Food and Agriculture Organization
of the United Nations

Climate change and food security: risks and responses

Climate change and food security: risks and responses

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS | 2016

ISBN 978-92-5-108998-9

Contents

Acronyms

AgMIP	Agricultural Model Intercomparison and Improvement Project
AMIS	agricultural market information system
ASIS	Agricultural Stress Index System (FAO)
BPACC	Bonne Pratique Adaptation au Changement Climatique (Best CCA practices introduced by the project)
CAC	Central American Agricultural Council
CATIE	Center for Tropical Agricultural Research and Higher Education
CAU	China Agricutural University
CBSUA	Central Bicol State University of Agriculture
CCA	climate change adapation
CEPAL	Economic Commission for Latin America and the Caribbean
CCAFS	Research Program on Climate Change, Agriculture and Food
CFS	Committee on World Food Security
CGIAR	Consultative Group on International Agricultural Research
CIAT	International Center for Tropical Agriculture
CIRAD	Agricultural Research for Development
CMIP6	Coupled model intercomparison project
CORDEX3	Coordinated Regional Climate Downscaling Experiment
CPPs	Country Programming Papers
CSA	climate-smart agriculture
DA	Department for Agriculture
DAD-IS	Domestic Animal Diversity Information System
DLIS	Desert Locust Information Service
DRR	Disaster risk reduction
DRRM	Disaster risk reduction and management
EAF/EAA	ecosystem approach to fisheries and aquaculture
ENSO	El Niño-Southern Oscillation
EEZs	exclusive economic zones
FAO	Food and Agriculture Organization of the United Nations
FFS	farmer field schools
GDP	gross domestic product
GHG	greenhouse gas
GIEWS	Global Information and Early Warning System on Food and Agriculture
GIS	geographic information systems
HLPE	High Level Panel of Experts on Food Security and Nutrition
ICEM	International Centre for Environmental Management
ICTs	information and communications technologies
IDDRSI	Drought Disaster Resilience and Sustainability Initiative (IGAD)

IFAD	International Fund for Agricultural Development
IFPRI	International Food Policy Research Institute
IGAD	Intergovernmental Authority on Development
IICA	Inter-American Institute for Cooperation on Agriculture
IMFN	International Model Forest Network
INDCs	intended nationally determined contributions
IPCC	Intergovernmental Panel on Climate Change
IPPC	International Plant Protection Convention
IPPM	Integrated Pest Management Programme
IUCN	International Union for Conservation of Nature
LDC	least developed country
MAF	Ministry of Agriculture and Forestry
ME	metabolizable energy
MOSAICC	Modelling System for Agricultural Impacts of Climate Change
NANOOS	Northwest Association of Networked Ocean Observing Systems
NAPs	national adaptation plans
NAPAs	national adaptation plans of action
NGO	non-governmental organization
NPPO	National Plant Protection Organization
ODA	official development aid
OTC	over-the-counter
PACFA	Global Partnership for Climate, Fisheries and Aquaculture
PAGASA	Atmospheric, Geophysical and Astronomical Services Administration (Philippines)
PICs	Pacific island countries
PGRFA	plant genetic resources for food and agriculture
PNA	Parties to the Nauru Agreement
PP	Pratique Paysanne (farmers' traditional practices)
RCP	representative concentration pathways
RPP	Regional Programming Paper
SFDRR	Sendai Framework for Disaster Risk Reduction
SPS	Sanitary and Phytosanitary Measures
SRES	Special Report on Emission Scenarios
SSA	Africa south of the Sahara
SSC	South-South Cooperation
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
VDS	vessel day scheme
WFO	Word Farmers' Organisation
WFP	World Food Programme
WTO	World Trade Organization

Acknowledgments

The preparation of this publication has been a collaborative effort involving professionals from within several departments of FAO, under the coordination of Vincent Gitz, Alexandre Meybeck, Leslie Lipper, Cassandra De Young and Susan Braatz, and with contributions from Philippe Ankers, Aslihan Arslan, Nadine Azzu, Stephan Baas, Caterina Batello, Julie Belanger, Agnes Bernis-Fonteneau, Shakeel Bhatti, Sarah Brunel, Sally Bunning, Andrea Cattaneo, Romina Cavatassi, Mona Chaya, Remi Cluset, Keith Cressman, Toufic El-Asmar, Aziz Elbehri, Jean-Marc Faures, Irene Hoffmann, Hideki Kanamaru, Rodica Leahu, Dan Leskien, Damiano Luchetti, Chikelu Mba, Annie Monard, Stefano Mondovi, Anne Mottet, William Murray, Nicolas Picard, Eran Raizman, Natalia Winder Rossi, Federico Spano, Henning Steinfeld, Alvaro Toledo and Julia Wolf.

Suzanne Redfern provided editorial support for the text and tables, and design; Fabio Ricci for the figures.

The coordinating authors thank the following reviewers for their valuable review and comments of a pre-final draft of this publication: Modadugu Vijay Gupta, Sheryl Hendriks, Erda Lin, Gerald C. Nelson and Shivaji Pandey. Responsibility with the final content lies with the authors.

INTRODUCTION

End hunger, achieve food security and improve nutrition is at the heart of the sustainable development goals. At the same time, climate change is already impacting agriculture[1] and food security and will make the challenge of ending hunger and malnutrition even more difficult.

The effects of climate change on our ecosystems are already severe and widespread, and ensuring food security in the face of climate change is among the most daunting challenges facing humankind. While some of the problems associated with climate change are emerging gradually, action is urgently needed now in order to allow enough time to build resilience into agricultural production systems.

In spite of considerable progress, almost 800 million people are chronically undernourished, 161 million under-five year olds are estimated to be stunted. At the same time 500 million people are obese and 2 billion lack the essential micronutrients they need to lead healthy lives. Population and income increase as well as urbanization are driving increased and changing food and feed demand. FAO estimates that, to satisfy the growing demand driven by population growth and diet changes, food production will have to increase by at least 60 percent in the next decades.

According to the United Nations (2015), there are still 836 million people in the world living in extreme poverty (less than USD1.25/day). And according to the International Fund for Agricultural Development (IFAD), at least 70 percent of the very poor live in rural areas, most of them depending partly or completely on agriculture for their livelihoods. It is estimated that 500 million smallholder farms in the developing world are supporting almost 2 billion people, and in Asia and sub-Saharan Africa these small farms produce about 80 percent of the food consumed (IFAD, 2011). The rural poor often depend partly on forests for their livelihoods (World Bank, 2002). It is estimated that between 660 and 820 million people (workers and their families) depend totally or partly on fisheries, aquaculture and related industries as a source of income and support (HLPE, 2014).

"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" (World Food Summit, 1996). This definition points to four dimensions of food security: availability of food, accessibility (economically and physically), utilization (the way it is used and assimilated by the human body) and stability of these three dimensions. What is needed is not only enough food being produced globally –enough food is produced globally now but there are still almost 800 million hungry people – but that everybody has access to it, in the right quantity and quality, all the time.

Four out of the eight key risks identified by IPCC AR5 have close relations with or direct consequences to food security:

- Loss of rural livelihoods and income
- Loss of marine and coastal ecosystems, and livelihoods
- Loss of terrestrial and inland water ecosystems, and livelihoods
- Food insecurity and breakdown of food systems

This report brings together evidence from the IPCC, updated by the latest scientific findings and enriched by FAO's knowledge and experiences on the ground. It provides an overview of the cascading impacts of climate change on food security and nutrition, from physical impacts on agro-ecosystems to livelihoods and food security. It shows how the cascade of impacts acts

[1] Agriculture is to be understood here in its broad sense, covering crops and livestock production as well as forestry, fisheries and aquaculture.

on a series of vulnerabilities. It presents ways to adapt and build resilience to climate change to ensure food security and nutrition. It shows the importance to act now on climate change: to eliminate hunger; to enable the agriculture sectors to adapt to climate change; and to mitigate climate change in order to keep it at levels where it is still possible to ensure and safeguard everyone's food security and nutrition.

The aim of this paper is to provide an overview of the effects of climate change on food security and nutrition, intended as its four dimensions, and to explore ways to reduce negative impacts through adaptation and resilience. As such, the scope of the paper does not cover greenhouse gas (GHG) emissions from the agriculture sectors nor means to reduce them.

