica	3 466	-24 861	13 421	7	70	0

TABLE A.2

(CONTINUED)

	EMISSIONS FROM AGRICULTURE	FORESTS		OTHER LAND USE		
		EMISSIONS/ REMOVALS FROM FORESTS	EMISSIONS FROM NET FOREST CONVERSION	EMISSIONS FROM BURNING BIOMASS	EMISSIONS FROM CROPLANDS	EMISSIONS FROM GRASSLANDS
Cuba	10 498	-14 007	0	44	0	0
Dominica	33	30	87	0	0	0
Dominican Republic	7 783	-8 727	0	26	0	0
Ecuador	12 999	-552	34 285	17	150	0
El Salvador	2 625	-39	771	1	0	0
Falkland Islands (Malvinas)	142	0	0	0	0	0
French Guiana	59	-465	1 198	4	165	0
Grenada	14	0	0	0	0	0
Guadeloupe	132	-24	25	0	0	0
Guatemala	8 393	-5 642	13 122	65	0	0
Guyana	2 282	330	10 670	6 001	3 199	297
Haiti	3 904	-181	319	0	0	0
Honduras	5 916	-107	27 974	259	0	0
Jamaica	621	-50	197	2	631	0
Martinique	39	0	0	0	0	0
Mexico	84 719	-3 414	10 748	113	0	0
Montserrat	19	2	0	0	0	0
Netherlands Antilles	9	1	0	0	0	0
Nicaragua	7 681	-3 589	3 598	162	56	0
Panama	3 389	-240	7 573	6	1 208	0
Paraguay	27 645	-8 031	149 672	1 673	0	0
Peru	23 264	-13 761	84 077	173	1 358	0
Puerto Rico	790	-2 200	0	7	280	0
Saint Kitts and Nevis	66	7	0	0	0	0
Saint Lucia	28	14	20	0	0	0
Saint Vincent and the Grenadines	14	18	0	0	0	0
Suriname	759	33	1 755	803	1 961	71
Trinidad and Tobago	249	-921	420	2	0	0
Turks and Caicos Islands	0	23	0	0	0	0
United States Virgin Islands	16	-93	12	0	0	0
Uruguay	24 209	-10 663	0	2	103	40
Venezuela (Bolivarian Republic of)	36 053	-12 372	73 720	3 651	1 385	16
Northern Africa and Western Asia	**156 430**	**-85 564**	**5 757**	**72**	**1**	**0**
Algeria	12 794	-804	364	37	0	0
Armenia	1 366	-147	0	0	0	0
Azerbaijan	6 447	-8 474	0	7	0	0
Bahrain	35	-5	0	0	0	0
Cyprus	369	-312	7	0	0	0

TABLE A.2

(CONTINUED)

	EMISSIONS FROM AGRICULTURE	FORESTS		OTHER LAND USE		
		EMISSIONS/ REMOVALS FROM FORESTS	EMISSIONS FROM NET FOREST CONVERSION	EMISSIONS FROM BURNING BIOMASS	EMISSIONS FROM CROPLANDS	EMISSIONS FROM GRASSLANDS
Egypt	31 055	-219	0	1	0	0
Georgia	2 612	0	0	6	0	0
Iraq	8 577	-2 040	0	1	0	0
Israel	1 375	-73	0	0	0	0
Jordan	1 185	0	0	0	0	0
Kuwait	417	-15	0	0	0	0
Lebanon	752	-4	0	0	0	0
Libya	2 554	0	0	0	0	0
Morocco	13 644	-5 178	3 711	1	0	0
Palestine	273	-23	0	0	0	0
Oman	1 578	-5	0	0	0	0
Qatar	822	0	0	0	0	0
Saudi Arabia	7 221	0	0	0	0	0
Syrian Arab Republic	6 253	-1 214	0	2	0	0
Tunisia	4 436	-293	0	8	0	0
Turkey	43 192	-66 545	1 674	9	1	0
United Arab Emirates	1 676	-213	0	0	0	0
Western Sahara	184	0	0	0	0	0
Yemen	7 612	0	0	0	0	0
Oceania, excluding Australia and New Zealand	**7 570**	**-2 551**	**3 682**	**15 015**	**42 156**	**2**
American Samoa	5	-5	14	0	0	0
Cook Islands	14	0	0	0	0	0
Fiji	882	-3 124	0	7	127	0
French Polynesia	35	0	0	0	0	0
Guam	4	0	0	0	0	0
Kiribati	8	-6	0	0	0	0
Marshall Islands	0	0	0	0	0	0
Micronesia (Federated States of)	17	-29	0	0	0	0
Nauru	1	0	0	0	0	0
New Caledonia	221	0	0	3	0	0
Niue	0	0	48	0	0	0
Northern Mariana Islands	0	0	61	0	0	0
Palau	0	0	0	0	0	0
Papua New Guinea	5 658	331	1 869	15 005	42 029	2
Pitcairn Islands	0	0	0	0	0	0
Samoa	149	0	0	0	0	0
Solomon Islands	62	294	1 686	0	0	0
Tokelau	0	0	0	0	0	0
Tonga	89	0	0	0	0	0

TABLE A.2

(CONTINUED)

	EMISSIONS FROM AGRICULTURE	FORESTS		OTHER LAND USE		
		EMISSIONS/ REMOVALS FROM FORESTS	EMISSIONS FROM NET FOREST CONVERSION	EMISSIONS FROM BURNING BIOMASS	EMISSIONS FROM CROPLANDS	EMISSIONS FROM GRASSLANDS
Tuvalu	0	0	0	0	0	0
Vanuatu	426	-14	0	0	0	0
Wallis and Futuna Islands	0	2	5	0	0	0
Southern Asia	**929 770**	**178 218**	**24 761**	**3 455**	**47 940**	**269**
Afghanistan	14 794	0	0	0	0	0
Bangladesh	74 594	-5 037	2 507	501	31 226	24
Bhutan	453	-3 813	0	24	0	0
India	626 864	112 200	0	1 785	8 484	26
Iran (Islamic Republic of)	34 842	67 076	0	3	0	0
Maldives	2	2	0	0	0	0
Nepal	22 058	0	0	1 090	5 234	219
Pakistan	150 341	7 450	21 151	1	0	0
Sri Lanka	5 823	342	1 103	51	2 996	0
Sub-Saharan Africa	**768 886**	**-219 893**	**1 027 664**	**569 273**	**39 534**	**5 435**
Angola	29 584	155	34 311	59 602	111	97
Benin	4 776	-185	10 723	289	0	0
Botswana	5 569	-14 382	21 715	14 942	0	103
Burkina Faso	19 868	-3 845	12 646	296	0	0
Burundi	2 222	-1 606	0	789	3 068	6
Cabo Verde	112	-195	27	0	0	0
Cameroon	11 595	-1 273	109 806	3 810	1 078	0
Central African Republic	17 678	5 857	7 343	125	0	0
Chad	19 264	-700	25 633	275	0	0
Comoros	237	-42	108	1	0	0
Congo	1 810	-597	8 664	3 064	1 135	29
Côte d'Ivoire	4 790	555	3 112	37	1 697	68
Democratic Republic of the Congo	18 528	-431	145 631	20 318	28	5
Djibouti	650	0	0	0	0	0
Equatorial Guinea	21	52	5 301	0	7	0
Eritrea	4 114	-749	1 409	0	0	0
Ethiopia	96 256	-6 021	3 370	8 729	12 101	336
Gabon	438	-94 600	0	44	392	4
Gambia	1 210	-359	0	114	0	0
Ghana	9 185	8 103	0	60	146	0
Guinea	11 301	-783	13 249	967	656	55
Guinea-Bissau	1 651	-284	1 751	6	0	0
Kenya	37 133	-31 533	0	34	262	1
Lesotho	1 447	-264	66	5	0	0
Liberia	420	-13 973	15 154	47	116	14
Madagascar	21 957	4 918	9 749	4 340	1 321	1 360

TABLE A.2

(CONTINUED)

	EMISSIONS FROM AGRICULTURE	FORESTS		OTHER LAND USE		
		EMISSIONS/ REMOVALS FROM FORESTS	EMISSIONS FROM NET FOREST CONVERSION	EMISSIONS FROM BURNING BIOMASS	EMISSIONS FROM CROPLANDS	EMISSIONS FROM GRASSLANDS
Malawi	5 239	-1 764	4 698	857	550	1
Mali	29 722	6	6 536	625	0	0
Mauritania	7 693	-2 161	643	0	0	0
Mauritius	148	-15	0	0	0	0
Mayotte	0	-2	49	0	0	0
Mozambique	17 705	2 615	34 785	2 276	0	0
Namibia	6 060	45	7 846	1 059	0	0
Niger	23 128	27	1 440	80	0	0
Nigeria	64 239	-4 492	187 825	5 022	0	0
Réunion	163	0	0	0	0	0
Rwanda	2 996	-2 413	0	530	2 731	14
Saint Helena	2	1	0	0	0	0
Sao Tome and Principe	16	0	0	0	0	0
Senegal	10 599	-4 371	8 771	734	0	0
Seychelles	4	0	0	0	0	0
Sierra Leone	2 826	5 683	0	431	0	0
Somalia	20 309	-3 359	16 559	2	0	0
South Africa	30 000	0	0	2 067	248	7
South Sudan	43 098	..	..	..	..	..
Sudan	72 517	..	..	..	..	..
Sudan (former)	..	-27 982	72 044	75 394	750	154
Swaziland	925	8	138	98	0	0
Togo	2 605	-123	6 680	19	0	0
Uganda	23 999	-717	18 317	1 739	6 404	68
United Republic of Tanzania	49 696	-4 326	165 381	40 463	6 721	165
Zambia	22 954	-24 381	30 152	319 957	12	2 951
Zimbabwe	10 428	10	36 034	25	0	0
COUNTRIES AND TERRITORIES IN DEVELOPED REGIONS	1 269 845	-1 228 711	126 373	255 187	251 525	7 758
Albania	2 830	-737	224	0	156	0
Andorra	0	-22	0	0	0	0
Australia	141 847	-72 969	0	3 269	3 150	29
Austria	6 601	-5 428	295	0	234	7
Belarus	19 989	-25 520	0	377	24 708	107
Belgium	8 787	-3 156	274	0	245	8
Bermuda	4	0	0	0	0	0
Bosnia and Herzegovina	2 573	0	0	13	135	0
Bulgaria	5 493	-11 367	0	11	1 441	0
Canada	61 783	-53 446	60 330	100 626	12 937	1 440
Croatia	2 572	-4 133	290	0	0	0

TABLE A.2

(CONTINUED)

	EMISSIONS FROM AGRICULTURE	FORESTS		OTHER LAND USE		
		EMISSIONS/ REMOVALS FROM FORESTS	EMISSIONS FROM NET FOREST CONVERSION	EMISSIONS FROM BURNING BIOMASS	EMISSIONS FROM CROPLANDS	EMISSIONS FROM GRASSLANDS
Czech Republic	6 295	-12 687	0	0	190	0
Denmark	9 445	-2 200	0	0	1 700	5
Estonia	2 636	-1 531	108	9	5 742	65
Faroe Islands	27	0	0	0	0	0
Finland	5 612	0	0	0	5 619	95
France	72 264	-92 657	6 857	8	6 700	257
Germany	60 636	-49 867	0	0	11 979	521
Gibraltar	0	0	0	0	0	0
Greece	8 396	-2 200	0	30	1 492	0
Greenland	5	0	0	0	0	0
Holy See	0	..	..	..	0	0
Hungary	7 034	-3 593	0	12	7 819	11
Iceland	452	-183	0	0	0	0
Ireland	20 476	-1 393	0	0	477	476
Isle of Man	2	-3	0	0	5	0
Italy	30 073	-35 200	0	1	905	7
Japan	20 709	-678	1 065	22	7 027	25
Kazakhstan	20 712	0	0	216	0	0
Kyrgyzstan	4 537	-816	0	0	0	0
Latvia	3 150	-17 027	967	4	5 183	32
Liechtenstein	18	0	0	..	0	0
Lithuania	4 724	-7 594	1 654	1	6 345	30
Luxembourg	645	0	0	0	4	0
Malta	99	0	0	0	0	0
Monaco	0	..	..	..	0	0
Montenegro	384	0	0	0	62	0
Netherlands	18 325	-2 493	0	0	3 505	148
New Zealand	38 654	-18 731	398	0	2 846	85
Norway	4 616	-25 770	1 570	2	2 135	114
Poland	34 158	-40 333	0	1	14 867	357
Portugal	6 324	-603	1 924	11	427	3
Republic of Moldova	1 613	-1 254	0	5	165	1
Romania	13 963	-165 066	0	142	1 155	0
Russian Federation	92 228	-232 738	12 738	80 894	29 855	1 563
Saint Pierre and Miquelon	0	-1	3	0	0	0
San Marino	0	0	0	..	0	0
Serbia	6 453	-3 105	1 785	1	3	0
Slovakia	2 549	-5 296	163	0	43	0
Slovenia	1 433	-6 387	81	0	62	0
Spain	36 426	-33 587	0	23	409	1

TABLE A.2

(CONTINUED)

	EMISSIONS FROM AGRICULTURE	FORESTS		OTHER LAND USE		
		EMISSIONS/ REMOVALS FROM FORESTS	EMISSIONS FROM NET FOREST CONVERSION	EMISSIONS FROM BURNING BIOMASS	EMISSIONS FROM CROPLANDS	EMISSIONS FROM GRASSLANDS
Svalbard and Jan Mayen Islands	0	..	..	0	0	0
Sweden	6 640	-42 436	34 003	296	4 148	29
Switzerland	5 192	-1 833	0	0	268	13
Tajikistan	5 530	0	0	0	0	0
The former Yugoslav Republic of Macedonia	1 203	0	0	0	0	0
Turkmenistan	8 076	0	0	1	0	0
Ukraine	30 967	-18 333	0	2 400	12 400	117
United Kingdom	45 014	-15 400	0	0	2 801	383
United States of America	351 475	-192 867	0	66 783	72 180	1 828
Uzbekistan	28 195	-18 071	1 645	30	0	0

TABLE A.3

AGRICULTURAL EMISSIONS IN CARBON DIOXIDE EQUIVALENT BY SOURCE, 2014

(Thousand tonnes)