This report serves three purposes.

First, to raise awareness that climate change is already impacting the food security and nutrition of the most vulnerable, and that if action is not very quickly taken, climate change will increasingly threaten the achievement of the goal to eradicate hunger. This is one more reason for governments to take ambition action to tackle climate change in all sectors.

Second, to describe precisely the pathways by which climate change finally impacts the food security of people, and to show the range of actions needed. Understanding these pathways and the potential responses, not only agronomics, but also from social protection to strengthened international cooperation, is indispensable to ground FAO's action to eradicate hunger and malnutrition.

Third, it also aims to fuel the ongoing discussions on how to operationalize adaptation of agriculture and food systems to climate change, and to show that food security and nutrition, as well as the agriculture sectors that support it, should be a priority area of intervention. As such, it also aims to answer the adaptation needs and demands conveyed by many countries in their Intended Nationally Determined Contributions for COP21.

Chapter 1 aims to identify and describe the pathways by which climate change impacts food security and nutrition. It starts by summarizing the main effects of climate change relevant to agriculture, livelihoods and food security. It then describes the main direct and indirect impacts on the agriculture sectors. This leads to consider impacts on livelihoods. The net impacts on food security and nutrition are the result of the interaction of the physical and economic shock/stressors with the underlying vulnerabilities.

Chapter 2 reflects on how reducing vulnerabilities and building resilience can reduce the overall negative impacts on production, livelihoods and food security and nutrition. It examines various means to achieve this objective. First, by reducing vulnerability at household level through social protection and by addressing gender-specific vulnerabilities. Second, by reducing vulnerabilities in production systems, at farm level, through landscape approaches and by providing appropriate technological solutions. Third, by investing for a resilient agricultural development. Such an undertaking requires appropriate institutional arrangements and policies at local, national and international levels. The chapter concludes by synthetizing what needs to be done by the various actors, now, to enable resilient food systems for food security, now, and in the future.

A. CLIMATE CHANGE IMPACTS ON FOOD SECURITY: OVERVIEW OF LATEST KNOWLEDGE

Climate change is profoundly impacting the conditions in which agricultural activities are conducted. In every region of the world, plants, animals, and ecosystems are adapted to the prevailing climatic conditions. When these conditions change, even slightly, even in a direction that could seem more favourable, the plants and animals present will be impacted, some will become less productive, or even disappear. Some of these impacts can be easily predicted, like the direct impact of a heat wave on a specific plant at a specific moment of its growth (provided that it has been well studied enough). Others are more complex to predict, like the effect of a certain climatic change on a whole ecosystem, because each element will react differently and interact with the other. For instance, many cultivated plants react favourably, in controlled conditions, to an increase of CO_2 in the atmosphere. But at the same time many weeds also react favourably. The result, in the field, can be an increase or decrease in yield of the cultivated plant depending on weeds competing for nutriments and water and on remedial agricultural practices. Pests and diseases are likely to move, following climate change, thus arriving in areas less prepared to them, biologically and institutionally, with potentially higher negative impacts.

These additional risks on agricultural production directly translate into additional risks for the food security and nutrition of the people who directly depend on agriculture for their food and livelihood. They can also have an impact on the food security and nutrition of distant populations through price volatility and disrupted trade. As shown in Figure 1, there is thus a cascade of risks from climate changes to agro-ecosystems, to agricultural production, to economic and social consequences and finally to food security and nutrition.

This first chapter aims to show the multiple links through which climate change impacts food security and nutrition. It starts from knowledge about climate change itself, with a focus on recent knowledge improvements that are of major interest for the agriculture sectors. It then briefly recalls some of the main known impacts on crops, livestock, forestry, fisheries and aquaculture. The third section analyses the economic and social consequences of these impacts on agricultural production. The fourth section focuses on vulnerabilities (biophysical, social, institutional) to better understand the links leading from climate change to negative impacts on food security and nutrition, in order to be able to identify means to address them. The fifth section provides insight on how these translate into impacts on food security and nutrition in its four dimensions.

A.1 MAIN CLIMATE CHANGES OF IMPORTANCE FOR THE AGRICULTURE SECTORS

The latest IPCC report confirms the main findings of previous IPCC reports on the evolution of the climate as well as its main physical effects, such as consequences for land and ocean temperature change, sea-level rise and ocean acidification. It also brings better understanding of potential spatial changes in precipitation, in intensity and seasonal distribution. Moreover, improvements in modelling as well as in data collection and use enable making better projections on a medium-term perspective and at a much more localized scope. These improvements are of crucial importance to better understand and project potential impacts on agricultural systems. As stated in the Synthesis of the last IPCC report "cascading impacts of climate change can now be attributed along chains of evidence from physical climate through to intermediate systems and then to people" (IPCC, 2014a).

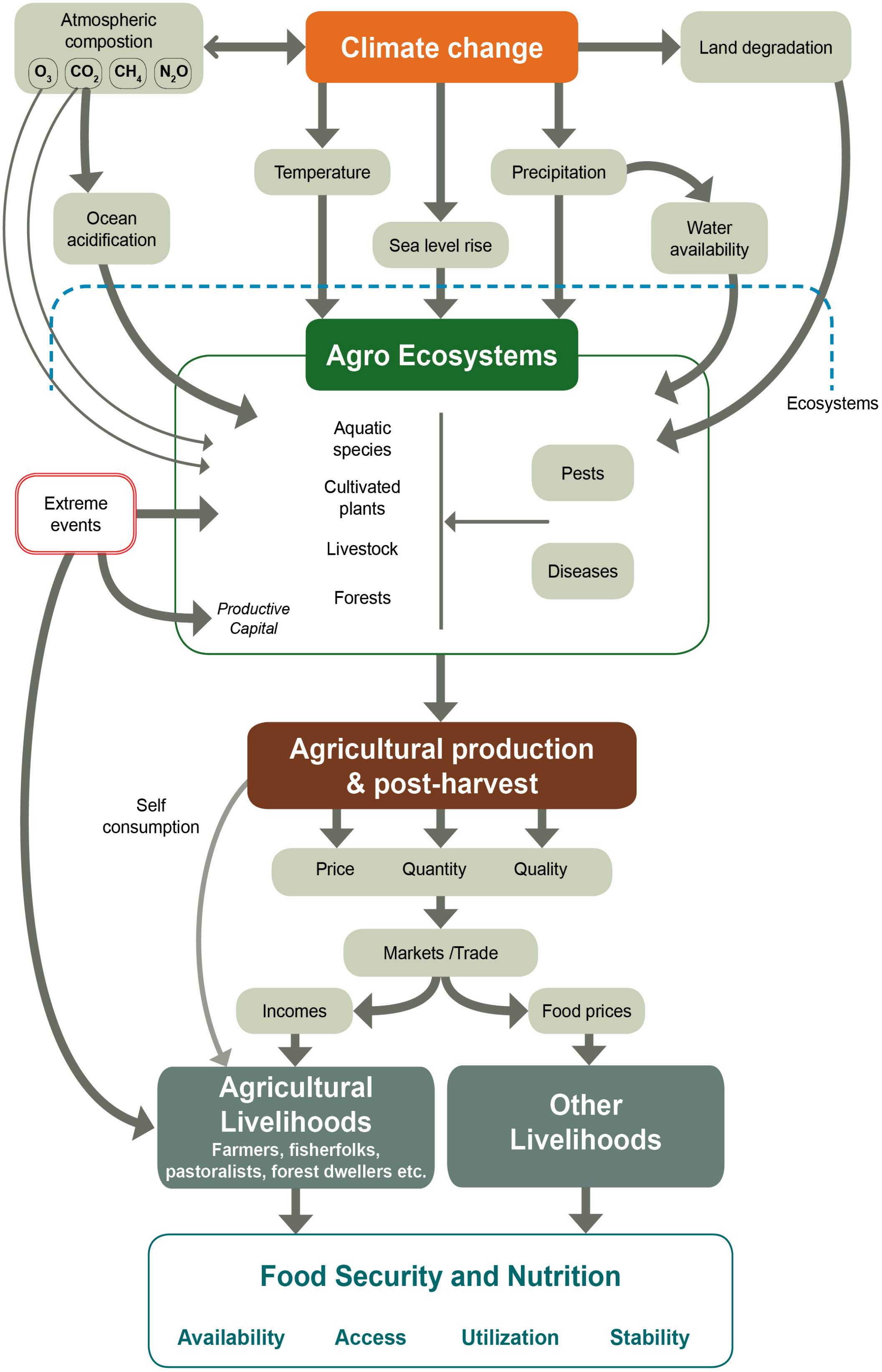


Figure 1. Schematic representation of the cascading effects of climate change impacts on food security and nutrition. A range of physical, biological and biophysical impacts bear on ecosystems and agro-ecosystems, translating into impacts on agricultural production. This has quantity, quality and price effects, with impacts on the income of farm households and on purchasing power of non-farm households. All four dimensions of food security and nutrition are impacted by these effects.

There has been an increasing understanding of the scientific basis of what we know about climate change through the five rounds of IPCC reports. The projections of climate change will be revised in the next few years as the design and organization of the next phase of the Coupled Model Intercomparison Project (CMIP6) was finalized in late 2014 (WCRP, 2014). Until CMIP6 is complete, IPCC AR5 provides the best consensus of climate chance projections. The magnitude of warming towards the end of the twenty-first century depends highly on GHG emissions for the next decades, which are driven by many socio-economic and technological factors, and climate policy. The Representative Concentration Pathways (RCPs) describe four different pathways of GHG emissions and atmospheric concentrations, air pollutant emissions and land use, from a stringent mitigation scenario (RCP2.6) to higher GHG emissions (RCP8.5) (IPCC, 2014a). In the relatively near term (up to mid-twenty-first century) climate warming is determined by historical GHG emissions, internal climate variability, aerosol, land-use change and volcanic eruptions. Decadal climate prediction (from one year to several decades in advance) is a rapidly evolving field of science and will provide useful user-oriented information soon (Meehl *et al.*, 2014).

As seawater continues to warm and glaciers and ice sheets are lost, global average sea level will rise during the twenty-first century faster than the past decades. In 2046–2065 (relative to 1986–2005), global average sea-level rise is likely in the range of 0.17 to 0.32 m and 0.22 to 0.38 m for the lowest and highest GHG concentration pathways, respectively (Church *et al.*, 2013). It is also likely that there will be a significant increase in the frequency of future sea-level extremes in some regions. Ocean acidification in the surface ocean will follow the rise of atmospheric CO_2 concentration. It is also likely that salinity will increase in the tropical and subtropical Atlantic, and a decrease in the western tropical Pacific is predicted over the next few decades.

Regional climates vary strongly by location, especially variables associated with the water cycle (e.g. precipitation). Climate models agree that the Mediterranean and Southern Africa will be drier in the future while there is less confidence in model projections in the Sahel and West Africa. Downscaling techniques (dynamical and statistical) have been applied to produce regional climate change projections. Many developed countries produce downscaled climate projections on their own.[2] There are several multimodel intercomparison projects such as the Coordinated Regional Climate Downscaling Experiment (CORDEX)[3], which covers almost all regions of the world in 14 different spatial domains. Through such initiatives, a large amount of high-resolution climate information is becoming available in regions like Africa[4] (Nikulin *et al.*, 2012; Gbobaniyi *et al.*, 2014) where localized future climate information had been scarce.

The projected change in global average temperature will likely be from 0.3 °C to 0.7 °C for the period 2016–2035 relative to the reference period 1986–2005 (Kirtman *et al.*, 2013). The increase in temperature will be larger on the land than over the ocean and larger than the mean. It will be larger in the Arctic (IPCC, 2014b). There will be more frequent hot-temperature extreme episodes over most land areas (IPCC, 2014b). Average precipitation will very likely increase in high- and parts of the mid-latitudes, and the frequency and intensity of heavy precipitation will also likely increase on average. The contrast in precipitation between wet and dry regions and between wet and dry seasons will increase. Short-duration precipitation events will shift to more intense individual storms and fewer weak storms are likely as temperature rises. Globally averaged, maximum windspeed and rates of precipitation from tropical cyclones will likely increase in the long run. In any given year, however, internal

[2] For example: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/ for the United States of America; http://www.climatechangeinaustralia.gov.au/en/climate-projections/ for Australia

[3] http://www.cordex.org

[4] http://www.cordex.org/index.php/community/domain-africa-cordex

Box 1: *El Nino*-Southern Oscillation

El Niño-Southern Oscillation (ENSO) is a recurring cycle that refers to year-to-year variations in sea-surface temperatures, convective rainfall, surface air pressure, and atmospheric circulation that occur across the equatorial Pacific Ocean. The warm phase, in which the central and east-central equatorial Pacific Ocean warms, occurs at intervals of two to seven years (*El Niño*) and alternates with an opposite cold phase (*La Niña*) (Guilyardi *et al.*, 2009). ENSO is known to affect weather events globally (teleconnection) such as, depending on location, warmer/colder or drier/wetter climate than normal conditions (potential droughts or floods), monsoon rainfall changes, and intensity and frequency of tropical cyclones. ENSO will very likely continue to be the dominant mode of interannual variability in the future (Christensen *et al.*, 2013). It is not well understood how ENSO will change in the twenty-first century, but the associated precipitation variability on regional scales is likely to increase due to larger moisture availability in the atmosphere.

natural climate variability can be large enough to mask climate-warming trends in the near-term future, especially at local scales.

The relatively large interannual climate variability in the near term underlines the importance of managing risks to food security from current climate variability and extreme weather events (see also Box 1 on *El Nino*). However, a growing body of literature also suggests current adaptations will not be sufficient for coping with long-term climate change impacts (Niang *et al.*, 2014), and the need for strengthening adaptive capacities with investment in institutional and capacity development cannot be stressed enough.

Impacts of climate change on freshwater availability

An increase in temperature will trigger increased demand for water for evapotranspiration by crops and natural vegetation and will lead to more rapid depletion of soil moisture (FAO, 2013a).

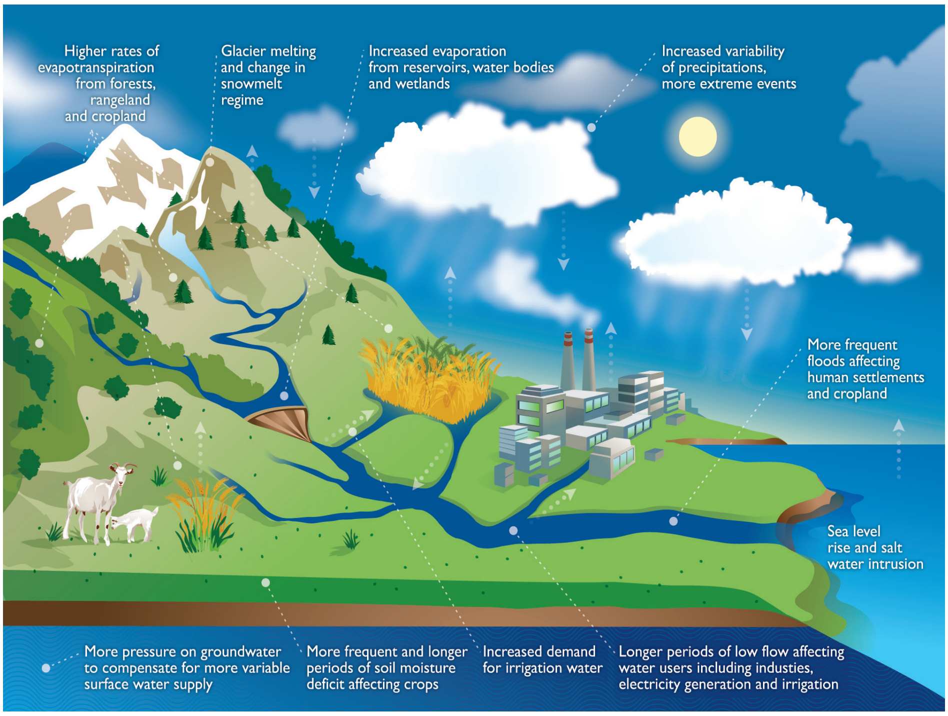


Figure 2. How climate change affects all the elements of the water cycle and its impact on agriculture.
Source: FAO (2013b)

Climate change is adding significant uncertainty to the availability of water in many regions in the future. It will affect precipitation, runoff and snow/ice melt, with effects on hydrological systems as well as on water quality, water temperature and groundwater recharge (see Figure 2). Climate change will also significantly impact sea level with potential impacts on the salinity of surface and groundwater in coastal areas.