	BURNING CROP RESIDUES	BURNING SAVANNA	CROP RESIDUES	CULTIVATION OF ORGANIC SOILS	ENTERIC FERMENTATION	MANURE MANAGEMENT	MANURE LEFT ON PASTURES	MANURE APPLIED TO SOILS	RICE CULTIVATION	SYNTHETIC FERTILIZERS
WORLD	29 732	213 438	211 685	132 815	2 084 835	350 874	845 353	191 495	522 790	658 744
COUNTRIES AND TERRITORIES IN DEVELOPING REGIONS	21 721	165 043	133 883	65 465	1 617 857	198 919	712 007	116 462	500 039	440 522
Eastern and South-Eastern Asia	**8 125**	**3 776**	**54 597**	**45 521**	**291 009**	**107 795**	**117 309**	**53 302**	**315 408**	**203 238**
Brunei Darussalam	0	0	0	40	5	20	42	30	8	2
Cambodia	148	1 216	834	0	3 740	1 291	936	408	10 159	622
China, Hong Kong SAR	..	0	..	0	6	26	5	7	..	37
China, Macao SAR	..	0	..	0	..	1	1	1	..	0
China, mainland	5 011	112	35 899	883	203 958	73 639	82 777	38 049	112 860	154 453
Democratic People's Republic of Korea	67	2	428	45	1 051	322	588	171	1 869	..
Indonesia	920	217	5 914	34 168	20 844	7 454	11 156	4 902	61 260	18 779
Lao People's Democratic Republic	62	66	365	0	3 219	1 154	871	382	1 976	..
Malaysia	31	8	205	4 289	1 065	927	1 122	756	2 592	3 282
Mongolia	9	825	45	3 065	9 956	1 183	5 406	868	..	119
Myanmar	336	859	2 393	1 962	21 549	7 554	5 787	2 725	22 315	1 029
Philippines	431	15	1 833	0	6 489	3 323	2 257	1 073	33 300	4 452
Republic of Korea	37	0	386	0	3 486	1 594	1 173	801	3 596	1 637
Singapore	..	0	..	0	6	52	12	15	..	17
Thailand	625	327	3 018	122	6 380	3 054	2 127	1 179	36 389	9 819
Timor-Leste	4	6	14	0	365	136	110	39	110	..
Viet Nam	445	123	3 263	947	8 891	6 067	2 936	1 895	28 972	8 991
Latin America and the Caribbean	**3 886**	**13 017**	**25 960**	**2 667**	**528 368**	**24 866**	**211 737**	**26 422**	**17 107**	**55 151**
Anguilla	..	0	..	0	..	..	..	..	..	..
Antigua and Barbuda	0	0	0	0	13	1	6	2	..	0
Argentina	578	2 040	7 393	638	65 016	2 036	26 805	1 405	1 430	5 036
Aruba	..	0	..	0	..	..	..	..	..	..
Bahamas	0	6	0	0	4	3	8	5	..	..
Barbados	0	0	0	0	18	7	15	9	..	3
Belize	3	3	6	76	118	7	51	6	2	46
Bolivia (Plurinational State of)	55	394	452	0	14 180	857	6 214	652	226	153
Brazil	1 932	7 726	12 386	5	265 069	10 990	103 429	12 184	3 193	24 992
British Virgin Islands	..	0	..	0	5	0	3	0	..	..
Cayman Islands	..	0	..	0	3	0	1	0	..	..
Chile	18	32	222	107	4 437	491	2 027	801	104	1 601
Colombia	92	943	287	539	30 928	1 485	11 199	2 196	2 027	3 930

TABLE A.3

(CONTINUED)

	BURNING CROP RESIDUES	BURNING SAVANNA	CROP RESIDUES	CULTIVATION OF ORGANIC SOILS	ENTERIC FERMENTATION	MANURE MANAGEMENT	MANURE LEFT ON PASTURES	MANURE APPLIED TO SOILS	RICE CULTIVATION	SYNTHETIC FERTILIZERS
Costa Rica	6	10	20	7	1 856	123	558	274	33	579
Cuba	43	21	81	0	5 625	354	2 397	325	1 009	643
Dominica	0	0	0	0	21	1	7	3	..	0
Dominican Republic	14	4	58	0	3 935	310	1 826	416	940	280
Ecuador	54	2	207	16	6 055	504	2 434	720	1 755	1 252
El Salvador	29	2	68	0	1 389	95	499	149	4	390
Falkland Islands (Malvinas)	..	0	..	0	80	2	60	0	..	..
French Guiana	0	0	0	18	22	1	9	1	7	..
Grenada	0	0	0	0	8	1	5	1	..	..
Guadeloupe	1	0	..	0	89	4	36	3	..	..
Guatemala	82	41	138	0	4 489	436	1 685	508	7	1 008
Guyana	13	12	72	466	170	30	111	46	1 285	78
Haiti	33	0	55	0	2 295	183	1 063	167	108	..
Honduras	24	49	39	0	3 544	175	1 348	259	5	474
Jamaica	2	0	0	67	270	44	162	46	0	31
Martinique	0	0	..	0	23	3	11	2	..	..
Mexico	616	243	2 215	0	45 492	3 491	20 542	3 233	98	8 789
Montserrat	0	0	0	0	13	0	5	1	..	..
Netherlands Antilles	..	0	..	0	4	1	3	1	..	..
Nicaragua	31	56	78	6	4 878	202	1 711	337	56	326
Panama	11	6	33	128	2 026	105	817	112	26	124
Paraguay	91	305	1 059	0	17 307	490	6 928	256	353	856
Peru	63	15	370	144	12 349	866	5 103	756	1 880	1 716
Puerto Rico	0	0	0	30	486	31	192	52	..	..
Saint Kitts and Nevis	..	0	0	0	4	15	25	22	..	0
Saint Lucia	..	0	..	0	15	2	7	2	..	2
Saint Vincent and the Grenadines	0	0	0	0	7	1	4	1	..	..
Suriname	3	5	20	239	46	11	29	13	366	30
Trinidad and Tobago	0	0	1	0	57	39	84	59	9	0
Turks and Caicos Islands	..	0	..	0	..	..	..	..	..	..
United States Virgin Islands	..	0	..	0	11	1	5	1	..	..
Uruguay	30	1	490	28	14 923	361	6 143	276	984	973
Venezuela (Bolivarian Republic of)	61	1 101	212	154	21 091	1 105	8 171	1 119	1 199	1 840

TABLE A.3

(CONTINUED)

	BURNING CROP RESIDUES	BURNING SAVANNA	CROP RESIDUES	CULTIVATION OF ORGANIC SOILS	ENTERIC FERMENTATION	MANURE MANAGEMENT	MANURE LEFT ON PASTURES	MANURE APPLIED TO SOILS	RICE CULTIVATION	SYNTHETIC FERTILIZERS
Northern Africa and Western Asia	**793**	**266**	**6 259**	**0**	**61 043**	**3 559**	**50 067**	**2 101**	**4 929**	**27 414**
Algeria	52	141	348	0	5 531	293	4 538	170	1	1 721
Armenia	4	1	51	0	625	50	502	29	..	105
Azerbaijan	22	5	190	0	3 239	164	2 483	101	6	237
Bahrain	..	0	0	0	16	1	14	1	..	4
Cyprus	0	1	3	0	116	68	100	35	..	46
Egypt	138	0	1 423	0	10 072	471	6 556	230	3 702	8 463
Georgia	13	0	31	0	1 143	85	897	48	..	394
Iraq	72	54	477	0	3 505	200	2 669	113	541	946
Israel	2	0	28	0	423	86	510	69	..	258
Jordan	1	0	9	0	467	35	467	22	..	184
Kuwait	0	0	3	0	112	35	232	35	..	0
Lebanon	1	0	18	0	192	40	346	47	..	107
Libya	5	0	34	0	1 273	71	1 129	41	..	0
Morocco	105	2	615	0	5 690	357	5 105	240	26	1 504
Palestine	0	1	3	0	128	9	126	6	..	..
Oman	0	0	2	0	803	47	561	10	..	156
Qatar	0	0	0	0	138	13	104	7	..	561
Saudi Arabia	5	1	65	0	2 297	212	2 328	149	..	2 165
Syrian Arab Republic	42	11	260	0	3 105	128	2 519	36	..	152
Tunisia	22	10	195	0	1 761	133	1 684	108	..	523
Turkey	301	38	2 427	0	15 514	793	13 325	508	652	9 634
United Arab Emirates	0	0	3	0	883	59	605	19	..	107
Western Sahara	..	0	..	0	129	5	49	1	..	..
Yemen	7	0	73	0	3 883	204	3 217	78	..	150
Oceania, excluding Australia and New Zealand	**3**	**103**	**2**	**4 482**	**1 090**	**1 043**	**536**	**175**	**14**	**121**
American Samoa	0	0	..	0	0	4	0	1	..	..
Cook Islands	..	0	..	0	1	11	0	1	..	0
Fiji	2	1	1	14	462	108	242	29	6	18
French Polynesia	0	0	0	0	13	12	7	3	..	1
Guam	0	0	0	0	1	2	0	1	..	..
Kiribati	..	0	..	0	0	5	0	2	..	..
Marshall Islands	..	0	..	0	..	..	..	..	..	0
Micronesia (Federated States of)	0	0	0	0	1	12	1	2	1	..
Nauru	..	0	..	0	0	1	0	0	..	..
New Caledonia	0	1	0	0	124	24	64	5	..	4

TABLE A.3

(CONTINUED)

	BURNING CROP RESIDUES	BURNING SAVANNA	CROP RESIDUES	CULTIVATION OF ORGANIC SOILS	ENTERIC FERMENTATION	MANURE MANAGEMENT	MANURE LEFT ON PASTURES	MANURE APPLIED TO SOILS	RICE CULTIVATION	SYNTHETIC FERTILIZERS
Niue	..	0	..	0	..	..	..	..	..	..
Northern Mariana Islands	..	0	..	0	..	..	..	..	..	..
Palau	..	0	..	0	..	..	..	..	..	..
Papua New Guinea	1	102	1	4 469	162	682	62	101	2	77
Pitcairn Islands	..	0	..	0	..	..	..	..	..	..
Samoa	0	0	..	0	45	72	21	11	..	0
Solomon Islands	0	0	0	0	22	21	10	4	5	..
Tokelau	..	0	..	0	0	0	0	0	..	..
Tonga	..	0	..	0	22	30	11	5	..	21
Tuvalu	..	0	..	0	..	..	..	..	..	..
Vanuatu	0	0	0	0	237	59	119	11	..	..
Wallis and Futuna Islands	0	0	..	0	..	..	..	..	..	..
Southern Asia	**5 447**	**270**	**34 818**	**5 223**	**426 528**	**42 739**	**112 636**	**25 483**	**138 043**	**138 583**
Afghanistan	103	8	554	0	8 415	680	3 257	514	647	616
Bangladesh	546	4	4 067	3 329	23 793	2 268	9 530	1 695	24 673	4 690
Bhutan	3	2	12	0	275	25	67	13	49	6
India	3 779	160	24 759	913	283 500	28 428	64 594	15 216	96 207	109 309
Iran (Islamic Republic of)	247	53	1 391	0	15 070	2 053	9 149	2 467	2 723	1 690
Maldives	0	0	0	0	..	..	..	..	..	2
Nepal	164	8	749	663	11 930	1 112	2 928	664	3 270	570
Pakistan	562	25	3 013	0	82 329	8 024	22 830	4 827	8 500	20 232
Sri Lanka	44	10	272	318	1 216	150	282	88	1 974	1 468
Sub-Saharan Africa	**3 467**	**147 611**	**12 247**	**7 571**	**309 819**	**18 917**	**219 721**	**8 980**	**24 538**	**16 017**
Angola	129	21 097	207	53	3 922	618	2 918	341	177	122
Benin	79	1 012	136	0	1 816	155	1 373	75	44	86
Botswana	8	2 287	10	44	1 742	71	1 247	26	..	137
Burkina Faso	65	1 268	354	0	9 062	826	6 846	378	755	312
Burundi	9	13	48	329	896	101	699	56	35	36
Cabo Verde	2	0	1	0	44	16	39	10	..	..
Cameroon	78	1 279	260	115	4 944	502	3 755	255	248	158
Central African Republic	9	10 911	19	0	3 596	298	2 674	143	25	1
Chad	23	4 898	210	0	8 176	382	5 259	96	221	..
Comoros	1	0	4	0	52	2	42	1	134	..
Congo	2	1 145	3	133	271	27	209	13	5	2
Côte d'Ivoire	45	834	190	209	1 461	153	1 288	91	241	277
Democratic Republic of the Congo	166	15 497	208	5	1 045	220	921	130	256	81
Djibouti	0	0	0	0	377	17	251	4	..	..

TABLE A.3

(CONTINUED)

	BURNING CROP RESIDUES	BURNING SAVANNA	CROP RESIDUES	CULTIVATION OF ORGANIC SOILS	ENTERIC FERMENTATION	MANURE MANAGEMENT	MANURE LEFT ON PASTURES	MANURE APPLIED TO SOILS	RICE CULTIVATION	SYNTHETIC FERTILIZERS
Equatorial Guinea	..	0	..	1	9	2	8	1	..	..
Eritrea	2	26	31	0	2 375	98	1 536	42	..	3
Ethiopia	221	3 432	1 289	1 436	50 196	2 048	35 179	794	138	1 524
Gabon	2	186	3	43	67	39	60	24	1	12
Gambia	6	131	20	0	389	19	283	7	351	5
Ghana	90	3 580	207	15	2 290	249	2 050	141	316	246
Guinea	81	1 714	265	93	3 835	173	2 768	68	2 288	17
Guinea-Bissau	6	228	25	0	612	100	448	55	176	..
Kenya	175	218	371	45	20 718	869	13 942	420	42	334
Lesotho	8	68	11	0	755	27	557	20	..	..
Liberia	11	0	37	18	101	54	109	34	54	..
Madagascar	92	1 669	393	719	7 388	532	5 238	279	5 574	73
Malawi	138	237	340	59	1 554	507	1 273	307	103	721
Mali	93	3 904	531	0	12 418	591	8 978	221	1 006	1 980
Mauritania	4	45	31	0	4 409	217	2 677	57	253	..
Mauritius	3	0	0	0	10	12	60	9	2	52
Mozambique	153	12 685	212	0	1 732	373	1 411	229	553	357
Namibia	2	2 032	10	0	2 215	102	1 644	38	..	16
Niger	2	215	547	0	12 766	598	8 689	179	23	110
Nigeria	599	2 331	2 143	0	25 847	2 313	20 967	1 167	7 117	1 755
Réunion	1	0	1	0	34	22	87	17	0	..
Rwanda	21	17	124	296	1 215	208	922	124	24	45
Saint Helena	..	0	..	0	1	0	1	0	..	..
Sao Tome and Principe	0	0	0	0	3	6	3	4	..	..
Senegal	18	2 630	96	0	3 970	289	3 128	132	198	137
Seychelles	..	0	..	0	1	1	1	1	..	0
Sierra Leone	30	157	135	0	837	67	679	28	894	..
Somalia	8	25	33	0	13 010	648	6 439	143	4	..
South Africa	290	2 341	1 030	29	12 529	869	9 677	407	7	2 823
South Sudan	22	21 485	106	145	11 911	488	8 727	214	..	0
Sudan	15	4 142	926	0	37 898	1 563	24 742	893	46	2 293
Swaziland	10	40	7	0	482	25	348	13	0	..
Togo	58	344	127	0	901	128	811	72	20	144
Uganda	94	1 164	294	720	11 737	830	8 484	464	140	72
United Republic of Tanzania	377	6 734	871	787	21 102	874	14 977	453	3 019	502
Zambia	99	13 453	224	2 277	3 075	313	2 341	162	49	960
Zimbabwe	120	2 135	157	0	4 020	275	2 957	141	0	621

TABLE A.3

(CONTINUED)