There are a number of challenges to estimate impacts of climate change on future water availability. First, there are a series of general circulation models and global climate models available, but they result in significantly different predictions of rainfall changes, especially at finer geographical scales. Second, changes in rainfall do not linearly correlate with changes in water availability: factors such as rainfall duration and intensity, surface temperature and vegetation all play a role in determining what percentage of rainfall is converted into surface water runoff into rivers, dams and wetlands, or into groundwater. Climate change will also reduce glaciers, which often play a key role to provide river flows in summer. Current models only imperfectly capture these mechanisms, and there is a need for more research to be able to more accurately assess national, regional and local impacts of climate change on water, particularly in areas of greatest vulnerability. The impacts of changed rainfall patterns on water quality have not been sufficiently studied; heavy rainfall may well increase pollutant loadings, which would impact the quality of raw water for agriculture, industries and other uses as well as for drinking purposes, exacerbating existing access and quality problems, even with conventional treatment (Jiménez Cisneros *et al.*, 2014).

Climate change is projected to reduce renewable surface water and groundwater significantly in most dry subtropical regions (Jiménez Cisneros *et al.,* 2014). This will intensify competition for water use. According to the IPCC (2012), there is “medium confidence” that “droughts will intensify in the twenty-first century in some seasons and areas, due to a combination of more variable precipitation and/or increased evapotranspiration”. This includes central and Southern Europe and the Mediterranean region, Central North America, Mexico and Central America, Northeast Brazil and Southern Africa. Reduction of rainfall in arid and semi-arid areas will translate into a much larger reduction in river runoff. In Cyprus, for instance, studies have shown that a 13 percent reduction in rainfall translates into a 34 percent reduction in runoff (Faurès, Bernardi and Gommes, 2010).

In many regions of the world, increased water scarcity under climate change will present a major challenge for climate adaptation. Globally, dry land has doubled since the 1970s and water storage in mountain glaciers significantly contracted. Climate model simulations for the twenty-first century consistently show yearly average of precipitation, river runoff and water availability increase in high latitudes and parts of the tropics, and decrease in some subtropical and lower mid-latitude regions. Increased precipitation intensity and variability are projected to increase the risks of flooding and drought, while water supplies stored in glaciers and snow cover are projected to decline, thus modifying water availability during warm and dry periods in regions supplied by melt water from major mountain ranges. In rivers receiving their water from glacier or snowmelt, as is the case for the 40 percent of the world’s irrigation supported by flows originating from the Himalayas (FAO, 2013a), high flows will occur earlier in the year.

As a result of climate change, freshwater availability increases in regions in the temperate zones but decreases in regions in the low latitudes, including prominent agricultural and heavily irrigated areas in India, China and Egypt (Elbehri and Burfisher, 2015). Constraints on freshwater availability in heavily irrigated areas, however, may lead to large reductions in the irrigated share of overall agricultural production, amplifying direct climate change impacts and increasing weather-induced variability in these regions. Liu *et al.* (2014) modelled how future climate-induced irrigation shortage will affect crop production, food prices and the resultant effects on bilateral trade patterns. Regional irrigation shortfalls tend to boost international agricultural trade and alter its geography. Finally, adaptation to climate change needs to carefully consider competing water uses and their various implications for food security and nutrition (HLPE, 2015). Measures that can mitigate one type of adverse impact could also exacerbate another. For example, increased storage infrastructure to meet the water needs of irrigated agriculture arising from increased crop water demands, higher evapotranspiration and longer or more intense dry spells might exacerbate conflicts in river basins and negatively impact downstream fisheries.

A.2 IMPACTS ON AGRO-ECOSYSTEMS

Climate change can have both direct and indirect impacts on agricultural production systems. We qualify here as direct impacts those that are directly caused by a modification of physical characteristics such as temperature levels and distribution along the year and water availability on a specific agricultural production. Indirect effects are those that affect production through changes in other species such as pollinators, pests, disease vectors, invasive species. Direct effects are easier to predict because they can be simulated and/or easily modelled. They are now quite well projected for main staple crops. There are fewer confirmed results for many plants, livestock and aquaculture. Indirect effects, which can play a major role, particularly in less controlled environments such as for forestry and fisheries, are much more difficult to model given the high number of interacting parameters and links, many of which are often not known yet. In some cases, to predict impacts, either a reference to a comparable system under the predicted climate or to the observation of the impacts of a comparable climate change on another system can be of use.

A.2.1 Crops

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 more common than positive ones, including several periods of price spikes following climate extremes in key producing regions. There is evidence that climate change has already negatively affected wheat and maize yields in many regions and also at global level (Lobell, Schlenker and Costa-Roberts, 2011). The increased frequency of unusually hot nights in most regions is damaging for most crops, with observed impacts on rice yields and quality.

Several methods and many distinct crop models and model types can be used to estimate how future climate change will affect crop production. Convergent research results from globally consistent, multimodel climate change assessment for major crops with explicit characterization of uncertainty (Frieler *et al.*, 2015; Rosenzweig *et al.*, 2014) show that climate change will fundamentally alter global food production patterns. Negative crop productivity impacts from climate change for wheat, rice and maize – everything else being equal given present day agricultural areas, levels of management and technology – are expected in low-latitude and tropical regions, even at low levels of warming.

Impacts in the mid to high latitudes are expected to be more mixed, especially at lower levels of warming (IPCC, 2014a). Some high-latitude regions are expected to benefit – sometimes substantially – from warmer temperatures and longer growing seasons; however, other environmental conditions, such as soil quality issues in the far north, will likely constrain expansion (Porter *et al.*, 2014; FAO, 2015a). Spatial differences are also observed at regional and subregional scales, particularly where there are substantial differences in elevation. Contrasted impacts between high- and low-latitude regions indicate that climate change is likely to exacerbate existing imbalances between the developed and developing world (Elbehri, Elliott and Wheeler, 2015). Overall climate change will also increase variability in crop yields in many regions.

Effects of temperature are generally well understood up to the optimum temperature for crop development. Effects above these optimum temperatures are much less known. Studies also show a large negative sensitivity of crop yields to extreme daytime temperatures around 30 °C to 34 °C depending on the crop and region.

The effect of climate change on crop yield will depend on many parameters: temperature, precipitation patterns and atmospheric CO_2 increase given the stimulatory effect of elevated atmospheric CO_2 on plant growth (increasing the rate of leaf photosynthesis and improving the efficiency of water use) in most cases, especially for C3 crops like wheat and rice. There are uncertainties related to the interactions between CO_2, nitrogen stress and high temperature effects. The response of crops is genotype-specific. Recent results also confirm the damaging effects of elevated tropospheric ozone on crop yields, with estimates of losses for soybean, wheat and maize in 2000 ranging from 8.5 to 14 percent, 4 to 15 percent, 2.2 to 5.5 percent, respectively (Porter *et al.*, 2014).

The recent consolidated study on the impact of global climate change on agriculture, conducted in the framework of the Agricultural Model Intercomparison and Improvement Project (AgMIP) and Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP), finds that by 2100 the impact of climate change on crop yields for 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 (Müller and Elliott, 2015). Assuming full effectiveness of CO_2 fertilization, climate change impacts would then range 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 nitrogen limitations are explicitly considered, crops show less profit from CO_2 fertilization (Müller and Elliott, 2015) and amplified negative climate impacts.

A recent multimodel study using IPCC's high scenario of end-of-century radiative forcing of 8.5 W/m^2 found a mean effect on yields of four crop groups (coarse grains, oil seeds, wheat and rice, accounting for about 70 percent of global crop harvested area) of –17 percent globally by 2050 relative to a scenario with unchanging climate (Nelson *et al.*, 2014a). The hypothesis for this multimodel assessment combined the most extreme radiative forcing scenario with an assumption of limited CO_2 fertilization effects in 2050, but has not included the deleterious effects of increased ozone concentrations and biotic stresses from a range of pests and diseases, nor the likelihood of increased occurrence of extreme events.