	BURNING CROP RESIDUES	BURNING SAVANNA	CROP RESIDUES	CULTIVATION OF ORGANIC SOILS	ENTERIC FERMENTATION	MANURE MANAGEMENT	MANURE LEFT ON PASTURES	MANURE APPLIED TO SOILS	RICE CULTIVATION	SYNTHETIC FERTILIZERS
COUNTRIES AND TERRITORIES IN DEVELOPED REGIONS	8 011	48 395	77 803	67 350	466 978	151 955	133 347	75 033	22 752	218 222
Albania	7	0	47	17	1 479	426	410	248	0	197
Andorra	..	0	..	0	..	..	..	..	..	..
Australia	422	42 022	3 040	348	50 475	5 251	29 635	1 092	496	9 066
Austria	27	0	339	47	3 199	1 282	468	684	..	555
Belarus	32	2	578	5 708	6 778	1 991	600	1 357	..	2 944
Belgium	12	0	243	43	3 786	1 959	526	995	..	1 224
Bermuda	..	0	0	0	2	1	0	0	..	..
Bosnia and Herzegovina	15	0	66	25	1 049	375	207	231	..	605
Bulgaria	72	0	626	161	1 294	357	243	267	65	2 408
Canada	393	1 516	4 058	8 873	15 820	6 121	5 050	1 655	..	18 296
Croatia	25	0	176	0	889	433	163	223	..	664
Czech Republic	34	0	602	40	2 103	705	205	486	..	2 121
Denmark	22	0	677	383	3 015	2 704	359	1 134	..	1 151
Estonia	5	0	89	1 496	472	182	66	95	..	231
Faroe Islands	..	0	0	0	16	2	7	2	..	..
Finland	8	0	292	1 600	1 543	604	223	322	..	1 019
France	312	2	4 674	934	29 666	9 881	4 836	5 969	177	15 815
Germany	139	0	3 410	4 740	22 018	10 346	2 950	5 268	..	11 766
Gibraltar	..	0	..	0	..	..	..	..	..	..
Greece	32	9	294	159	3 102	745	1 505	473	321	1 756
Greenland	..	0	..	0	3	0	1	0	..	..
Holy See	..	..	..	0	..	..	..	..	..	..
Hungary	128	0	961	899	1 509	752	226	539	14	2 006
Iceland	..	0	0	0	231	45	78	28	..	70
Ireland	2	0	181	1 402	10 705	2 683	1 881	1 709	..	1 912
Isle of Man	..	0	..	2	..	..	..	..	..	..
Italy	136	3	1 242	99	11 970	5 323	2 170	2 933	2 323	3 873
Japan	76	0	795	833	4 647	2 111	1 606	1 178	6 876	2 587
Kazakhstan	388	2 524	1 551	0	9 474	1 751	3 116	1 082	439	387
Kyrgyzstan	18	0	119	0	2 559	443	859	299	37	202
Latvia	12	0	164	1 237	733	267	100	152	..	485
Liechtenstein	..	..	..	0	11	3	2	2	..	..
Lithuania	24	0	349	1 476	1 294	487	171	265	..	658
Luxembourg	0	0	10	1	299	87	43	50	..	155
Malta	0	0	2	0	30	27	5	10	..	25
Monaco	..	..	..	0	..	..	..	..	..	..
Montenegro	0	0	3	7	225	63	43	35	..	8

TABLE A.3

(CONTINUED)

	BURNING CROP RESIDUES	BURNING SAVANNA	CROP RESIDUES	CULTIVATION OF ORGANIC SOILS	ENTERIC FERMENTATION	MANURE MANAGEMENT	MANURE LEFT ON PASTURES	MANURE APPLIED TO SOILS	RICE CULTIVATION	SYNTHETIC FERTILIZERS
Netherlands	5	0	180	1 373	7 749	4 208	1 084	2 132	..	1 594
New Zealand	3	1	75	379	21 179	3 198	11 240	465	..	2 115
Norway	2	1	89	937	1 719	511	399	303	..	657
Poland	127	0	1 679	4 676	9 758	3 900	865	2 620	..	10 534
Portugal	12	6	79	47	2 673	1 345	567	683	301	612
Republic of Moldova	47	0	199	33	509	195	113	181	..	336
Romania	263	0	1 401	123	5 520	1 917	1 316	1 389	75	1 959
Russian Federation	962	1 415	8 379	12 791	35 487	11 157	4 980	8 197	1 150	7 710
Saint Pierre and Miquelon	..	0	..	0	0	0	0	0	..	..
San Marino	..	..	..	0	..	..	..	..	..	..
Serbia	102	0	641	0	2 093	1 067	393	520	..	1 637
Slovakia	29	0	302	9	792	286	99	195	..	837
Slovenia	4	0	38	7	729	229	112	133	..	180
Spain	106	22	1 401	44	12 289	7 847	3 036	3 404	1 164	7 112
Svalbard and Jan Mayen Islands	..	0	..	0	..	..	..	..	..	..
Sweden	14	0	395	1 006	2 398	818	382	457	..	1 169
Switzerland	4	0	67	105	2 766	966	396	521	..	367
Tajikistan	11	4	101	0	3 151	593	886	366	51	366
The former Yugoslav Republic of Macedonia	5	0	46	0	597	168	135	96	30	125
Turkmenistan	15	24	121	0	4 560	785	1 745	549	277	..
Ukraine	552	5	4 627	3 104	8 273	4 393	885	2 487	60	6 582
United Kingdom	61	0	1 775	2 164	20 019	4 935	5 175	3 396	..	7 490
United States of America	3 297	808	31 024	10 021	119 973	42 990	37 995	16 463	8 682	80 221
Uzbekistan	51	32	597	0	14 349	3 039	3 788	1 696	212	4 433

REFERENCES

CHAPTER 1

Alexandratos, N. & Bruinsma, J. 2012. *World agriculture towards 2030/2050: the 2012 revision*. Rome, FAO.

Asfaw, S., McCarthy, N., Lipper, L., Arslan, A. & Cattaneo, A. 2014. *Climate variability, adaptation strategies and food security in Malawi*. ESA Working Paper No. 14–08. Rome, FAO.

Branca, G., McCarthy, N., Lipper, L. & Jolejole, M. 2011. *Climate-smart agriculture: a synthesis of empirical evidence of food security and mitigation benefits from improved cropland management*. FAO Mitigation of Climate Change in Agriculture Series No. 3. Rome, FAO.

Confalonieri, U., Menne, B., Akhtar, R., Ebi, K.L., Hauengue, M., Kovats, R.S., Revich, B. & Woodward, A. 2007. *In:* M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden & C.E. Hanson, eds. *Human health. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK, Cambridge University Press, pp. 391–431.

De Pinto, A., Thomas, T. & Wiebe, K. 2016. *Synthesis of recent IFPRI research on climate change impacts on agriculture and food security*. Background paper prepared for *The State of Food and Agriculture 2016*. Washington DC, IFPRI (International Food Policy Research Institute). (unpublished).

FAO. 2006. *Food security*. Policy brief, Issue 2, June 2006. Rome.

FAO. 2010. *"Climate-smart" agriculture: policies, practices and financing for food security, adaptation and mitigation*. Rome.

FAO. 2011. *"Energy-smart" food for people and climate*. An Issue Paper. Rome.

FAO. 2012. *The State of World Fisheries and Aquaculture 2012*. Rome.

FAO. 2013. *Climate change guidelines for forest managers*. FAO Forestry Paper 172. Rome.

FAO. 2014. *Building a common vision for sustainable food and agriculture. Principles and approaches*. Rome.

FAO. 2016. *The agriculture sectors in the Intended Nationally Determined Contributions: Summary*. Rome.

FAO. FAOSTAT. Online Statistical Database (available at http://faostat.fao.org/). Rome.

Hallegatte, S., Bangalore, M., Bonzanigo, L., Fay, M., Kane, T., Narloch U., Rozenberg, J., Treguer, D. & Vogt-Schilb, A. 2016. *Shock waves: managing the impacts of climate change on poverty*. Climate change and development series. Washington, DC, World Bank.

IFPRI (International Food Policy Research Institute). 2015. *Global nutrition report 2015: Actions and accountability to advance nutrition and sustainable development*. Washington, DC.

IPCC (Intergovernmental Panel on Climate Change). 2014. Summary for policy-makers. *In:* O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel & J.C. Minx, eds. *Climate change 2014: Mitigation of climate change. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK and New York, NY, USA, Cambridge University Press.

Myers, S.S., Zanobetti, A., Kloog, I., Huybers, P., Leakey, A.D.B., Bloom, A.J., Carlisle, E., Dietterich, H.L., Fitzgerald, G., Hasegawa, T., Holbrook, N.M., Nelson, R.L., Ottman, M.J., Raboy, V., Sakai, H., Sartor, K.A., Schwartz, J., Seneweera, S., Tausz, M. & Usui, Y. 2014. Increasing CO_2 threatens human nutrition. *Nature*, 510: 139–142.

Paerl, H. & Huisman, J. 2009. Climate change: a catalyst for global expansion of harmful cyanobacterial blooms. *Environmental Microbiology Reports*, 1(1): 1–95.

Paterson, R. & Lim, N. 2010. How will climate change affect mycotoxins in food? *Food Research International*, 43: 1902–1914.

Porter, J.R., Xie, L., Challinor, A.J., Cochrane, K., Howden, S.M., Iqbal, M.M., Lobell, D.B. & Travasso, M.I. 2014. Food security and food production systems. *In:* C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy,

S. MacCracken, P.R. Mastrandrea & L.L. White, eds. *Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK and New York, NY, USA, Cambridge University Press, pp. 485–533.

Schleussner, C.F., Lissner, T.K., Fischer, E.M., Wohland, J., Perrette, M., Golly, A., Rogelj, J., Childers, K., Schewe, J., Frieler, K., Mengel, M., Hare, W. & Schaeffer, M. 2016. Differential climate impacts for policy-relevant limits to global warming: the case of 1.5 °C and 2 °C. *Earth system dynamics, 7*:327–351.

Searchinger, D.T., Zhang, X., Davidson, E.A., Mauzerall, D.L., Dumas, P. & Shen, Y. 2015. Managing nitrogen for sustainable development. *Nature,* 528: 51–59.

Smith P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Haberl, H., Harper, R., House, J., Jafari, M., Masera, O., Mbow, C., Ravindranath, N. H., Rice, C.W., Robledo Abad, C., Romanovskaya, A., Sperling, F. & Tubiello, F. 2014. Agriculture, forestry and other land use (AFOLU). *In:* O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel & J.C. Minx, eds. *Climate change 2014: mitigation of climate change. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK and New York, NY, USA, Cambridge University Press.

Thornton P., Ericksen P.J., Herrero M. & Challinor A.J. 2014. Climate variability and vulnerability to climate change: a review. *Global change biology,* 20:3313–3328.

UNFCCC (United Nations Framework Convention on Climate Change). 1992. *United Nations framework convention on climate change.* New York, USA, United Nations.

UNFCCC. 2015. *Adoption of the Paris Agreement. United Nations framework convention on climate change.* Paris.

Vermeulen, S.J., Campbell, B.M. & Ingram, J.S.I. 2012. Climate change and food systems, *annual review of Environment and Resources,* 37: 195–222.

WHO (World Health Organization). 2003. *Climate change and human health – risks and responses. Summary.* Geneva.

Wijesinha-Bettoni, R., Kennedy, G., Dirorimwe, C. & Muehlhoff, E. 2013. Considering seasonal variations in food availability and caring capacity when planning complementary feeding interventions in developing countries. *International Journal of Child Health and Nutrition,* 2 (4): 335–352.

Wollenberg, E., Richards, M., Smith, P., Havlik, P., Obersteiner, M., Tubiello, F.N., Herold, M., Gerber, P., Carter, S., Reisinger, A., van Vuuren, D., Dickie, A., Neufeldt, H., Sander, B.O., Wassman, R., Sommer, R., Amonette, J.E, Falcucci, A., Herrero, M., Opio, C., Roman-Cuesta, R., Stehfest, E., Westhoek, H., Ortiz-Monasterio, I., Sapkota, T., Rufino, M.C., Thornton, P.K., Verchot, L., West, P.C., Soussana, J.-F., Baedeker, T., Sadler, M., Vermeulen, S. & Campbell, B.M. 2016. Reducing emissions from agriculture to meet 2 °C target. *Global Change Biology.* In press.

World Bank. 2008. *World Development Report 2008. Agriculture for development.* Washington, DC.

Zezza, A., Davis, B., Azzarri, C., Covarrubias, K., Tasciotti, L. & Anríquez, G. 2008. *The impact of rising food prices on the poor.* ESA Working Paper 08-07. Rome, FAO.

CHAPTER 2

Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D.D., Hogg, E.H., Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J.H., Allard, G., Running, S.W., Semerci, A. & Cobb, N. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management,* 259(4): 660–684.

Alling, A., Doherty, O., Logan, H., Feldman, L. & Dustan, P. 2007. Catastrophic coral mortality in the remote Central Pacific Ocean: Kiribati, Phoenix Islands. *Atoll Research Bulletin,* 551: 1–19.

REFERENCES

Antle, J.M. & Crissman, C.C. 1990. Risk, efficiency, and the adoption of modern crop varieties: evidence from the Philippines. *Economic Development and Cultural Change*, 38(3): 517–537.

Arnell, N.W., Cannell, M.G., Hulme, M., Kovats, R.S., Mitchell, J.F., Nicholls, R.J., Parry, M.L., Livermore, M.T.J. & White, A. 2002. The consequences of CO_2 stabilisation for the impacts of climate change. *Climatic Change*, 53(4): 413–446.

Arslan, A., McCarthy, N., Lipper, L., Asfaw, S., Cattaneo, A. & Kokwe, M. 2015. Climate-smart agriculture? Assessing the adaptation implications in Zambia. *Journal of Agricultural Economics*, 66(3): 753–780.

Arslan, A., Belotti, F. & Lipper, L. 2016. *Smallholder productivity under climatic variability: Adoption and impact of widely promoted agricultural practices in Tanzania*. ESA Working Paper 16–03. Rome, FAO.

Asfaw, S., Coromaldi, M. & Lipper, L. 2015a. *Welfare cost of weather fluctuations and climate shocks in Ethiopia*. Mimeo

Asfaw, S., Coromaldi, M. & Lipper, L. 2015b. *Adaptation to climate change and food security in Ethiopia*. https://www.economic.com/esa/publications/details/en/c/279717/. Rome, FAO.

Asfaw, S., Di Battista, F. & Lipper, L. 2015. *Effects of weather fluctuations and climate shocks on household welfare: evidence from Niger*. Mimeo

Asfaw, S., Maggio, G. & Lipper, L. 2015. *Gender differentiated impact of climate shock in Malawi*. ESA Working Paper.

Bárcena, A., Prado, A., Samaniego, J. & Pérez, R. 2014. *The economics of climate change in Latin America and the Caribbean: paradoxes and challenges*. Santiago, United Nations Economic Commission for Latin America and the Caribbean.

Brander, K.M. 2007. Global fish production and climate change. *PNAS*, 104(50): 19709–19714.

CGIAR, CCAFS & University of Leeds. 2016. Agriculture Impacts. (Available at http://www.ag-impacts.org).

Challinor, A.J., Watson, J., Lobell, D.B., Howden, S.M., Smith, D.R. & Chhetri, N. 2014. A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change*, 4: 287–291.

Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L., Kearney, K., Watson, R., Zeller, D. & Pauly, D. 2010. Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Global Change Biology*, 16: 24–35.

Chomo, V. & De Young, C. 2015. Towards sustainable fish food and trade in the face of climate change. *BIORES*, 9(2).

Ciais, P., Schelhaas, M.J., Zaehle, S., Piao, L., Cescatti, A., Liski, J., Luyssaert, S., Le-Maire, G., Schulze, E.D., Bouriaud, O., Freibauer, A., Valentini, R. & Nabuurs, G.J. 2008. Carbon accumulation in European forests. *Nature Geoscience*, 1(7): 425–429.

Cline, W.R. 2007. *Global warming and agriculture: impact estimates by country*. Washington, DC, Center for Global Development and Peterson Institute for International Economics.

Dercon, S. & Christiaensen, L. 2011. Consumption risk, technology adoption and poverty traps: evidence from Ethiopia. *Journal of Development Economics*, 96: 159–173.

De Pinto, A., Thomas, T. & Wiebe, K. 2016. Synthesis of recent IFPRI research on climate change impacts on agriculture and food security. Background paper prepared for *The State of Food and Agriculture 2016*. Washington DC, IFPRI (International Food Policy Research Institute). (unpublished).

Fafchamps, M. 1992. Solidarity networks in pre-industrial societies: rational peasants with a moral economy. *Economic Development and Cultural Change*, 41: 147–174.

FAO. 2011. *FAO-Adapt: Framework Programme on Climate Change Adaptation*. Rome.

FAO. 2015. *The impact of natural hazards and disasters on agriculture and food security and nutrition*. Rome.

FAO. 2016a. *Climate change and food security: risks and responses.* Rome.

FAO. 2016b. *2015–2016 El Niño – Early action and response for agriculture, food security and nutrition.* Rome.

FAO. 2016c. *Climate change implications for fisheries and aquaculture: Summary of the findings of the intergovernmental panel on climate change fifth assessment report*, by A.Seggel, & C.De Young. FAO Fisheries and Aquaculture Circular No. 1122. Rome.