Major agricultural producers in temperate zones, such as the European Union for wheat or the United States of America for maize, can be subject to strong negative impacts of climate change, due to: reduced water availability during the growing season; more frequent and intense heat events, which are most damaging during flowering (Müller and Elliott, 2015); and accelerated phenology, which can lead to reduced biomass production. However, these regions also tend to have more flexibility for adaptation.

Maize, sorghum and millet occupy the highest crop areas for all of Africa, but with considerable variation across regions. An International Food Policy Research Institute (IFPRI) climate change impact study on crop yields in Africa (Thomas and Rosegrant, 2015) shows significant geographical variation of impacts, indicating that, while most direct climate change impacts will be negative, there will be positive impacts on yields in some areas with projected increases in precipitation, and in some elevated areas that will be able to be cultivated due to warmer temperatures.

Several studies based on coupling climate and crop models indicate that the agro-ecological potential of the grain-producing zone of Central Eurasia may increase due to warmer temperatures, longer growing seasons, decrease of frosts and positive impact of higher atmospheric concentrations of CO_2 on crops, while other modelling experiments project the decline of agricultural potential due to increasing frequency of droughts (Lioubimtseva, Dronin and Kirilenko, 2015). Agro-ecological projections driven by climate change scenarios suggest that the grain production potential in Russian Federation, Ukraine and Kazakhstan may increase due to a combination of winter temperature increase, extension of the growing season, and CO_2 fertilization effect on agricultural crops; however, the most productive semi-arid zone could suffer a dramatic increase in drought frequency.

In a study on the likely impacts of climate change in agriculture in Norway, Uleberg *et al.* (2014) noted that, despite challenges such as unstable winters, increased autumn precipitation and possibly more weeds and diseases, a prolongation of the current short growth season together with higher growth temperatures can give new opportunities for agriculture in the region, but that it will require tailored adaptive strategies, breeding of new plant varieties, changes in sowing calendar and crop rotation, etc. – adaptive changes that seem feasible given the agronomical knowledge base in the region.

The impact on other crops and higher nutritional value products (such as roots and tubers, pulses, vegetables, fruits and other horticultural products) than the major staple crops has been much less studied (HLPE, 2012a), despite their importance for nutrition and livelihood opportunities. Earlier flowering and maturity have been observed worldwide for grapes, apples and other perennial horticultural crops (Porter *et al.*, 2014). Some recent studies suggest that cassava could benefit as it is characterized by high optimum temperature for photosynthesis and growth and a positive response to CO_2 increase. Winter chill accumulation, which is important for many fruit and nut trees, is expected to continue to decline. Several studies have projected negative impacts on apples and cherries in the United States of America. Reductions in suitability for grapevines are expected in most wine-producing regions. In Brazil, sugar cane and coffee are expected to move to more favourable zones. Suitability for coffee in Costa Rica, Nicaragua and El Salvador is expected to be reduced by 40 percent (Porter *et al.*, 2014).

Potential impacts from changes in relations between species

The models used to make projections of crop yields generally do not take into account the impacts of climate change on the functioning of ecosystems such as the balance between crops and weeds, pests, nor the effects on pollinators. These can have potentially important effects and in particular may counter-balance direct positive effects of climate change in some regions. There are, for instance, concerns that in high-latitude regions climate change will favour proliferation of pests (Uleberg *et al.*, 2014). Pests are defined as "any species, strain or biotype of plant, animal or pathogenic agent injurious to plants or plant products" (FAO, 2015b). An estimated 10–16 percent of global harvest is lost to plant pests each year. The cost of these losses is estimated to be at least USD220 billion (Chakraborty and Newton, 2011). Weeds have been noted to be the highest potential cause of losses, estimated at 36 percent (Oerke, 2006). Estimations of climate change impacts on plant health are based on three types of information: already observed effects of climate change on plant diseases, extrapolation from expert knowledge and experimental studies, and computer models (Pautasso *et al.*, 2012). Changes in climate and CO_2 concentration will enhance the distribution and increase the competitiveness of agronomically important and invasive weeds. There are important potential interactions with CO_2 and ozone concentrations, calling for specific systemic assessments.

Climate change may increase the impact of pests by allowing their establishment in areas where they could previously not establish. Changes in temperature can result in changes in geographic ranges and facilitate overwintering. Some species could therefore extend their geographic range towards the pole and to higher altitudes (Porter *et al.*, 2014; Svobodová *et al*., 2014). For instance, the increase of temperatures in the Mediterranean Basin allows the establishment of tropical species that were not able to thrive in the region so far. This is the case for water hyacinth that recently established in Sardinia, while it was thought to be confined to higher temperatures.

Climate change may also increase the impact of pests by allowing them to appear earlier in the season due to higher temperatures. Potential changes in temperature, rainfall and wind patterns associated with climate change are expected to have a dramatic effect on desert locust in Africa (see Box 2), the most dangerous of all migratory pests (Cressman, 2013). In Finland, over 70 years, earlier and more frequent epidemics of potato late blight (Hannukkala *et al.,* 2007) have been observed. In the United States of America, the potato leafhopper (Empoasca fabae) appears now on average ten days earlier than in the early 1950s, and its infestations are more severe in the warmest years. With over 200 plant species recorded as potential hosts for this pest, its earlier arrival causes millions of dollars of losses each year (Baker, Venugopal and Lamp, 2015).

Stem and stripe rusts are important diseases of wheat, and moisture, temperature and wind are the three most important weather factors affecting epidemics (Luck *et al.*, 2011). They are especially serious in the Near East, Central Asia and Eastern and Northern Africa, creating severe epidemics and causing significant losses in wheat production. With climate change, they are likely to move and arrive in areas less prepared.

Studies also predict increased generations under climate change, such as for the coffee nematode in Brazil (Ghini *et al.*, 2008) and walnut pests in California (Luedeling *et al.*, 2011), as well as for several crop pest species in Europe (Svobodová *et al.*, 2014).

Plant pests can migrate or be introduced through the millions of plants and plant products such as grain, vegetables, fruits and wood that are traded across the globe. Increased volumes and types of commodities being exported to an increasing number of countries increase the risk of pests contaminating consignments.

Importantly, negative impacts can also be expected because of the increased vulnerability of plants weakened by the direct impacts of climate change, as part of the classic triangle between plant hosts, pathogens and environment in causing disease (Pautasso *et al.*, 2012).

Changes are also occurring in the distribution and properties of pollinators and other species that make essential contributions to production through the ecosystem services they provide (FAO, 2011b). Approximately 80 percent of all flowering plant species are pollinated by animals, including vertebrates and mammals – but the main pollinators are insects. Pollinators such as bees, birds and bats affect 35 percent of the world's crop production, increasing outputs of 87 of the leading food crops worldwide, as well as many plant-derived medicines. Pollination was estimated to be worth EUR153 billion worldwide in 2015 (Gallai *et al.*, 2009) and contributes to the yield and quality of at least 70 percent of the world's major food crops, especially many nutritionally significant fruit and vegetable crops (Klein, Steffan Dewenter and Tscharntke, 2003).

Pollination depends to a large extent on the symbiosis between species, the pollinated and the pollinator. In many cases, it is the result of intricate relationships between plants and animals, and the reduction or loss of either will affect the survival of both. There is growing concern that the impact of climate change can affect this symbiosis – for example, by disrupting the synchronicity of the plant/pollinator relationship due to pollinators' sensitivity to high temperatures, together with entomophilous crop sensitivity to high temperatures/drought. In the tropics, most pollinators are already close to their optimal range of temperature tolerance (hence effects of climate change on crop pollination are expected to be most severe here).