FAO. 2016d. FAOSTAT. Online Statistical Database (retrieved 30 July 2016) (available at http://faostat.fao.org/).

FAO. FAOSTAT. Online Statistical Database (available at http://faostat.fao.org/).

Feder, G., Just, R. & Zilberman, D. 1985. Adoption of agricultural innovations in developing countries: a survey. *Economic Development and Cultural Change*, 33: 255–298.

Gray, J., Dautel, H., Estrada-Peña, A., Kahl, O. & Lindgren, E. 2009. Effects of climate change on ticks and tick-borne diseases in Europe. *Interdisciplinary Perspectives on Infectious Diseases,* 2009: ID 593232.

Hallegatte, S., Mook B., Bonzanigo, L., Fay, M., Kane, T., Narloch, U., Rozenberg, J., Treguer, D. & Vogt-Schilb, A. 2015. *Shock waves: managing the impacts of climate change on poverty.* Climate Change and Development Series. Washington, DC, World Bank.

Heltberg, R. & Tarp, F. 2002. Agricultural supply response and poverty in Mozambique. *Food Policy*, 27(2): 103–124.

HLPE (High Level Panel of Experts). 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.

Hurley, T. 2010. *Review of agricultural production risk in the developing world.* Harvest Choice Working Paper 11. Washington, DC, IFPRI.

IPCC (Intergovernmental Panel on Climate Change). 2007. *Climate change 2007: synthesis report. Contribution of working groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change.* [Core Writing Team, R.K. Pachauri and A. Reisinger, eds.]. Geneva, Switzerland, 104 pp.

IPCC. 2014. *Climate change 2014: impacts, adaptation, and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.In:* V.R. Barros, C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea & L.L. White, eds. Cambridge, UK and New York, NY, USA, Cambridge University Press.

Kassie, M., Pender, J., Mahmud, Y., Kohlin, G., Bluffstone, R. & Mulugeta, E. 2008. Estimating returns to soil conservation adoption in the Northern Ethiopian Highlands. *Agricultural Economics*, 38: 213–232.

Kirtman, B., Power, S.B., Adedoyin, J.A., Boer, G.J., Bojariu, R., Camilloni, I., Doblas-Reyes, F.J., Fiore, A.M., Kimoto, M., Meehl, G.A., Prather, M., Sarr, A., Schär, C., Sutton, R., van Oldenborgh, G.J., Vecchi, G. & Wang, H.J. 2014. Near-term climate change: projections and predictability. *In:* T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex & P.M. Midgley, eds. *Climate change 2013: the physical science basis. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK and New York, NY, USA, Cambridge University Press.

Krishnamurthy, P.K., Lewis, K. & Choularton R.J. 2014. A methodological framework for rapidly assessing the impacts of climate risk on national-level food security through a vulnerability index. *Global Environmental Change*, 25: 121–132.

Lam, V.W.Y., Cheung, W.W.L., Swartz, W. & Sumaila, U.R. 2012. Climate change impacts on fisheries in West Africa: implications for economic, food and nutritional security. *African Journal of Marine Science*, 34(1): 103–117.

REFERENCES

Lancelot, R., de La Rocque, S. & Chevalier, V. 2008. Bluetongue and Rift Valley fever in livestock: a climate change perspective with a special reference to Europe, the Middle East and Africa. *In:* P. Rowlinson, M. Steele & A. Nefzaoui, eds. *Livestock and global climate change. Proceedings of the british society of animal science (BSAS) international conference on livestock and global climate change, Hammamet, Tunisia, 17–20 May 2008, pp. 87–89*. Cambridge, UK, Cambridge University Press.

Lobell, D.B., Schlenker, W. & Costa-Roberts, J. 2011. Climate trends and global crop production since 1980. *Science*, 333(6042): 616–620.

Lozanoff, J. & Cap, E. 2006. *Impact of climate change over Argentine agriculture: an economy study.* Argentina, INIA (Instituto Nacional de Tecnología Agropecuaria).

Marlier M.E., DeFries R.S., Voulgarakis A., Kinney P.L., Randerson J.T., Shindell D.T., Chen Y. & Faluvegi G. 2013. El Niño and health risks from landscape fire emissions in Southeast Asia. *Nature Climate Change*, (3): 131–6.

Mendelsohn, R.O., Arellano, J. & Christensen, P. 2010. A Ricardian analysis of Mexican farms. *Environment and Development Economics*, 15(2): 153–171.

Met Office Hadley Centre & WFP. 2015. Food Insecurity and Climate Change. Web site. (Available at: http://www.metoffice.gov.uk/food-insecurity-index/)

Miles, L., Newton, A.C., DeFries, R.S., Ravilious, C., May, I., Blyth, S., Kapos, V. & Gordon, J.E. 2006. A global overview of the conservation status of tropical dry forests. *Journal of Biogeography*, 33(3): 491–505.

Moss, R.H., Babiker, M., Brinkman, S., Calvo, E., Carter, T., Edmonds, J., Elgizouli, I., Emori, S., Erda, L., Hibbard, K., Jones, R., Kainuma, M., Kelleher, J., Lamarque, J.F., Manning, M., Matthews, B., Meehl, J., Meyer, L., Mitchell, J., Nakicenovic, N., O'Neill, B., Pichs, R., Riahi, K., Rose, S., Runci, P., Stouffer, R., van Vuuren, D., Weyant, J., Wilbanks, T., van Ypersele, J.P., & Zurek, M. 2008. *Towards new scenarios for analysis of emissions, climate change, impacts, and response strategies. Geneva, Switzerland,* Intergovernmental Panel on Climate Change.

Müller, C. & Elliott, J. 2015. The Global Gridded Crop Model intercomparison: approaches, insights and caveats for modelling climate change impacts on agriculture at the global scale. *In:* A. Elbehri, ed. *Climate change and food systems: global assessments and implications for food security and trade.* Rome, FAO.

Nelson, G.C., Rosegrant, M.W., Koo, J., Robertson, R., Sulser, T., Zhu, T., Ringler, C., Msangi, S., Palazzo, A., Batka, M., Magalhaes, M., Valmonte-Santos, R., Ewing, M. & Lee, D. 2009. *Climate change – impact on agriculture and cost of adaptation.* Washington, DC, IFPRI.

Nelson, G.C., Rosegrant, M.W., Palazzo, A., Gray, I., Ingersoll, C., Robertson, R., Tokgoz, S., Zhu, T., Sulser, T.B., Ringler, C. & Msangi, S. 2010. *Food security, farming, and climate change to 2050: scenarios, results, policy options.* Washington, DC, IFPRI.

Nelson, G., van der Mensbrugghe, D., Ahammad, H., Blanc, E., Calvin, K., Hasegawa, T., Havlík, P., Heyhoe, E., Kyle, P., Lotze-Campen, H., von Lampe, M., Mason d'Croz, D., van Meijl, H., Müller, C., Reilly, J., Robertson, R., Sands, R., Schmitz, C., Tabeau, A., Takahashi, K., Valin, H. & Willenbockel, D. 2014a. Agriculture and climate change in global scenarios: why don't the models agree? *Agricultural Economics*, 45(1): 85–101.

Nelson, G.C., Valin, H., Sands, R.D., Havlik, P., Ahammad, H., Deryng, D., Elliott, J., Fujimori, S., Hasegawa, T., Heyhoe, E., Kyle, P., Von Lampe, M., Lotze-Campen, H., d'Croz, D.M., van Meijl., H., van der Mensbrugghe, D., Müller, C., Popp, A., Robertson, R., Robinson, S., Schmid, E., Schmitz, C., Tabeau, A. & Willenbockel, D. 2014b. Climate change effects on agriculture: economic responses to biophysical shocks. *Proceedings of the National Academy of Sciences*, 111(9): 3274–3279.

Niang, I., Ruppel, O.C., Abdrabo, M.A., Essel, A., Lennard, C., Padgham, J. & Urquhart, P. 2014. Africa. *In:* V.R. Barros, C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea & L.L. White, eds. *Climate change 2014: Impacts, adaptation, and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge,* UK and New York, NY, USA, Cambridge University Press.

NOAA (National Oceanic and Atmospheric Administration). 2015. NOAA declares third ever global bleaching event. (Available at: http://www.noaanews.noaa.gov/stories2015/100815-noaa-declares-third-ever-global-coral-bleaching-event.html).

Obura, D. & Mangubhai, S. 2011. Coral mortality associated with thermal fluctuations in the Phoenix Islands, 2002–2005. *Coral Reefs,* 30(3): 607–619.

O'Neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., Mathur, R. & van Vuuren, D.P. 2014. A new scenario framework for climate change research: the concept of shared socio-economic pathways. *Climatic Change,* 122(3): 387–400.

O'Neill, B.C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M. & Solecki, W. 2015. The roads ahead: narratives for shared socio-economic pathways describing world futures in the 21st century. *Global Environmental Change.*

Parry, M., Rosenzweig, C. & Livermore, M. 2005. Climate change, global food supply and risk of hunger. *Philosophical Transactions of the Royal Society B,* 360 (1463): 2125–2138.

Porter, J.R., Xie, L., Challinor, A.J., Cochrane, K., Howden, S.M., Iqbal, M.M., Lobell, D.B. & Travasso, M.I. 2014. Food security and food production systems. *In:* C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea & L.L. White, eds. *Climate Change 2014: Impacts, adaptation, and vulnerability. part A: global and sectoral aspects. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge,* UK and New York, NY, USA, Cambridge University Press, pp. 485–533.

Roe, T. & Graham-Tomasi, T. 1986. Yield risk in a dynamic model of the agricultural household. *In:* I. Singh, L. Squire & J. Strauss, eds. *Agricultural household models: extension, applications and policy.* A World Bank Research Publication. Baltimore, USA, Johns Hopkins University Press, pp. 255–276.

Rosenthal, J. 2009. Climate change and the geographic distribution of infectious diseases. *Ecohealth,* 6: 489–495.

Rosenzweig, C. & Parry, M.L. 1994. Potential impact of climate change on world food supply. *Nature,* 367: 133–138.

Rosenzweig, M.R. & Binswanger, H.P. 1993. Wealth, weather risk and the composition and profitability of agricultural investments. *The Economic Journal,* 103: 56–78.

Rosenzweig, C., Jones, J., Hatfield, J., Ruane, A., Boote, K., Thorburne, P., Antle, J., Nelson, G., Porter, C., Janssen, S., Asseng, S., Basso, B., Ewert, F., Wallach, D., Baigorria, G. & Winter, J. 2013. The Agricultural model intercomparison and improvement project (AgMIP): Protocols and pilot studies. *Agricultural and Forest Meteorology,* 170: 166–182.

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A.C., Müller, C., Arneth, A., Boote, K.J., Folberth, C., Glotter, M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T.A.M., Schmid, E., Stehfest, E., Yang, H. & Jones, J.W. 2014. Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proceedings of the National Academy of Sciences,* 111(9): 3268–3273.

Rozenberg, J. & Hallegatte, S. 2015. *The impacts of climate change on poverty in 2030 and the potential from rapid, inclusive, and climate-informed development.* Policy Research Paper No. 7483. Washington, DC, World Bank.

Sadoulet, E. & de Janvry, A. 1995. *Quantitative development policy analysis.* Chapter 5. Baltimore, USA, Johns Hopkins University Press.

Sanghi, A. & Mendelsohn, R. 2008. The impacts of global warming on farmers in Brazil and India. *Global Environmental Change,* 18(4): 655–665.

Sejian, V., Maurya, V.P., Kumar, K. & Naqvi, S.M.K. 2012. Effect of multiple stresses (thermal, nutritional and walking stress) on growth, physiological response, blood biochemical and endocrine responses in Malpura ewes under semi-arid tropical environment. *Tropical Animal Health and Production,* 45: 107–116.

Seo, N. & Mendelsohn, R. 2007. *An analysis of crop choice: adapting to climate change in Latin American farms.* Washington, DC, World Bank.

REFERENCES

Seo, N. & Mendelsohn, R. 2008. A Ricardian analysis of the impact of climate change on south american farms. *Chilean Journal of Agricultural Research*, 68(1): 69–79.

Seo, N. 2011. An analysis of public adaptation to climate change using agricultural water schemes in South America. *Ecological Economics*, 70(4): 825–834.

Settele, J., Scholes, R., Betts, R., Bunn, S., Leadley, P., Nepstad, D., Overpeck, J.T. & Taboada, M.A. 2014. Terrestrial and inland water systems. *In:* C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea & L.L. White, eds. *Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK, and New York, USA, Cambridge University Press.

Skees, J., Hazell, P. & Miranda, M. 1999. *New approaches to crop yield insurance in developing countries.* Environmental and Production Technology Division (EPTD) Discussion Paper No. 55. Washington, DC, IFPRI, 40 pp.

Thornton, P., 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.

Tirado, M.C., Clarke, R., Jaykus, L.A., McQuatters-Gallop, A. & Frank, J.M. 2010. Climate change and food safety: a review. *Food Research International*, 43(7): 1745–1765.

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

Valenzuela, E. & Anderson, K. 2011. *Climate change and food security to 2050: a global economy-wide perspective,* Paper presented at the 55th Annual Conference of the Australian Agricultural and Resource Economics Society, 9–11February 2011.

Van der Mensbrugghe, D. 2015. *Shared Socio-Economic Pathways and Global Income Distribution.* Paper presented at the 18th Annual Conference on Global Economic Analysis, 17–19 June 2015, Melbourne, Australia.

Wiebe, K., Lotze-Campen, H., Sands, R., Tabeau, A., van der Mensbrugghe, D., Biewald, A., Bodirsky, B., Islam, S., Kavallari, A., Mason-D'Croz, D., Müller, C., Popp, A., Robertson, R., Robinson, S., van Meijl, H. & Willenbockel, D. 2015. Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios, *Environmental Research Letters,* 10(08): 1–15.

Williams, A.P., Allen, C.D., Macalady, A.K., Griffin, D., Woodhouse, C.A., Meko, D.M., Swetnam, T.W., Rauscher, S.A., Seager, R., Grissino-Mayer, H.D., Dean, J.S., Cook, E.R., Gangodagamage, C., Cai, M. & McDowell, N.G. 2013. Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Climate Change*, 3: 292–297.

Wollenberg, E., Richards, M., Smith, P., Havlik, P., Obersteiner, M., Tubiello, F.N., Herold, M., Gerber, P., Carter, S., Reisinger, A., van Vuuren, D., Dickie, A., Neufeldt, H., Sander, B.O., Wassman, R., Sommer, R., Amonette, J.E, Falcucci, A., Herrero, M., Opio, C., Roman-Cuesta, R., Stehfest, E., Westhoek, H., Ortiz-Monasterio, I., Sapkota, T., Rufino, M.C., Thornton, P.K., Verchot, L., West, P.C., Soussana, J.-F., Baedeker, T., Sadler, M., Vermeulen, S. & Campbell, B.M. 2016. Reducing emissions from agriculture to meet 2 °C target. *Global Change Biology.* In press.

World Bank. 2010. *World Development Report 2010. Development and climate change.* Washington, DC.

Yohe, G.W., Lasco, R.D., Ahmad, Q.K., Arnell, N.W., Cohen, S.J., Hope, C., Janetos, A.C. & Perez, R.T. 2007. Perspectives on climate change and sustainability. *In:* M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden & C.E. Hanson, eds. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK, Cambridge University Press, pp. 811–841.

CHAPTER 3

Acosta, M., Ampaire, E., Okolo, W. & Twyman, J. 2015. *Gender and climate change in Uganda: effects of policy and institutional frameworks.* CCAFS Info Note. Copenhagen, CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

Agwu, J. & Okhimamwe, A.A. 2009. *Gender and climate change in Nigeria.* Lagos, Nigeria, Heinrich Böll Stiftung (HBS).

Altieri, M.A., Nicholls, C.I., Henao, A., Lana, M.A. 2015, Agroecology and the design of climate change-resilient farming systems, *Agronomy for Sustainable Development,* 35: 869–890.