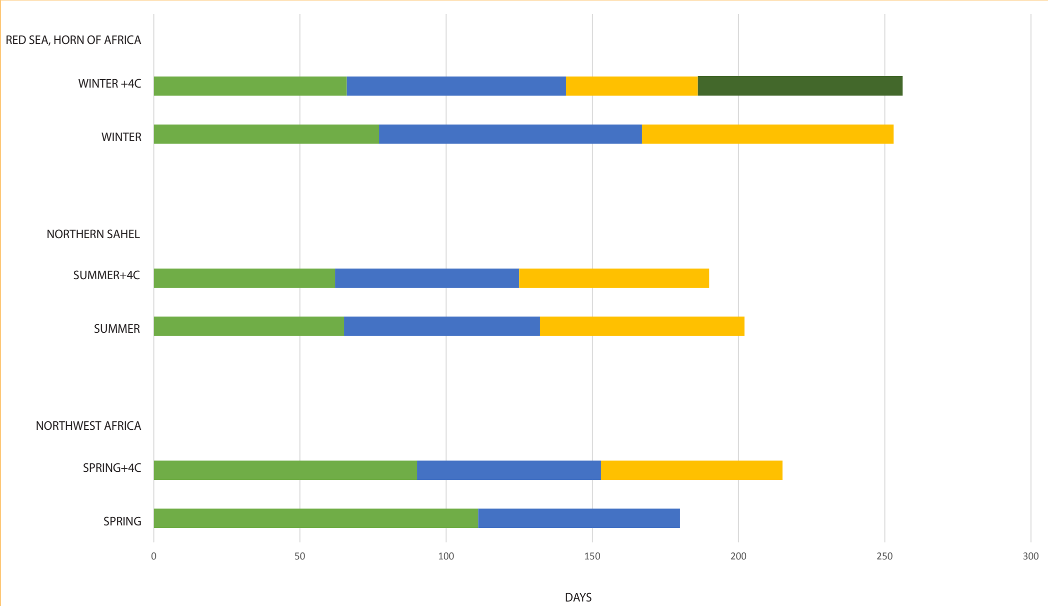
Until recently, there was a paucity of information on effects of climate change on pollinators and pollination. There is now a growing body of literature addressing the consequences of warming for phenological and distributional shifts, and some on the physiological responses of plants and insect pollinators to climate warming. A diverse assemblage of pollinators, with different traits and responses to ambient conditions, is one of the best ways of minimizing risks due to climatic change. The "insurance" provided by a diversity of pollinators ensures that there are effective pollinators not just for current conditions, but for future conditions as well. Resilience can be built in agro-ecoystems through biodiversity.

A.2.2 Livestock and pastoral systems

Of the one-third of all humankind for whom farming is a source of livelihood, about 60 percent own livestock. Nearly 800 million livestock keepers live with less than USD2 a day (FAO, 2011b). Livestock are a rapidly growing subsector, with already 40 percent of global agricultural GDP, and it is key to food security in all regions. They produce 13 percent of

Box 2: The potential impact of climate change on transboundary pests – the case of desert locust in Africa

Potential changes in temperature, rainfall and wind patterns associated with climate change are expected to have a dramatic effect on Desert Locust in Africa, the most dangerous of all migratory pests (Cressman, 2013). The greatest impacts will be caused by warmer temperatures and increased rainfall in desert areas extending from West Africa to the Horn of Africa, the Arabian Peninsula and southwest Asia. Warmer temperatures will cause locusts to mature sooner, leading to an overall shorter lifecycle of the insect, and allow seasonal breeding to commence earlier and last longer. This could result in an extra generation of breeding during the winter along the Red Sea coastal plains and in the Horn of Africa. Coupled with a general increase in precipitation or more frequent extreme high rainfall events, including tropical cyclones in the Arabian Sea, locust numbers could increase much more rapidly than at present, leading to a greater risk of outbreaks that, if uncontrolled, could

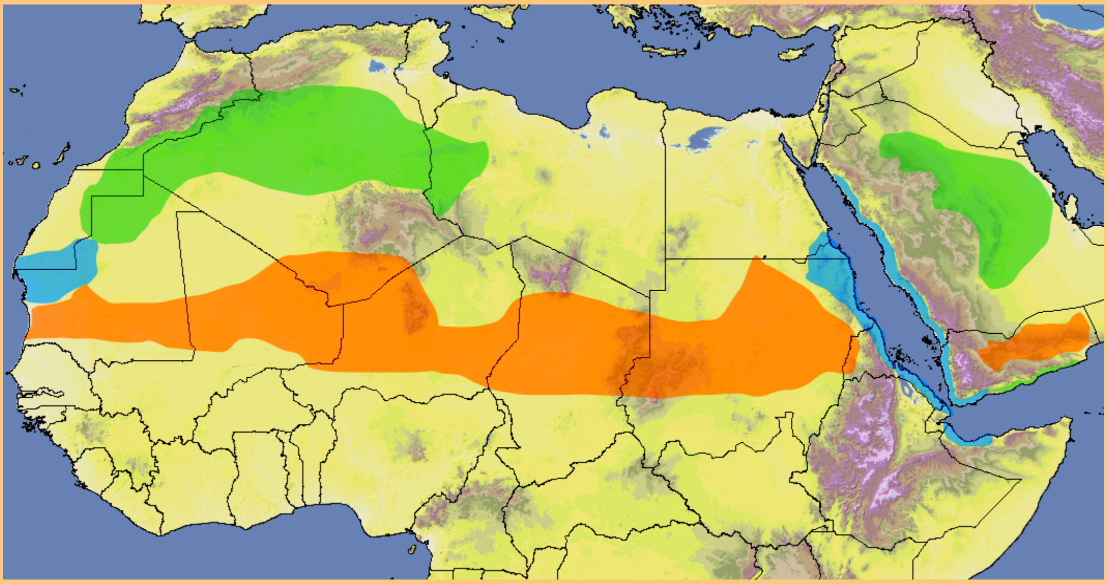


kcal consumed globally and 25 percent of protein. In mixed systems, livestock consume crop residues and by-products and produce manure used to fertilize crops. Cattle, camels, horses and donkeys also provide transport and draught power for ploughing croplands, In drylands, livestock are the only option to turn a sparse and erratic biomass resource into edible products. Livestock are a major asset among rural communities, providing a range of essential services, including saving, credit and buffering against climatic shocks and other crises. Beyond agriculture and food security, the income from livestock thus directly contributes to education and human health. In sub-Saharan Africa, more than one person in two keep livestock and one in three can be considered as poor livestock keeper (FAO, 2012a). Livestock, especially small ruminants and chicken, are also key to women's empowerment and gender equity.

Climate change affects livestock production in multiple ways, both directly and indirectly. The most important impacts are experienced in animal productivity, yields of forages and feed crops, animal health and biodiversity, as summarized in Table 1.

While impacts on labour force and/or capital allocation have not been quantified yet, individual impacts of climate change on animals and feed/forages are quantified to some extent. For example, the May 2015 heat wave with temperatures beyond 40 °C has killed more than 17 million birds in India (The Times of India, 2015). According to an industry survey, develop into plagues. Increased frequency of extreme *El Niño* and *La Niña* events due to climate change will allow greater breeding during the winter in the Horn of Africa and during the summer in the Sahel of West Africa, respectively. Any changes in wind circulation flows could allow locust adults and swarms to reach previously unaffected areas to the north, south and east of their current habitat that stretches from West Africa to India and includes the Sahara and deserts of the Near East and Southwest Asia. An understanding of climate change impacts on desert locust will lead to more robust contingency planning in affected countries for enhancing adaptation.

The figure shows the number of potential desert locust generations (bars show successive locust generations during a year, here shown by successive colours) and their length under normal and warmer (+4 °C) conditions. The map shows breeding areas: orange for summer, blue for winter; green for spring.



Source: Desert Locust Information Service (DLIS), FAO

dairy cows in the hotter Southern European countries spent more than half of the day under heat stress, resulting in an estimated milk loss of up to 5.5 kg/cow/day (FeedInfo, 2015). In Italy, Crescio *et al.* (2010) reported that high temperatures and air humidity could lead to a 60 percent increase in cattle mortality. In various countries from sub-Saharan Africa, 20 percent to 60 percent losses in animal numbers were recorded during serious drought events in the past two or three decades. In South Africa, Niang *et al.* (2014) reported that dairy yields may decrease by 10 to 25 percent under certain climate change scenarios. Another case study reported by the same authors estimated a 23 percent rise in the cost of supplying water to animals from boreholes in Botswana.

Impacts of climate change on animal health are also documented, especially for vector-borne diseases, rising temperatures increasing winter survival of vectors and pathogens. Diseases such as West Nile virus and schistosomiasis are projected to expand into new areas, so are bluetongue or Lyme. Outbreaks of Rift Valley fever in East Africa are also 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).