Archer, L. & Yamashita, H. 2003. Theorizing inner-city masculinities: race, class, gender and education. *Gender and Education,* 15(2): 115–132.

Arslan, A., McCarthy, N., Lipper, L., Asfaw, S., Cattaneo, A. & Kokwe, M. 2015. Climate smart agriculture? Assessing the adaptation implications in Zambia. *Journal of Agricultural Economics,* 66(3): 753–780.

Arslan, A., McCarthy, N., Lipper, L., Asfaw, S. & Cattaneo, A. 2014. Adoption and Intensity of adoption of conservation agriculture in Zambia. *Agriculture, Ecosystem and Environment,* 187: 72–86.

Arslan, A., Lamanna, C., Lipper, L., Rosenstock, T. & Rioux, J. 2016a. *A meta-analysis on the barriers to adoption of practices with CSA potential in Africa.* Mimeo.

Arslan, A., Cavatassi, R., Alfani, F., McCarthy, N., Lipper, L. & Kokwe, M. 2016b. *Is diversification a climate-smart agriculture strategy in rural Zambia?* Contributed Paper accepted to the Seventh International Conference in Agricultural Statistics, organized by FAO and ISTAT (Italian National Institute of Statistics), Rome. (Forthcoming as FAO ESA working paper).

Asfaw, S. & Lipper, L. 2016. *Managing climate risk using climate-smart agriculture.* Rome, FAO.

Asfaw, S., McCarthy, N., Lipper, L., Arslan, A. & Cattaneo, A. 2014. *Climate variability, adaptation strategies and food security in rural Malawi.* ESA Working Paper 14-08, Rome, FAO.

Asfaw, S., McCarthy, N., Arslan, A., Lipper, L. & Cattaneo, A. 2015. Livelihood diversification and vulnerability to poverty in rural Malawi. FAO-ESA Working Paper 15-02. Rome, FAO.

Asfaw, S., McCarthy, N., Lipper, L., Arslan, A. & Cattaneo, A. 2016a. What determines farmers' adaptive capacity? Empirical evidence from Malawi. *Food Security,* Vol. 8(3): 643–664

Asfaw, S., Maggio, G. & Lipper, L. 2016. *Gender, climate shock and welfare: evidence from Malawi.* Mimeo.

Asfaw, S., Di Battista, F. & Lipper, L. 2016. Agricultural technology adoption under climate change in the Sahel: micro-evidence from Niger. *Journal of African Economies.*

Asfaw, S., Coromaldi, M. & Lipper, L. 2016. *Welfare cost of climate and weather fluctuation in Ethiopia.* Mimeo.

Asfaw, S., Mortari, A., Arslan, A., Karfakis, P. & Lipper, L. 2016b, *Welfare impacts of climate shocks: evidence from Uganda.* FAO technical report.

Barrett, C.B., Reardon, T. & Webb, C. 2001. Nonfarm income diversification and household livelihood strategies in rural Africa: concepts, dynamics, and policy implications. *Food Policy,* 26(4): 315–331.

Barrett, C.B. & Swallow, B.M. 2006. Fractal poverty traps. *World Development,* 34(1): 1–15.

Bates, B.C., Kundzewicz, Z.W., Wu, S. & Palutikof, J.P., eds. 2008. *Climate change and water.* Technical Paper of the Intergovernmental Panel on Climate Change. Geneva, Switzerland, IPCC Secretariat, 210 pp.

Baudron, F., Moti J., Oriama O. & Asheber T. 2013. Conservation agriculture in African mixed crop-livestock systems: Expanding the niche. *Agriculture, Ecosystems & Environment,* 187(4): 171–182.

Bondeau, A., Smith, P., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gert en, D., Lotze-Campen, H., Müller, C., Reichstein, M. & Smith, B. 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology,* 13: 679–706.

REFERENCES

Burney J.A., Davis S.J. & Lobell, D.B. 2010. Greenhouse gas mitigation by agricultural intensification. *Proceedings of the National Academy of Sciences*, 107: 12052–12057.

Cacho, O.J., Moss, J., Thornton, P., Herrero, M., Henderson, B. & Bodirsky, B.L. 2016. Adaptation paths for vulnerable areas Background paper prepared for The State of Food and Agriculture 2016. (unpublished).

Carter, M.R. & Barrett, C.B. 2006. The economics of poverty traps and persistent poverty: an asset-based approach. *Journal of Development Studies*, 42(2): 178–199.

Cassman, K. 1999. Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. *Proceedings of the National Academy of Sciences*, 96(11): 5952–5959.

Challinor, A.J., Koehler, A.-K., Ramirez-Villegas, J., Whitfield, S. & Das, B. 2016. Current warming will reduce yields unless maize breeding and seed systems adapt immediately. *Nature Climate Change* (in press).

Cole, S.A., Giné X. & Vickery, J.I. 2013. *How does risk management influence production decisions? Evidence from a field experiment.* World Bank Policy Research Working Paper 6546. Washington DC, World Bank.

Dankelman, I. 2008. *Gender and climate change: an introduction.* London, UK, Earthscan.

De Pinto, A., Thomas, T. & Wiebe, K. 2016. *Synthesis of recent IFPRI research on climate change impacts on agriculture and food security.* Background paper prepared for *The State of Food and Agriculture 2016*. Washington DC, IFPRI (International Food Policy Research Institute). (unpublished).

Dercon, S. 1996. Risk, crop choice, and savings. *Economic Development and Cultural Change*, (44): 485–513.

Dercon, S. & Christiaensen L. 2007. *Consumption risk, technology adoption and poverty traps: evidence from Ethiopia*. The Centre for the Study of African Economies Working Paper Series, 2007-06. Oxford, UK, Centre for the Study of African Economies.

Erickson, P., Thornton, P., Notenbaert, A., Cramer, L., Jones, P. & Herrero, M. 2011. *Mapping hotspots of climate change and food insecurity in the global tropics. Copenhagen,* CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

Fafchamps, M. 2003. *Rural poverty, risk and development.* Cheltenham, UK, Edward Elgar Publishing.

FAO. 2007. *The State of Food and Agriculture 2007. Paying Farmers for Environmental Services*. Rome.

FAO. 2009. *Food security and agricultural mitigation in developing countries: options for capturing synergies*. Rome.

FAO. 2011a. *The State of Food and Agriculture 2010–11. Women in agriculture: closing the gender gap for development*. Rome.

FAO. 2011b. *The State of the World's Land and Water Resources for Food and Agriculture (SOLAW) – Managing systems at risk*. Rome, FAO and London, Earthscan.

FAO. 2011c. *Save and Grow: a policymaker's guide to the sustainable intensification of smallholder crop production*. Rome.

FAO. 2012. *Coping with water scarcity: an action framework for agriculture and food security*. Rome.

FAO. 2013a. *Guidelines to control water pollution from agriculture in China: decoupling water pollution from agricultural production*. Rome.

FAO. 2013b. *Climate-smart agriculture source book*. Rome.

FAO. 2014a. *The State of Food and Agriculture 2014. Innovation in family farming*. Rome.

FAO. 2014b. *The Water-Energy-Food Nexus – a new approach in support of food security and sustainable agriculture*. Rome.

FAO. 2015a. *Voluntary Guidelines to Support the Integration of Genetic Diversity into National Climate Change Adaptation Planning*. Commission on Genetic Resources for Food and Agriculture. Rome.

FAO. 2015b. *The economic lives of smallholder farmers: an analysis based on household data from nine countries*. Rome.

FAO. 2015c. *The State of Food and Agriculture 2015. Social protection and agriculture: breaking the cycle of rural poverty*. Rome.

FAO. 2016a. *Climate change and food security: risks and responses*. Rome.

FAO. 2016b. *Smallholder productivity under climatic variability: Adoption and impact of widely promoted agricultural practices in Tanzania*, by A. Arslan, F. Belotti, & L. Lipper, ESA Working Paper No. 16–03. Rome.

FAO. 2016c. *Welfare impacts of climate shocks: evidence from Uganda*, by S. Asfaw, A. Mortari, A. Arslan, P. Karfakis & L. Lipper. Rome.

FAO. 2016d. *Social protection in protracted crises, humanitarian and fragile contexts. FAO's agenda for action for social protection and cash-based programmes*. Rome.

FAO & World Bank. 2011. *Climate change, water and food security*. FAO Water Reports. Rome.

FAO & World Water Council. 2015, *Towards a water and food secure future critical perspectives for policy-makers*. Rome and Marseille.

Fixen, P., Brentrup, F., Bruulsema, T.W., Garcia, F., Norton, R. & Zingore, S. 2015. Nutrient/fertilizer use efficiency: measurement, current situation and trends. *In:* P. Dreschler, P. Heffer, H. Magen, R. Mikkelsen & D. Wichelns. 2015. *Managing water and fertilizer for sustainable agricultural intensification*. Paris, International Fertilizer Industry Association (IFA), International Water Management Institute (IWMI), International Plant Nutrition Institute (IPNI), and International Potash Institute (IPI).

Goh, A.H.X. 2012. *A literature review of the gender-differentiated impacts of climate change on women's and men's assets and well-being in developing countries*. CAPRI Working Paper No. 106. Washington DC, IFPRI.

Gray, E. & A. Srinidhi. 2013. *Watershed development in India: economic valuation and adaptation considerations*. Working paper. Washington, DC, World Resources Institute.

Gumucio T. & Tafur-Rueda M. 2015. Influencing gender-inclusive climate change policies in Latin America. *Journal of Gender, Agriculture, Food Security*, 1(2): 42–61.

Hansen J.W., Mason, S.J., Sun, L. & Tall, A. 2011. Review of seasonal climate forecasting for agriculture in sub-Saharan Africa. *Experimental Agriculture*, 47(2): 205–240.

Herrero, M., Thornton, P.K., Notenbaert, A.M., Wood, S., Msangi, S., Freeman, H.A., Bossio, D., Dixon, J., Peters, M., van de Steeg, J., Lynam, J., Parthasarathy, R., Macmillan, S., Gerard, B., McDermott, J., Seré, C. & Rosegrant, M. 2010. Smart investments in sustainable food production: revisiting mixed crop-livestock systems. *Science*, 327(1): 822–825.

Herrero, M., Havlík, P., Valin, H., Notenbaert, A., Rufino, M.C., Thornton, P.K., Blümmel M, Weiss F, Grace D. & Obersteiner, M. 2013. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proceedings of the National Academy of Sciences,* 110(52): 20888–20893.

Hijioka, Y., Lin, E., Pereira, J.J., Corlett, R.T., Cui, X., Insarov, G.E., Lasco, R.D., Lindgren, E. & Surjan, A. 2014. Asia. *In:* V.R. Barros, C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea & L.L. White, eds. *Climate Change 2014: Impacts, adaptation, and vulnerability. part B: regional aspects. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK and New York, NY, USA, Cambridge University Press, pp. 1327–1370.

HLPE (High Level Panel of Experts). 2015. *Water 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, FAO.

HLPE. 2016. *Sustainable agricultural development for food security and nutrition, including the role of livestock*. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. Rome, FAO.

REFERENCES

Holmes, R. & Jones, N. 2009. *Gender inequality, risk and vulnerability in the rural economy: refocusing the public works agenda to take account of economic and social risk*. ESA Working Paper No. 11-13. Rome, FAO.

Huynh, P.T. & Resurrección, B.P. 2014. Women's differentiated vulnerability and adaptations to climate-related agricultural water scarcity in rural Central Vietnam. *Climate and Development*, 6(3): 226–237.

IIED (International Institute for Environment and Development). 2010. *Moving to adapt to climate change. Reflect & Act*. London, International Institute for Environment and Development.

IPCC (Intergovernmental Panel on Climate Change). 2001. *In:* J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell & C.A. Johnson, eds. *Climate change 2001: the scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK and New York, NY, USA, Cambridge University Press, 881pp.

Jost, C., Kyazze, F., Naab, J., Neelormi, S., Kinyangi, J., Zougmore, R., Aggarwal, P., Bhatta G., Chaudhury, M., Tapio-Bistrom M.L., Kristjanson, P. & Nelson, S. 2015. Understanding gender dimensions of agriculture and climate change in smallholder farming communities. *Climate and Development*, 8(2): 133–144.

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.

Kebede, Y. 1992. Risk taking behaviour & new technologies: the case of producers in the Central Highlands of Ethiopia. *Quarterly Journal of International Agriculture*, 31: 269–289.

Kelly, V., Adesina, A. A. & Gordon, A. 2003. Expanding access to agricultural inputs in Africa: a review of recent market development experience. *Food Policy*, 28(4): 379–404.

KNOMAD (Global Knowledge Partnership on Migration and Development). 2014. *Environmental change and migration: State of the Evidence*. KNOMAD Thematic Working Group on Environmental Change and Migration. Washington DC.

Klopper, E. & Bartman, A. 2003. Forecasts and commercial agriculture: a survey of user needs in South Africa. *In:* K. O'Brien & C. Vogel, eds. *Coping with climate variability: the use of seasonal climate forecasts in Southern Africa*, pp. 170–182. Abingdon, UK, Ashgate Publishing.

Kremen, C. & Miles, A. 2012. Ecosystem services in biologically diversified versus conventional farming systems: benefits, externalities, and trade-offs. *Ecology and Society*, 17(4): 40.

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. *Science*, 304: 1623–1626.

Lipper, L., Thorton, P., Campbell, B.M., Baedeker, T., Braimoh, A., Bwalya, M., Caron, P., Cattaneo, A., Garrity, D., Henry, K., Hottle, R., Jackson, L., Jarvis, A., Kossam, F., Mann, W., McCarthy, N., Meybeck, A., Neufeldt, H., Remington, T., Sen, P.T., Sessa, R., Shula, R., Tibu, A. & Torquebiau, E.F. 2015. Climate-smart agriculture for food security. *Nature Climate Change*, 4: 1068–1072.

Liu, J., You, L., Amini, M., Obersteiner, M., Herrero, M., Zehnder, A.J. & Yang, H. 2010. A high-resolution assessment on global nitrogen flows in cropland. *Proceedings of the National Academy of Sciences*, 107(17): 8035–8040.

Lotze-Campen, H., Müller, C., Bondeau, A., Rost, S., Popp, A. & Lucht, W. 2008. Global food demand, productivity growth, and the scarcity of land and water resources: a spatially explicit mathematical programming approach. *Agricultural Economics*, 39 (3): 325–338.

Markanday, A., Cabot-Venton, C. & Beucher, O. 2015. *Economic assessment of the impacts of climate change in Uganda. Final Study Report.* Uganda, Climate and Development Knowledge Network (CDKN).

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.

McCarthy, N., Lipper, L. & Branca, G. 2011. *Climate-Smart Agriculture: Smallholder Adoption and Implications for Climate Change Adaptation and Mitigation*. Mitigation of Climate Change in Agriculture Series 4. Rome, FAO.

McOmber, C., Bartels, W., McKune, S., Panikowski, A. & Russo, S. 2013. *Investigating climate information services through a gendered lens*. CCAFS Working Paper No. 42. Copenhagen, CCAFS.

Morduch, J. 1994. Poverty and vulnerability. *The American Economic Review*, 84(2): 221–225.

Mudombi, S. & Nhamo, G. 2014. Access to weather forecasting and early warning Information by communal farmers in Seke and Murewa Districts, Zimbabwe. *Journal of Human Ecology*, 48(3): 357–366.

Nelson, V. 2011. *Gender, generations, social protection & climate change: a thematic review*. London, ODI.

Nelson, V., Stathers, T. 2009. Resilience, power, culture, and climate: a case study from semi-arid Tanzania, and new research directions. *Gender and Development,* Vol. 17 (1): 81–95

Ngugi, R.K., Mureithi, S.M. & Kamande P.N. 2011. Climate forecast information: the status, needs and expectations among smallholder agro-pastoralists in Machakos district, Kenya. *International Journal of Current Research,* 3(11): 006–012.