Impacts on feed crops and forages, and grasslands to a lesser extent, have also been quantified, despite uncertainties resulting from complex interactions between climatic

Table 1: Pathways of impacts of climate change on livestock

	Animals	Forages and feed crops	Labour force and capital
Variability in rainfall	- Shortages in drinking and servicing water - Diseases . Increased pathogens, parasites and vectors . Changed distribution and transmission . New diseases	- Decreased yields - Decreased forage quality - Changes in pasture composition (species, communities) . Changes in production system (e.g. from mixed crop-livestock to rangelands)	- Altered human health and resources allocation to livestock - Decreased productivity - Migrations - Conflicts
Temperature	- Heat stress . Decreased feed intake and livestock yields . Decreased conception rates . Altered metabolism and increased mortality - Diseases . distribution and transmission through pathogens, parasites and vectors . Decreased resistance of livestock . New diseases - Domestic biodiversity losses	- Decreased yields - Decreased forage quality - Change in pasture composition	
CO_2 in the atmosphere		- Partial stomata closure and reduced transpiration - Change in pasture composition	

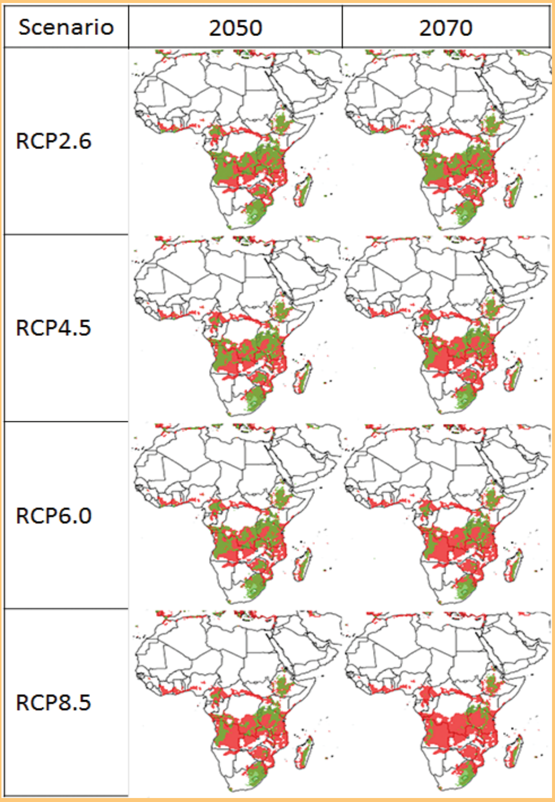
Source: from Thornton *et al.* (2009), IUCN (2010), Niang *et al.* (2014)

factors, mainly temperatures and CO_2 concentrations. Increased temperatures and reduced precipitation have direct negative impacts on yields, and records during drought events can reveal important drops in forage production, such as the 60 percent deficit of green fodder during the 2003 summer in France, for example. But climate change can also affect fodder quality through shifts from C3 to C4 plants and increased shrub cover, an increase in lignification as well as plant secondary metabolites such as tannins, alkaloids, saponins among others, and in plant tissues under higher temperatures (Wilson, Deinum and Engels, 1991). An increase in fungi and mould infestation and its prevalence in feed resources under increased variability in precipitation could impact feed and food safety.

But there is still a lack of assessments of livestock production under climate constraints to support policies that aim at improving resilience in the sector (IPCC, 2014b). In particular, modelling and quantifying aggregated impacts on livestock production systems still need to overcome a number of challenges (Thornton, Boone and Ramirez-Villegas, 2015). First, regional climate scenarios are becoming more available but are still associated with significant uncertainties, which limit our capacity to model livestock productivity under climate change. In extensive grazing and pastoral systems, impacts on rangeland primary productivity, grass species mix and carrying capacity are still mostly unknown. In addition, most models do not take into account management. Second, animal diseases are affected by climate change but future patterns of distribution should be modelled to understand their impact on scenarios and projections. Finally, the impact of groundwater availability is also an area where more assessments are needed, in particular in grazing systems.

Livestock's vulnerability depends first on their exposure to climate shocks: duration, frequency and severity of shocks, location of stock and of relevant assets such as feedstock, housing, water points etc. It also depends on their sensitivity: type of breed, of housing or feeding system, status of animal health (e.g. vaccination rate) and the importance of livestock

Box 3: The potential impact of climate change on breed distribution – an example from Kenya



The distribution of Kenyan Kamba cattle was projected, taking several temperature and humidity characteristics of their habitat and production environment into account. Future habitats were projected, based on Kenyan Kamba cattle's current geographic distribution as recorded in the Domestic Animal Diversity Information System (DAD-IS) hosted by FAO, and using the "Hadley Global Environment Model 2 – Earth System" and four of IPCC's representative concentration pathways.

Analyses of this kind can potentially contribute to more informed decision-making on breed management in a changing climate and hence strengthen the capacity of national governments, livestock keepers and farmers to protect and enhance food security and manage their animal genetic resources sustainably.

Red areas: places with habitat loss; dark green areas: places with no expected change in habitat; light green: places with habitat gain with respect to current distribution.

Source: Maps based on DAD-IS (http://fao.org/dad-is) data and the Hadley Global Environment Model 2 – Earth System and four scenarios or representative concentration pathways (RCP). In: FAO (2015c).

to the household in terms of food security and livelihoods (ICEM, 2013). In addition, a number of factors increase livestock's vulnerability to climate change, especially in semi-arid and arid regions. They include rangeland degradation, fragmentation of grazing area, changes in land tenure, conflicts and insecure access to land and finally markets (e.g. crop residues and by-products for feed, animal products).

Box 3 illustrates the potential impact of climate change on the geographical distribution of the production environment of a Kenyan cattle breed.

A.2.3 Forests

Climate change and climate variability are threatening the delivery of a range of crucial goods (wood and non-wood) and environmental services from forests on which an estimated 1.6 billion people fully or partly depend. Forests' and trees' roles are varied, including, among others, delivering clean and reliable water supply, protecting against landslides, erosion and land degradation, providing or enhancing the habitat of aquatic and terrestrial animals, providing a range of products for household use or sale, and providing employment. Given that forest resources directly contribute to more than 1 billion of the 1.2 billion people living in extreme poverty (World Bank, 2002), climate change impacts on forests can be expected to hit the poorest the hardest, thus making already vulnerable people even more so. The risks that climate change and variability pose to forests and trees are well recognized. Negative impacts are apparent in many places. Although it is often difficult to separate climate change from other stresses, evidence shows that in various places climate change is contributing to decreased productivity and dieback of trees from drought and temperature stress, increased wind and water erosion, increased storm damage, increased frequency of forest fires, pest and disease outbreaks, landslides and avalanches, changes in ranges of forest plants and animals, inundation and flood damage, saltwater intrusion and sea-level rise, and damage from coastal storms (Braatz, 2012).

Recent evidence suggests that in a wide range of forest systems, warming 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 productivity declines that have been attributed to warming-induced drought (Williams *et al.*, 2013). Where they occur, 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 been until recently an increase in growth rates, due to a combination of increasing growing season length, higher atmospheric CO_2 and nitrogen deposition and forest management (Ciais *et al.*, 2008). Recent indications point to signs of climate stress, with increasing tree mortality, changes in fire regime, insect outbreaks and pathogen attacks (Settele *et al.,* 2014). Models predict that the potential climatic space for most tree species will shift poleward and to higher altitude, faster than natural migration. For tropical forests a key uncertainty is the strength of direct CO_2 effects on photosynthesis and transpiration. Moist tropical forests have many species that are vulnerable to drought and fire-induced mortality during extreme dry periods. And there is evidence that forest fire frequency and severity is increasing, due to a combination of land-use change and drought, including in the Amazon. Climate change, deforestation, fragmentation, fire and human pressure place virtually all dry tropical forests at risk of replacement or degradation (Miles *et al.*, 2006).