Nicholls, C.I., Altieri, M.A. & Vazquez, L. 2016. Agroecology: principles for the conversion and redesign of farming systems. *Journal of Ecosystem & Ecography*, S5: 010.

O'Brien, K., Sygna, L., Naess, L.O., Kingamkono, R. & Hochobeb, B. 2000. Is Information enough? User responses to seasonal climate forecasts in Southern Africa. Oslo, *Centre for International Climate and Environmental Research (CICERO)*, University of Oslo, Report 2003:3.

ODI (Overseas Development Institute). 2015. *Cash transfers. Doing cash differently: how cash transfers can transform humanitarian aid.* Report of the High Level Panel on Humanitarian Cash Transfers, London.

OECD (Organisation for Economic Co-operation and Development). 2012. *OECD environmental outlook to 2050: the consequences of inaction*. Paris.

OECD. 2015. *The Economic consequences of climate change*. Paris.

Olinto, P., Beegle, K., Sobrado, C., & Uematsu, H. 2013. *The state of the poor: where are the poor, where is extreme poverty harder to end, and what is the current profile of the world's poor? Economic Premise No. 125. Washington, DC, World Bank.*

Oweis, T. 2014. The need for a paradigm change: agriculture in water-scarce MENA region. *In:* G. Holst-Warhaft, T. Steenhuis & F. de Châtel, eds. *Water scarcity, security and democracy: a mediterranean mosaic*. Athens, Global Water Partnership Mediterranean, Cornell University and the Atkinson Center for a Sustainable Future.

Phillips, J.G., Makaudze, E. & Unganai, L. 2001. Current and potential use of climate forecasts for resource-poor farmers in Zimbabwe. *In:* C. Rosenzweig, ed. *Impacts of El Niño and climate variability in agriculture*, pp. 87–100. *American Society of Agronomy Special Publication* (63), Madison, Wisconsin, USA.

Pinca, V. 2016. *Water management in smallholder agriculture under climate change*. Background Paper prepared for The *State of Food and Agriculture 2016*. Rome, FAO. (unpublished).

Popp, A., Calvin, K., Fujimori, S., Havlik, P., Humpenöder, F., Stehfest, E., Bodirsky, B.L. *et al.* 2016. In revision. Land use futures in the shared socio-economic pathways. *Global Environmental Change*. (forthcoming).

Poulton, C., Kydd, J. & Dorward, A. 2006. Overcoming market constraints to pro-poor agricultural growth in sub-Saharan Africa. *Development Policy Review*, 24(3): 243–277.

REFERENCES

Rasmussen, L. V., Mertz, O., Rasmussen, K., Nieto, H., Ali, A. & Maiga, I. 2014. Weather, climate, and resource information should meet the needs of Sahelian pastoralists. *Weather, Climate, and Society*, 6: 482–494.

Ricketts, T.H. 2001. Conservation biology and biodiversity. *Encyclopedia of Life Sciences*. London, MacMillan Reference Ltd.

Rosegrant, M.W., Jawoo K., Cenacchi, N., Ringler, C., Robertson, R., Fisher, M., Cox, C., Garrett, K., Perez, N.D. & Sabbagh, P. 2014. *Food security in a world of natural resource scarcity: the role of agricultural technologies*. Washington, DC, IFPRI.

Rural and Agricultural Finance Learning Lab. 2016. *Inflection point: unlocking growth in the era of farmer finance*. (Available at https://www.raflearning.org/post/inflection-point-unlocking-growth-era-farmer-finance).

Sadoff, C.W. & Muller, M. 2009. *Better water resources management: greater resilience today, more effective adaptation tomorrow*. GWP TEC Perspectives Paper. Stockholm, Global Water Partnership.

Shames, S., Wollenberg, E., Buck, L.E., Kristjanson, P., Masiga, M. & Biryahaho, B. 2012. *Institutional innovations in African smallholder carbon projects*. CCAFS Report No. 8. Copenhagen, CCAFS.

Simtowe, F. 2006. Can risk-aversion towards fertilizer explain part of the non-adoption puzzle for hybrid maize? Empirical evidence from Malawi. *Journal of Applied Sciences*, 6(7): 1490–1498.

Stern, N. 2007. *Stern Review: The economics of climate change*. Cambridge, UK, Cambridge University Press.

Stern, N. 2014. *Growth, climate and collaboration: towards agreement in Paris 2015*. Policy Paper. London, Centre for Climate Change Economics and Policy and Grantham Research Institute on Climate Change and the Environment.

Stocking, M.A. 2003. Tropical soils and food security: the next 50 years. *Science*, 302(5649): 1356–1359.

Swiderska, K., Reid, H., Song, Y., Li, J., Mutta, D., Ongogu, P., Mohamed, P., Oros, R., Barriga, S. 2011. *The role of traditional knowledge and crop varieties in adaptation to climate change and food security in SW China, Bolivian Andes and coastal Kenya*. Paper prepared for the UNU-IAS workshop on Indigenous Peoples, Marginalised Populations and Climate Change: Vulnerability, Adaptation and Traditional Knowledge, Mexico.

Tall, A., Mason, S. J., Suarez, P., Ait-Chellouche, Y., Diallo, A.A., Braman, L. & van Aalst, M. (In press). 2012. Using seasonal forecasts to guide disaster management: The experience of the Red Cross during the 2008 floods in West Africa. *International Journal of Geophysics*.

Tall, A., Kristjanson, P., Chaudhury, M., McKune, S. & Zougmoré, R. 2014. *Who gets the information? Gender, power and equity considerations in the design of climate services for farmers*. CCAFS Working Paper No. 89. Copenhagen, CCAFS.

Thornton, P. & Lipper, L. 2014. *How does climate change alter agricultural strategies to support food security?* IFPRI Discussion Paper 01340, Washington DC, IFPRI

Timmer, C.P. 2014. *Managing Structural transformation: a political economy approach*. UNU-WIDER Annual Lecture 18. Helsinki, United Nations University World Institute for Development Economics Research.

Trinh, T., Tran, N. & Cao, Q. 2016. *Climate-smart aquaculture: evidences and potentials for northern coastal area of Vietnam*. CCAFS Working Paper No. 169. Copenhagen, Denmark: CCAFS.

United Nations. 2010. *The World's Women 2010: trends and statistics*. (Available at: unstats.un.org/unsd.org).

UN-DESA (United Nations Department of Economic and Social Affairs). 2012. *World urbanization prospects, the 2011 revision*. New York, USA, United Nations.

UNDP. (United Nations Development Programme). 2010. Human Development Report 2010. *The real wealth of nations: pathways to human development. 20th Anniversary Edition*. New York, USA, Palgrave Macmillan for UNDP.

UNEP (United Nations Environment Programme). 2016. *UNEP frontiers 2016 report: emerging issues of environmental concern*. Nairobi, UNEP

Vi Agroforestry. 2015. Vi Agroforestry and climate offsetting. (Available at: http://www.viagroforestry.org/what-we-do/carbon-credit/).

Yang, X., Chen, Y., Pacenka, S., Gao, W., Zhang, M., Sui, P. & Steenhuis, T.S. 2015. Recharge and groundwater use in the North China Plain for six irrigated crops for an eleven year period. *PLoS ONE,* 10(1: e0115269.).

Watkiss, P. 2015. *A review of the economics of adaptation and climate-resilient development. Working Paper* No. 205. London, Grantham Research Institute on Climate Change and the Environment.

Wheeler, D. 2011. *Quantifying vulnerability to climate change: implications for adaptation assistance*. CGD Working Paper 240. Washington, DC, Center for Global Development.

Wiggins, S. 2016. *Agricultural and rural development reconsidered. A guide to issues and debates.* IFAD Research Series No. 1. Rome, IFAD.

Winder Rossi N., Spano F., Sabates-Wheeler R. & Kohnstamm, S. 2016. Social protection and resilience building: Supporting livelihoods in protracted crises, fragile and humanitarian contexts. FAO position paper. Rome and Brighton, UK, FAO and Institute for Development Studies.

Wollenberg, E., Richards, M., Smith, P., Havlik, P., Obersteiner, M., Tubiello, F.N., Herold, M., Gerber, P., Carter, S., Reisinger, A., van Vuuren, D., Dickie, A., Neufeldt, H., Sander, B.O., Wassman, R., Sommer, R., Amonette, J.E, Falcucci, A., Herrero, M., Opio, C., Roman-Cuesta, R., Stehfest, E., Westhoek, H., Ortiz-Monasterio, I., Sapkota, T., Rufino, M.C., Thornton, P.K., Verchot, L., West, P.C., Soussana, J.-F., Baedeker, T., Sadler, M., Vermeulen, S. & Campbell, B.M. 2016. Reducing emissions from agriculture to meet 2 °C target. *Global Change Biology.*

World Bank. 2010a. *World Development Report 2010. Development and climate change*. Washington, DC.

World Bank. 2010b. *Economics of adaptation to climate change. Synthesis Report.* Washington, DC.

World Bank. 2010c. *Vietnam: economics of adaptation to climate change*. Washington, DC.

World Bank, FAO & IFAD. 2015. *Gender in climate-smart agriculture: module 18 for gender in agriculture source-book*. Agriculture global practice. Washington, DC.

Wright, H. & Chandani, A. 2014. *Gender in scaling up community based adaptation to climate change. In:* L. Schipper, J. Ayers, H. Reid, S. Huq & A. Rahman, eds. *Community based adaptation to climate change: scaling it up*. New York, USA, Routledge.

Zhu, Y., Fen, H., Wang, Y., Li, Y., Chen, J., Hu, L. & Mundt, C.C. 2000. Genetic diversity and disease control in rice. *Nature*, 406: 718–772.

CHAPTER 4

Bajželj, B., Richards, K.S., Allwood, J.M., Smith, P., Dennis, J.S., Curmi, E. & Gilligan, C.A. 2014. Importance of food-demand management for climate mitigation. *Nature Climate Change,* 4: 924–929.

Bellarby, J. Foereid, B., Hastings, A. & Smith, P. 2008. *Cool farming: climate impacts of agriculture and mitigation potential.* Amsterdam, Greenpeace International.

Burney, J.A., Davis, S.J. & Lobell, D.B. 2010. Greenhouse gas mitigation by agricultural intensification. *Proceedings of the National Academy of Sciences,* 107: 12052–12057.

Chappell, A., Baldock, J. & Sanderman, J. 2016. The global significance of omitting soil erosion from soil organic carbon cycling schemes. *Nature Climate Change*, 6: 187–191.

CIFOR (Center for International Forestry Research) 2010. *Forests and climate change toolbox.* (Available at http://www.cifor.org/fctoolbox/).

CIFOR. Annual Report. 2015. *A new landscape for forestry.* Montpellier, France.

DEFRA. (Department for Environment, Food and Rural Affairs). 2001. Third National Communication under the United Nations Framework Convention on Climate Change. London, DEFRA.

EEA (European Environment Agency). 2016. *Renewable energy in Europe 2016: recent growth and knock-on effects.* Luxembourg, Publications Office of the European Union.

REFERENCES

EC (European Commission). 2013. *Assessing the impact of biofuels production on developing countries from the point of view of Policy Coherence for Development* - Final report. Brussels, European Commission.

Erb, K.-H., Haberl, H., Krausmann, F., Lauk, C., Plutzar, C., Steinberger, J.K., Muller, C., Boundeau, A., Waha, K. & Pollack, G. 2009. *Eating the Planet: feeding and fuelling the world sustainably, fairly and humanely – a scoping study.* Potsdam, Germany, PIK.

Erisman, J.W., Sutton, M.A., Galloway, J., Klimont, Z. & Winiwarter, W. 2008. How a century of ammonia synthesis changed the world. *Nature Geoscience*, 1: 636–639.

FAO. 2011a. *Food security through commercialization of agriculture (FSCA) project, Liberia – GTFS/LIR/010/ITA.* FAO Global Trust Fund for Food Security and Food Safety. Italian contribution, West Africa Platform.

FAO. 2011b. *The State of the World's Land and Water Resources for Food and Agriculture (SOLAW) – Managing systems at risk.* Rome, FAO and London, Earthscan.

FAO. 2011c. *Global food losses and food waste: extent, causes and prevention.* Rome.

FAO. 2011d. *"Energy-smart" food for people and climate* – an issue paper. Rome.

FAO. 2012. *State of the World's Forests 2012.* Rome.

FAO. 2013a. *Climate-smart agriculture source book.* Rome.

FAO. 2013b. *Greenhouse gas emissions from ruminant supply chains, a global life cycle assessment.* Rome.

FAO. 2014. *Walking the nexus talk – assessing the water-energy-food nexus.* Rome.

FAO. 2016a. FAOSTAT Online Data Base. (Available at http://faostat.fao.org). Rome.

FAO. 2016b. *Forty years of community-based forestry: a review of its extent and effectiveness.* FAO Forestry Paper 176. Rome.

FAO & ITPS (Intergovernmental Technical Panel on Soils). 2015. *Status of the World's Soil Resources (SWSR)* – Main Report. Rome.

FAO & FCRN (Food Climate Research Network). 2016. *Plates, pyramids, planet. Developments in national healthy and sustainable dietary guidelines: a state of play assessment.* Rome and Oxford.

Fischbeck, P.S., Tom, M.S. & Hendrickson C.T. 2016. Energy use, blue water footprint, and greenhouse gas emissions for current food consumption patterns and dietary recommendations in the US. *Environmental System.* Dec 1–12. 36(1): 92–103.

Garnett, T., Appleby, M.C., Balmford, A., Bateman, I.J., Benton, T.G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D., Herrero, M., Hoffmann, I., Smith, P., Thornton, P.K., Toulmin, C., Vermeulen, S.J., Godfray H.C.J. 2013. Sustainable Intensification in Agriculture: Premises and Policies. *Science*, 341(6141): 33–34.

Garibaldi, L.A., Carvalheiro, L.G., Vaissière, B. E., Gemmill-Herren, B., Hipólito, J., Freitas, B.M. & An, J. 2016. Mutually beneficial pollinator diversity and crop yield outcomes in small and large farms. *Science*, 351(6271): 388–391.

Garg, M.R., Sherasia, P.L., Bhanderi, B.M., Phondba, B.T., Shelke S.K. & Makkar, H.P.S. 2013. Effects of feeding nutritionally balanced rations on animal productivity, feed conversion efficiency, feed nitrogen use efficiency, rumen microbial protein supply, parasitic load, immunity and enteric methane emissions of milking animals under field conditions, *Animal Feed Science and Technology*, 179–4): 24–35.

Gerber, P.J., Vellinga, T., Opio, C. & Steinfeld, H. 2011. Productivity gains and greenhouse gas emissions intensity in dairy systems. *Livestock Science*, 139: 100–108.

Gerber, P.J., Hristov, A.N., Henderson, B., Makkar, H.P. S., Oh, J., Lee, C., Meinen, R., Montes, F., Ott, T., Firkins, J. Rotz, A., Dell, C., Adesogan, A.T., Yang, W.Z., Tricarico, J.M., Kebreab, E., Waghorn, G., Dijkstra, J. & Oosting, S. 2013a. Technical options for the mitigation of direct methane and nitrous oxide emissions from livestock – a review. *Animal*, 7: 220–34.

Gerber, P.J., Henderson, B., Opio, C., Mottet, A. & Steinfeld, H. 2013b. *Tackling climate change through livestock – a global assessment of emissions and mitigation opportunities.* Rome, FAO.

Henderson, B., Falcucci, A., Mottet, A., Early, L., Werner, B., Steinfeld, H. & Gerber, P. 2015. Marginal costs of abating greenhouse gases in the global ruminant livestock sector. *Mitigation and Adaptation Strategies for Global Change*, 1–26.

Herrero, M., Havlík, P., Valin, H., Notenbaert, A., Rufino, M.C., Thornton, P.K., Blümmel, M., Weiss, F., Grace, D. & Obersteiner, M. 2013. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proceedings of the National Academy of Sciences*, 110(52): 20888–93.

Herrick, J.E., Sala, O.E. & Jason, K. 2013. Land degradation and climate change: A sin of omission? *Frontiers in Ecology and the Environment,* 11: 283.

Houghton, R. A. 2012. Historic changes in terrestrial carbon storage. *In:* R. Lal, K. Lorenz, R.F. Hüttl, B.U. Schneider, J. von Braun, eds. *Recarbonization of the biosphere: ecosystems and the global carbon cycle*, pp. 59–82. Dordrecht, Netherlands, Springer.

HLPE (High Level Panel of Experts). 2014. *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, FAO.

Hristov, A.N., Oh, J., Firkins, J.L., Dijkstra, J., Kebreab, E., Waghorn, G., Makkar, H.P.S., Adesogan, A.T., Yang, W., Lee, W., Gerber, P.J., Henderson, B. & Tricarico, J.M. 2013. Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options. *Journal of Animal Science*, 91 (11): *5045–5069.*

INRA (Institut National de la Recherche Agronomique), CIRAD (Centre de Coopération Internationale en Recherche Agronomique pour le Développement) & FAO. 2016. *Feedipedia. Animal feed resources online system.* (Available at http://www.feedipedia.org/).

INRA & CIRAD. 2009. *Agrimonde: Agricultures et alimentations du monde en 2050. Scénarios et défis pour un développement durable.* Paris, Quae.

IPCC (Intergovernmental Panel on *Climate Change*). *2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.*

IPCC. 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.*

Khatiwala, S., Tanhua, T., Mikaloff Fletcher, S., Gerber, M., Doney, S.C., Graven, H.D., Gruber, N., McKinley, G. A, Murata, A., Rios, A.F. & Sabine, C.L. 2013. Global ocean storage of anthropogenic carbon. *Biogeosciences,* 10: 2169–2191.

Krausmann, F., Erb, K.-H., Gingrich, S., Haberl, H., Bondeau, A., Gaube, V., Lauka, C., Plutzar, C. & Searchinger, T. D. 2013. Global human appropriation of net primary production doubled in the 20th century. *Proceedings of the National Academy of Sciences,* 110(25): 10324–10329.

Lal, R. 2004. Carbon emission from farm operations. *Environment International,* 30: 981–990.

Lal, R. 2006. Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. *Land Degradation & Development,* 17: 197–209.

Lal, R. 2010. Enhancing eco-efficiency in agro-ecosystems through soil carbon sequestration. *Crop science*, 50 (Supplement 1): S–120.

Lal, R., Griffin, M., Apt, J., Lave, L. & Morgan, M.G. 2004. Managing soil carbon. *Science,* 304(5669: 393).

Linquist, B.A., Anders, M.M., Adviento-Borbe, M.A.A., Chaney, R.L., Nalley, L.L., Da Rosa, E.F. & Kessel, C. 2015. Reducing greenhouse gas emissions, water use, and grain arsenic levels in rice systems. *Global Change Biology,* 21(1): 407–417.

Mery, G., Katila, P., Galloway, G., Alfaro, R.I., Kanninen, M., Lobovikov, M., & Varjo, J. 2010. Forests and Society – Responding to Global Drivers of Change. World Series Volume 25. Vienna, IUFRO (International Union of Forestry Research Organizations).

REFERENCES

Mottet, A., Henderson, B., Opio, C., Falcucci, A., Tempio, G., Silvestri, S., Chesterman, S. & Gerber, P.J. 2016. Climate change mitigation and productivity gains in livestock supply chains: insights from regional case studies. *Regional Environmental Change,* 1–13.

Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N. & Foley, J.A. 2012. Closing yield gaps through nutrient and water management. *Nature,* 490(7419): 254–257.

Nellemann, C., Hain, S. & Alder, J., eds. 2008. *In dead water: merging of climate change with pollution, over harvest and infestations in the world's fishing ground.* Arendal, Norway, UNEP, GRID-Arendal.

Newbold J. 2015. *Towards the zero methane cow.* Background paper for the conference "Animal Change Final Conference", Montpellier, France, March 19, 2015.

Oenema, O., Ju, X., de Klein, C., Alfaro, M., del Prado, A., Lesschen, J.P., Zheng, X., Velthof, G., Ma, L., Gao, B., Kroeze, C. & Sutton, M. 2014. Reducing nitrous oxide emissions from the global food system. *Current Opinion in Environmental Sustainability,* 9–10: 55–64.

Oliveira Silva, R. de, Barioni, L.G., Hall, J.A.J., Folegatti, M.M., Zanett, A.T., Fernandes, F.A. & Moran, D. 2016. Increasing beef production could lower greenhouse gas emissions in Brazil if decoupled from deforestation. *Nature Climate Change.* (in press).

Opio, C., Gerber, P., Mottet, A., Falcucci, A., Tempio, G., MacLeod, M., Vellinga, T., Henderson, B. & Steinfeld, H. 2013. *Greenhouse gas emissions from ruminant supply chains: a global life cycle assessment.* Rome, FAO.

Pan G., Smith, P. & Pan, W. 2009. The role of soil organic matter in maintaining the productivity and yield stability of cereals in China. *Agriculture, Ecosystems, Environment,* 129: 344–348.

Paustian, K., Babcock, B.A., Hatfield, J., Kling, C.L., Lal, R., McCarl, B.A., McLaughlin, S., Mosier, A.R., Post, W.M., Rice, C.W. & Robertson, G.P. 2004. *Climate change and greenhouse gas mitigation: challenges and opportunities for agriculture.* Council on Agricultural Science and Technology (CAST) Task Force Report No.141. Ames, USA, CAST.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P. & Smith, P. 2016. Climate-smart soils. *Nature,* 532, 49–57.

Penuelas, J., Poulter, B., Sardans, J., Ciais, P., van der Velde, M., Bopp, L., Boucher, O., Godderis, Y., Hinsinger, P., Llusia, J., Nardin, E., Vicca, S., Obersteiner, M. & Janssens, I.A. 2013. Human-induced nitrogen-phosphorus imbalances alter natural and managed ecosystems across the globe. *Nature Communications,* 4: 2934.

Pittelkow, C.M., Liang, X., Linquist, B.A., Van Groenigen, K.J., Lee, J., Lundy, M.E. & van Kessel, C. 2015. Productivity limits and potentials of the principles of conservation agriculture. *Nature,* 517(7534): 365–368.

Putz, F.E. & Romero, C. 2015. *Futures of tropical production forests.* Occasional Paper 143. Bogor, Indonesia, CIFOR (Center for International Forestry Research).

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T. van der Leeuw, S., Rodhe, H. Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P. & Foley, J.A. 2009. A safe operating space for humanity. *Nature,* 461(7263): 472–475.

Running, S.W. 2012. Ecology. A measurable planetary boundary for the biosphere. *Science,* 337: 1458–9

Scharlemann, J.P., Tanner, E.V., Hiederer, R. & Kapos, V. 2014. Global soil carbon: understanding and managing the largest terrestrial carbon pool. *Carbon Management,* 5: 81–91.

Siikamäki, J. & Newbold, S.C. 2012. Potential biodiversity benefits from international programs to reduce carbon emissions from deforestation. *Ambio,* 2012 41(Suppl 1): 78–89.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M. & Smith, J. 2008. Greenhouse gas mitigation in agriculture, *Philosophical Transactions of the Royal Society B*, 363: 789–813.

Smith, D.M., Scaife, A.A., Boer, G.J., Caian, M., Doblas-Reyes, F.J., Guemas, V., Hawkins, E., Hazeleger, W., Hermanson, L., Ho, C.K., Ishii, M., Kharin, V., Kimoto, M., Kirtman, B., Lean, J., Matei, D., Merryfield, W.J., Müller, W.A., Pohlmann, H., Rosati, A., Wouters, B. & Wyser, K. 2013. Real-time multi-model decadal climate predictions. *Climate Dynamics*, 41(11–12): 2875–2888.

Smith P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Haberl, H., Harper, R., House, J., Jafari, M., Masera, O., Mbow, C., Ravindranath, N. H., Rice, C.W., Robledo Abad, C., Romanovskaya, A., Sperling, F. & Tubiello, F. 2014. Agriculture, Forestry and Other Land Use (AFOLU). *In:* O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel & J.C. Minx, eds. *Climate Change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK and New York, NY, USA, Cambridge University Press.

Sommer S.G., Olesen J.E., Petersen S.O., Weisbjerg M.R., Valli L., Rohde L. & Béline F. 2009. Region-specific assessment of greenhouse gas mitigation with different manure management strategies in four agroecological zones. *Global Change Biology*, 15: 2825–2837.

Sommer, R. & Bossio, D. 2014. Dynamics and climate change mitigation potential of soil organic carbon sequestration. *Journal of Environmental Management*, 144: 83–87.

Soussana, J.-F., Dumont, B. & Lecomte, P. 2015. Integration with livestock. Agroecology for food security and nutrition. Proceedings of the FAO Intenational Symposium, 18–19 September 2014, Rome, Italy. pp. 225–249. Rome, FAO.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E., Biggs, R., Carpenter, S.R, Wim de Vries, S.R, de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B. & Sörlin S. 2015. Planetary boundaries: Guiding human development on a changing planet. *Science*, 347(6223).

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., de Haan, C. 2006. *Livestock's long shadow : environmental issues and options.* Rome, FAO.

Sutton, M.A., Oenema, O., Erisman, J.W., Leip, A., van Grinsven, H. & Winiwarter W. 2011. Too much of a good thing. *Nature*, 472: 159–61.

Tilman, D., Balzer, C., Hill, J. & Befort, B.L. 2011. Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences*, 108(50): 20260–20264.

Tilman, D. & Clark, M. 2014. Global diets link environmental sustainability and human health. *Nature*, 515: 518–522.

Tukker, A., Goldbohm, R.A., de Koning, A., Verheijden, M., Kleijn, R., Wolf, O., Perez-Dominguez, I. & Rueda Cantuche, J. 2011. Environmental impacts of changes to healthier diets in Europe. *Ecological Economics, 70* (10): 1776–1788.

Van Dooren, C., Marinussen, M., Blonkb, H., Aiking, H. & Vellinga, P. 2014. Exploring dietary guidelines based on ecological and nutritional values: A comparison of six dietary patterns. *Food Policy*, 44: 36–46.

Veneman, J.B., Saetnan, E.R., Newbold, C.J. 2014. MitiGate: an on-line meta-analysis database of mitigation strategies for enteric methane emissions. (Available at: http://mitigate.ibers.aber.ac.uk).

CHAPTER 5

Antón, J., Cattaneo, A., Kimura, S. & Lankoski, J. 2013. Agricultural risk management policies under climate uncertainty. *Global Environmental Change*, 23: 1726–1736.

Arslan, A., McCarthy, N., Lipper, L., Asfaw, S. & Cattaneo, A. 2014. Adoption and intensity of adoption of conservation farming practices in Zambia. *Agriculture, Ecosystems & Environment*, 187: 72–86.

Arslan, A., Belotti, F. & Lipper, L. 2015. *Smallholder productivity under climatic variability: adoption and impact of widely promoted agricultural practices in Tanzania.* Mimeo.

REFERENCES

Arslan, A., McCarthy, N., Lipper, L., Asfaw, S., Cattaneo, A. & Kokwe, M. 2015. Climate smart agriculture? Assessing the adaptation implications in Zambia. *Journal of Agricultural Economics*, 66(3): 753–780.

Asfaw, S., Di Battista, F. & Lipper, L. 2014. *Food security impact of agricultural technology adoption under climate change: micro-evidence from Niger*. ESA Working Paper 14-12. Rome, FAO.

Asfaw, S., Coromaldi, M. & Lipper, L. 2015. *Welfare cost of weather fluctuations and climate shocks in Ethiopia*. Mimeo.

Asfaw, S., McCarthy, N., Cavatassi, Cavatassi, R., Paolantonio, A. Amare, A. & Lipper, L. 2015. *Diversification, climate risk and vulnerability to poverty: evidence from rural Malawi*. Forthcoming ESA Working Paper. Rome.

Bebber, D.P., Ramotowski, M.A.T. & Gurr, S.J. 2013. Crop pests and pathogens move polewards in a warming world. *Nature, Climate Change*, 3, 985–988.

Braatz, S. 2012. Building resilience for adaptation to climate change through sustainable forest management. *In:* A. Meybeck, J. Lankoski, S. Redfern, N. Azzu & V. Gitz, eds. *Building resilience for adaptation to climate change in the agriculture sector*. Proceedings of a joint FAO/OECD Workshop. Rome, FAO.

De Gorter, H. & Just, D.R. 2009. The economics of a blend mandate for biofuels. *American Journal of Agricultural Economy* 91(3): 738–750

Earley, J. 2009. Climate change, agriculture and international trade: Potential conflicts and opportunities. *Biores*, 3(3).

Enciso, S.R.A., Fellmann, T., Pérez Dominguez, I. & Santini, F. 2016. Abolishing biofuel policies: possible impacts on agricultural price levels price variability and global food security. *Food Policy*, 61: 9–26.

FAO. 2008. *The State of Food and Agriculture 2008. Biofuels, prospects, risks and opportunities*. Rome.

FAO. 2013. *Climate change guidelines for forest managers*. Rome.

FAO. 2016. *Climate change and food security: risks and responses*. Rome.

FAO & AgriCord. 2012. *Strength in numbers – effective forest producer organizations*. Rome, FAO.

FAO & OECD. 2012. *Building resilience for adaptation to climate change in the agriculture sector*. Proceedings of a joint FAO/OECD Workshop. Meybeck, A., Lankoski, J., Redfern, S. Azzu, N. & Gitz, V. Rome.

Fixen, P., Brentrup, F., Bruulsema, T.W., Garcia, F., Norton, R. & Zingore, S. 2015. Nutrient/fertilizer use efficiency: measurement, current situation and trends. *In:* P. Dreschler, P. Heffer, H. Magen, R. Mikkelsen & D. Wichelns. *Managing water and fertilizer for sustainable agricultural intensification*. Paris: International Fertilizer Industry Association (IFA), International Water Management Institute (IWMI), International Plant Nutrition Institute (IPNI), and International Potash Institute (IPI), pp. 8–38.

Gregory, P.J., Johnson, S.N., Newton, A.C. & Ingram, J.S.I. 2009. Integrating pests and pathogens into the climate change/food security debate. *Journal of Experimental Botany*, 60(10): 2827–2838.

McCarthy, M., Best, M. & Betts, R. 2010. Climate change in cities due to global warming and urban effects. *Geophysical Research Letters*, 37(9).

Meybeck, A., Azzu, N., Doyle, M. & Gitz V. 2012. Agriculture in National Adaptation Programmes of Action (NAPA). *In:* A. Meybeck, J. Lankoski, S. Redfern, N. Azzu & V. Gitz. *Building resilience for adaptation to climate change in the agriculture sector*. Proceedings of a joint FAO/OECD Workshop. Rome, FAO.

OECD. 2015. *Aligning policies for a low-carbon economy*. Paris.

OECD. 2016. *Producer and consumer support estimates database of the OECD*. (Available at: http://www.oecd.org/tad/agricultural-policies/producerandconsumersupportestimatesdatabase.htm). Paris.

Place, F. & Meybeck, A. 2013. *Food security and sustainable resource use – what are the resource challenges to food security?* Background paper for the conference "Food Security Futures: Research Priorities for the 21st Century", 11–12 April 2013, Dublin, Ireland.

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A.C., Müller, C., Arneth, A., Boote, K.J., Folberth, C., Glotter, M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T.A.M., Schmid, E., Stehfest, E., Yang, H. & Jones, J.W. 2014. Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proceedings of the National Academy of Sciences,* 111(9): 3268–3273.

Sorda, G., Banse, M. & Kemfert, C. 2010. An overview of biofuel policies across the world. *Energy Policy,* 38 (11): 6977–6988.

Thomson, L.J., Macfadyen, S. & Hoffmann, A.A. 2010. Predicting the effects of climate change on natural enemies of agricultural pests. *Biological Control,* 52 (3): 296–306.

UNFCCC (United Nations Framework Convention on Climate Change). 2015. NAMA Registry. (Available at: http://www4.unfccc.int/sites/nama/SitePages/Home.aspx).

UNFCCC. 2016a. NAPAs received by the secretariat. (Available at: http://unfccc.int/adaptation/workstreams/national_adaptation_programmes_of_action/items/4585.php).

UNFCCC. 2016b. *Focus: Mitigation – NAMAs, Nationally Appropriate Mitigation Actions.*

UNISDR (United Nations International Strategy for Disaster Reduction) and OECD. 2013. *Disaster risk reduction – donor effort. A survey of development co-operation providers.* (Available at http://www.preventionweb.net/files/34577_34577donoreffortondisasterriskreduc.pdf).

Wilkes, A., Tennigkeit, T. & Solymosi, K. 2013. *National planning for GHG mitigation in agriculture.* A guidance document. Rome, FAO.

World Bank. 2013. World Development Report 2013. *Risk and opportunity: managing risk for development.* Washington DC.

Wu, M. & Salzman, J. 2014. The next generation of trade and environment conflicts: the rise of green industrial policy. *Scolarship Law Article, Northwestern University Law Review, 108(2): 401–474.*

CHAPTER 6

Buchner, B.K., Trabacchi, C., Mazza, F., Abramskiehn, D. & David Wang. 2015. *Global Landscape of climate finance 2015.* Venice, Italy, Climate Finance Initiative.

Cambodia Climate Change Alliance. 2015. *Planning and budgeting for climate change in Ministry of Agriculture, Forestry and Fisheries.* Cambodia Climate Change Alliance Phnom Penh.

Caravani A., Nakhooda S. & Terpstra P. 2014, *The Rio markers in practice.* London and Washington, ODI and World Resources Institute.

Cattaneo, A., Lubowski, R., Busch, J., Creed, A., Strassburg, B., Boltz, F. & Ashton, R. 2010. On international equity in reducing emissions from deforestation. *Environmental Science & Policy,* 13(8): 742–753.

Conway, D., Keenlyside, P., Roe, S., Streck, C., Vargas-Victoria, G. & Varns, T. 2015. *Progress on the New York Declaration on Forests – an assessment framework and initial report.* Prepared by Climate Focus, in collaboration with Environmental Defense Fund, Forest Trends, The Global Alliance for Clean Cookstoves, and The Global Canopy Program.

DONOR Tracker. 2014. Analyzing development strategies. (Available at http://www.donortracker.org/).

FAO. 2012. *The State of Food and Agriculture. Investing in agriculture for a better future.* Rome.

Government of Cambodia. 2016. *Report on Climate Public Expenditure Review 2012–14.* Ministry of Economy and Finance, Phnom Penh.

REFERENCES

Government of Thailand. 2014. *Strengthening the governance of climate change finance in Thailand.* Country Brief.

IFPRI (International Food Policy Research Institute). 2015. *Statistics on Public Expenditures for Economic Development (SPEED).* (Available at https://www.ifpri.org/).

Mery, G., Katila, P., Galloway, G., Alfaro, R.I., Kanninen, M., Lobovikov, M., & Varjo, J. 2010. Forests and Society – Responding to Global Drivers of Change. *World Series* Volume 25. Vienna, IUFRO (International Union of Forestry Research Organizations).

Michaelowa A. & Michaelowa, K. 2011. Coding error or statistical embellishment? The political economy of reporting climate aid. *World Development,* 39 (11): 2010–2020.

Nelson, G.C., Rosegrant, M.W., Palazzo, A., Gray, I., Ingersoll, C., Robertson, R., Tokgoz, S., Zhu, T., Sulser, T.B., Ringler, C., Msangi, S. & You L. 2010. *Food security, farming, and climate change to 2050.* Washington, DC, IFPRI.

Norman, M. & Nakhooda, S. 2014. *The State of REDD+ Finance.* Washington, DC, Center for Global Development.

ODI (Overseas Development Institute). 2015. Climate Funds Update dataset. (Available at: http://www.climatefundsupdate.org/).

OECD (Organisation for Economic Co-operation and Development). 2015a. Credit Reporting System (CRS). (Available at: https://stats.oecd.org/Index.aspx?DataSetCode=CRS1).

OECD. 2015b. *Toolkit to enhance access to adaptation finance: for developing countries that are vulnerable to adverse effects of climate change, including LIDCs, SIDS and African states.* Report to the G20 Climate Finance Study Group prepared by OECD in collaboration with GEF. Paris.

United Nations. 2013. *National Accounts Main Aggregates Database.* (Available at: http://unstats.un.org/unsd/snaama/dnlList.asp).

UNDP (United Nations Development Programme). 2015. *Budgeting for climate change: how governments have used national budgets to articulate a response to climate change.* Bangkok.

World Bank. 2015. *Mainstreaming climate action within financial institutions: five voluntary principles.* (Available at http://www.worldbank.org/content/dam/Worldbank/document/Climate/5Principles.pdf).

World Bank. 2016. Making *Climate Finance Work in Agriculture.* Background paper prepared for *The State of Food and Agriculture 2016*, Washington, D.C. (unpublished).

STATISTICAL ANNEX

Abraha, M.G. & Savage, M.J. 2006. Potential impacts of climate change on grain yield of maize for the midlands of KwaZulu-Natal, South Africa. *Agriculture Ecosystems and Environment,* 115(1–4): 150–160.

Alexandrov, V. & Hoogenboom, G. 2000. The impact of climate variability and change on crop yield in Bulgaria. *Agricultural and Forest Meteorology,* 104(4): 315–327.

Arndt, C., Strzepeck, K., Tarp, F., Thurlow, J., Fant IV, C. & Wright, L. 2011. Adapting to climate change: an integrated biophysical and economic assessment for Mozambique. *African Regional Perspectives,* 6(1): 7–20.

Berg, A., Noblet-Ducoudre, M. de. Sultan, B., Langaigne, M. & Guimberteau, M. 2013. Projections of climate change impacts on potential C4 crop productivity over tropical regions. *Agricultural and Forest Meteorology,* 170: 89–102.

Brassard, J.P. & Singh, B. 2007. Effects of climate change and CO_2 increase on potential agricultural production in Southern Québec, Canada. *Climate Research,* 34: 105–117.

Brassard, J.P. & Singh, B. 2008. Impacts of climate change and CO_2 increase on crop yields and adaptation options for Southern Quebec, Canada. *Mitigation and Adaptation Strategies for Global Change*, 13: 241–265.

Butt, T.A., McCarl, B.A., Angerer, J., Dyke, P.T. & Stuth, J.W. 2005. The economic and food security implications of climate change in Mali. *Climatic Change*, 68(3): 355–378.

Calzadilla, A., Zhu, T., Rehdanz, K., Tol, R.S.J. & Ringer, C. 2009. *Economywide impacts of climate change on agriculture in Sub-Saharan Africa*. Washington, DC, International Food Policy Research Institute (IFPRI) Discussion Paper No. 873. Washington, DC, IFPRI.

Challinor, A.J., Watson, J., Lobell, D.B., Howden, S.M., Smith, D.R. & Chhetri, N. 2014. A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change*, 4: 287–291.

Chhetri, N., Easterling, W.E., Terando, A. & Mearns, L. 2010. Modeling path dependence in agricultural adaptation to climate variability and change. *Annals of the Association of American Geographers*, 100(4): 894–907.

Ciscar, J., Iglesias, A., Feyen, L., Szabo, L., Regemorter, D., Amelung, B., Nicholls, R., Watkiss, P., Christensen, O., Dankers, R., Garrote, L., Goodess, C., Hunt, A., Moreno, A., Richards, J. & Soria, A. 2011. Physical and economic consequences of climate change in Europe. *Proceedings of the National Academy of Sciences,* 108: 2678–2683.

Deryng, D., Sacks, W.J., Barford, C.C. & Ramankutty, N. 2011. Simulating the effects of climate and agricultural management practices on global crop yield. *Global Biogeochemical Cycles,* 25: GB2006.

FAO. 2016d. FAOSTAT. Online Statistical Database (retrieved 30 July 2016) (available at http://faostat.fao.org/).

Giannakopoulos, C., Le Seger, P., Bindi, M., Moriondo, M., Kostopoulou, E. & Goodess, C. 2009. Climatic changes and associated impacts in the Mediterranean resulting from a 2 °C global warming. *Global and Planetary Change*, 68: 209–224.

Hermans, C., Geijzendorffer, I., Ewert, F., Metzger, M., Vereijken, P., Woltjer, G. & Verhgen, A. 2010. Exploring the future of European crop production in a liberalized market, with specific consideration of climate climate and the regional competitiveness. *Ecological Modeling*, 221: 2177–2187.

Iqbal, M.A., Eitzinger, J., Formayer, H., Hassan, A. & Heng, L.K. 2011. A simulation study for assessing yield optimization and potential for water reduction for summer-sown maize under different climate change scenarios. *Journal of Agricultural Science*, 149: 129–143.

Izaurralde, R., Rosenberg, N.J., Brown, R.A. & Thomson, A.M. 2001. Integrated assessment of Hadley Center (HadCM2) climate-change impacts on agricultural productivity and irrigation water supply in the conterminous United States Part II. Regional agricultural production in 2030 and 2095. *Agricultural and Forest Meteorology*, 117: 97–122.

Kim, C., Lee, S., Jeong, H., Jang, J., Kim, Y. & Lee, C. 2010. *Impacts of climate change on Korean agriculture and its counterstrategies. Seoul,* Korea Rural Economic Institute.

Lal, M. 2011. Implications of climate change in sustained agricultural productivity in South Asia. *Regional Environmental Change*, 11(Suppl. 1): S79–S94.

Li, X., Takahashi, T., Nobuhiro, S. & Kaiser, H.M. 2011. The impact of climate change on maize yields in the United States and China. *Agricultural Systems*, 104(4): 348–353.

Lobell, D.B., Burke, M.B., Tebaldi, C., Mastrandrea, M.D., Falcon, W.P. & Naylor, R.L. 2008. Prioritizing climate change adaptation needs for food security in 2030. *Science*: 319: 607–610.

REFERENCES

Moriondo, M., Bindi, M., Kundzewicz, Z., Szwed, M., Chorynski, A., Matczak, P., Radziejewski, M., McEvoy, D. & Wreford, A. 2010. Impact and adaptation opportunities for European agriculture in response to climatic change and variability. *Mitigation and Adaptation in Strategies for Global Change*, 15: 657–679.

Müller, C., Bondeau, A., Popp, A., Waha, K. & Fadar, M. 2010. *Climate change impacts on agricultural yields*. Background note for the *World Development Report 2010. Development and climate change*. Potsdam Institute for Climate Impact Research (PIK), Washington, DC, World Bank.

Osborne, T.M., Rose, G. & Wheeler, T. 2013. Variation in the global-scale impacts of climate change on crop productivity due to climate model uncertainty and adaptation. *Agricultural and Forest Meteorology*, 170: 183–194.

Peltonen-Sainio, P., Jauhiainen, L. & Hakala, K. 2011. Crop responses to temperature and precipitation according to long-term multi-location trials at high-latitude conditions. *The Journal of Agricultural Science*, 149(1): 49–62.

Piao, S., Ciais, P., Huang, Y., Shen, Z., Peng, S., Li, J., Zhou, L., Liu, H., Ma, Y., Ding, Y., Friedlingstein, P., Liu, C., Tan, K., Yu, Y., Zhang, T. & Fang, J. 2010. The impacts of climate change on water resources and agriculture in China. *Nature*, 467: 43–51.

Porter, J.R., Xie, L., Challinor, A.J., Cochrane, K., Howden, S.M., Iqbal, M.M., Lobell, D.B. & Travasso, M.I. 2014. Food security and food production systems. *In:* C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea & L.L. White, eds. *Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK, and New York, USA, Cambridge University Press.

Ringler, C., Zhu, T., Cai, X., Koo, J. & Wang, D. 2010. *Climate change impacts on food security in sub-Saharan Africa*. IFPRI Discussion Paper No. 01042. Washington, DC, IFPRI.

Rowhanji, P., Lobell, D., Lindermann, M. & Ramankutty, N. 2011. Climate variability and crop production in Tanzania. *Agriculture and Forest Meteorology*, 151: 449–460.

Schlenker, W. & Roberts, M.J. 2009. Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proceedings of the National Academy of Sciences*, 106(37): 15594–15598.

Shuang-He, S., Shen-Bin, Y., Yan-Xia, Z., Yin-Long, X., Xiao-Yan, Z., Zhu-Yu, W., Juan, L. & Wei-Wei, Z. 2011. Simulating the rice yield change in the middle and lower reaches of the Yangtze River under SRES B2 scenario. *Acta Ecologica Sinica*, 31(1): 40–48.

Southworth, J., Randolph, J.C., Habeck, M., Doering, O.C., Pfeifer, R.A., Rao, D.G. & Johnston, J.J. 2000. Consequences of future climate change and changing climate variability on maize yields in the midwestern United States. *Agriculture, Ecosystems & Environment*, 82: 139–158.

Tan, Z., Tieszen, L.L., Liu, S. & Tachie-Obeng, E. 2010. Modeling to evaluate the response of savanna-derived cropland to warming-drying stress and nitrogen fertilizers. *Climatic Change*, 100: 703–715.

Tao, F. & Zhang, Z. 2010. Adaptation of maize production to climate change in North China Plain: quantify the relative contributions of adaptation options. *European Journal of Agronomy*, 33(3):103–116.

Tao, F. & Zhang, Z. 2011. Impacts of climate change as a function of global mean temperature: maize productivity and water use in China. *Climatic Change*, 105: 409–432.

Tao, F., Zhang, Z., Liu, J. & Yokozawa, M. 2009. Modelling the impacts of weather and climate variability on crop productivity over a large area: a new super ensemble-based probabilistic projection. *Agricultural and Forest Meteorology*, 149: 1266–1278.

Thornton, P.K., Jones, P.G., Alagarswamy, G. & Andresen, J. 2009. Spatial variation of crop yield response to climate change in East Africa. *Global Environmental Change*, 19: 54–65.

Thornton, P.K., Jones, P.G., Alagarswamy, G. & Andresen, J. & Herrero, M. 2010. Adapting to climate change: agricultural system and household impacts in East Africa. *Agricultural Systems*, 103: 73–82.

Thornton, P.K., Jones, P.G., Ericksen, P.J. & Challinor, A.J. 2011. Agriculture and food systems in sub-Saharan Africa in a 4 °C+ world. *Philosophical Transactions of the Royal Society A*, 369: 117–136.

Tingem, M. & Rivington, M. 2009. Adaptation for crop agriculture to climate change in Cameroon: turning on the heat. *Mitigation and Adaptation Strategies for Global Change*, 14: 153–168.

Walker, N.J. & Schulze, R.E. 2008. Climate change impacts on agro-ecosystem sustainability across three climate regions in the maize belt of South Africa. *Agriculture, Ecosystems & Environment*, 124: 114–124.

Wang, M., Li, Y., Ye, W., Bornman, J. & Yan, X. 2011. Effects of climate change on maize production, and potential adaptation measures: a case study in Jilin Province, China. *Climate Research*, 46: 223–242.

Xiong, W., Lin, E., Ju, H. & Xu, Y. 2007. Climate change and critical thresholds in China's food security. *Climatic Change*, 81: 205–221.

Xiong, W., Conway, D., Lin, E. & Holman, I. 2009. Potential impacts of climate change and climate variability on China's rice yield and production. *Climate Research*, 40: 23–35.

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