A.2.4 Fisheries and aquaculture systems

Climate change, variability and extreme weather events are compounding threats to the sustainability of capture fisheries and aquaculture development in marine and freshwater environments. Impacts occur as a result of both gradual atmospheric warming and associated physical (sea surface temperature, ocean circulation, waves and storm systems) and chemical changes (salinity content, oxygen concentration and acidification) of the aquatic environment (IPCC, 2013). Extreme events such as deep sea ocean swells, particularly high temperatures and cyclones, can affect the ability of ecosystems such as coral reefs and mangroves to provide services crucial for livelihoods and food security. Climate change and carbon absorption in the aquatic systems are and will continue to manifest change in the aquatic systems through increases in water temperatures, increased thermal stratification, changes in salinity and freshwater content, changes in oxygen concentrations and ocean acidification. Coral reef systems, housing one out of four marine species, will be at increased risk due to double pressure of rising temperatures and increasing acidification. Mass coral bleaching events have been observed in, for example, the Phoenix Islands, with 100 percent of coral mortality in the lagoons and 62 percent of coral mortality on the outer leeward slopes of the Kanton Atoll in 2002–2003 (Alling *et al.,* 2007). Recently, the National Oceanic and Atmospheric Administration (NOAA) Coral Reef Watch (United States of America) has declared the third-ever global coral reef bleaching event after the preceding global events in 1998 and 2010. These global shocks, brought on by climate change and coupled with events like the 2015 *El Niño*, are the largest and most pervasive threats to coral reefs around the world (NOAA, 2015).

Since most aquatic animals are cold-blooded, their metabolic rates are strongly affected by external environmental conditions, especially temperature and available oxygen. Changes in temperature can have significant influences on the reproductive cycles of fish, including the speed at which they grow, reach sexual maturity, and the timing of spawning (Perry *et* *al.*, 2005; Pörtner, 2008). The reduction in available oxygen levels (related to the warming of surface water) will cause decreases in maximum body weight of fish species around the globe resulting in lower catch potentials in the near future. Furthermore, species intolerant to hypoxia (e.g. tuna) will see their habitat size shrink and might hence be less productive in the future (Stramma *et al.*, 2010; 2012). Various fish species are already migrating poleward resulting in the rapid 'tropicalization' of mid- and high-latitude systems. 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). Small-scale fisheries (SSF) in tropical, less developed, and economically poor regions are particularly vulnerable to climate change impacts (IPCC, 2014a). In the Mediterranean, it has been observed that invasive species from lower latitude regions have arrived in recent years at the rate of one introduction every four weeks. Most of the non-native species have been observed to migrate northward by an average of 300 km since the 1980s, trying to follow their natural chemical and physical habitat (Streftaris, Zenetos and Papathanassiou, 2005). The increasing pressure on aquatic resources through climatic drivers and human stressors such as pollution and overfishing could result in a serious shortage of capture fisheries production. In addition to the gradual development of climate change-related drivers, variability events (e.g. *El Niño*) and extreme events (e.g. floods, droughts, storms) are likely to affect the stability of marine and freshwater resources adapted to or affected by these. For example, rising sea levels and floods displace brackish and freshwaters in river deltas, wiping out some aquaculture practices and destroying wetlands.

The share of fish raised or caught in inland waters represented about 40 percent of total apparent fish consumption in 2013. The bulk of the reported production (95.5 percent) from inland capture fisheries is produced in least developed or developing countries and consumed locally (World Bank/FAO/Worldfish Center, 2010), with certain notable exceptions, e.g. Nile perch from Lake Victoria (Eggert, Greaker and Kidane, 2015). In fact, 45 percent of the reported capture fish production in the least developed countries is coming from inland fisheries. IPCC (2013) highlights that the observed and projected impacts of climate change on freshwater systems and their management are mainly due to increases in temperature and sea level, local changes of precipitation and changes in the variability of those quantities.

That the production from inland fisheries is threatened by changes in precipitation and water management and the frequency and intensity of extreme climate events (Brander, 2007) is clear. Importantly, abundance and species diversity of riverine fishes are particularly sensitive to disturbances, since lower dry season water levels reduce the number of individuals able to spawn successfully and many fish species are adapted to spawn in synchrony with the flood pulse to enable their eggs and larvae to be transported to nursery areas on floodplains. River ecosystems are particularly sensitive to changes in the quantity and timing of water flows, which are likely to change with climate change. Changes in river flows may be exacerbated by human efforts to retain water in reservoirs and irrigation channels (FAO, 2009a). Initial assessments show that the impacts of climate change on fisheries and aquaculture will be felt most acutely in Africa and South Asia (Allison *et al.*, 2009) and improvements in intersectoral water-use planning are required (Allison, Andrew and Oliver, 2007).

A.2.5 Genetic resources

Genetic resources for food and agriculture include the variety and variability of animals, plants and micro-organisms used by farmers, pastoralists, forest dwellers and fishers to provide food and non-food agriculture products and sustain the ecosystem structures, functions and processes in and around production systems. Genetic resources for food and agriculture can play a central role in meeting the challenges of climate change to food security and nutrition, and in maintaining and improving agricultural productivity, rural livelihoods, sustainability and resilience (FAO, 2015a; Asfaw and Lipper, 2011).

Climate change is also one of the key drivers of the erosion of genetic resources for food and agriculture, the raw materials that local communities and researchers rely upon to improve the quality and output of food production. The stressors and risks posed by climate change on the various sectors of genetic resources for food and agriculture (plants, animals, forests, aquatic resources, invertebrates and micro-organisms) are manifold.

The crop varieties, animal breeds or fish and forest species populations that will be required for the changing climate conditions will have to come from the existing pool of genetic resources for food and agriculture. Increased tolerance to abiotic stresses (e.g. heat, drought, flooding, frost, rising water temperatures) will be needed and new varieties, breeds and populations adapted to higher production temperatures and to increased or decreased amounts of rainfall are already being developed around the world. However, climate change is also threatening the strategic reservoir of crop and livestock genetic resources from which to breed the varieties that will be needed to adapt production systems to future challenges. As conditions change, varieties and breeds may be abandoned by farmers and livestock keepers, and may be lost forever. Catastrophic extreme weather events such as floods and droughts, which in many parts of the world are expected to become more frequent because of climate change, can pose an immediate threat to the survival of breeds and varieties that are raised only in specific small geographical areas. Forest tree populations are unlikely to be able to migrate sufficiently quickly to keep pace with the changing climate (Loo *et al.*, 2011). They will therefore have to adapt in situ, relying on their phenotypic plasticity and genetic diversity. Some scientists think that many tree populations will be able to cope relatively well with the effects of climate change. Others foresee significant problems. Predictions for tropical tree species tend to be more pessimistic than those for temperate and boreal species.

The vital contributions that micro-organisms and invertebrate genetic resources make to agriculture and food production (creation and maintenance of soils, pollination, biological control of pests, etc.) are often overlooked (Beed *et al.*, 2011; Cock *et al.*, 2011). These organisms also play key roles in the carbon cycle and are therefore vitally important to climate change mitigation efforts. Changes to temperature and moisture regimes and to atmospheric CO_2 levels affect these organisms and their capacities to provide ecosystem services. However, little is known about precisely how they will be affected by climate change.

Citrus is cultivated in more than 140 countries and is an important natural source of vitamin C. Predictions for the Mediterranean Basin indicate that reduction in annual rainfall, higher temperatures and increase of salinity and droughts resulting from climate change will seriously threaten citrus. Breeding citrus, similar to many other fruit trees, is extremely slow and inherently costly, as it takes years to evaluate fruit quality due to the natural long-term nature of tree breeding. Also the existing plantations are generally based on low genetic diversity. However, the rapid advancement of genomic science and techniques of genomic selection, along with international research cooperation, efficient use of genetic resources and innovative breeding strategies, are already opening ways for coping with climate change. Genotypes of citruses are being developed with better resilience to warming and dryness that can also suit the different requirements of consumers (e.g. fruit quality, size, easy peeling, organoleptic characteristics, etc.), producers (e.g. high yield, tree storage, etc.), and exporters (e.g. good post-harvest characteristics, etc.). We imperiously need innovative breeding strategies and a more efficient use of genetic resources to increase tolerance to climate change (Talon and Gmitter, 2008; Talon, undated).

There are more varieties of wheat than any other cereal crops – about 5 000 cultivars of bread wheat are in current use. In terms of dietary intake, wheat is one of the main food crops for human nutrition, second only to rice (FAO, 2013c). Genetic diversity of wheat has an influence on bread characteristics. The several parameters that have an influence range from protein contents, milling hardness, water absorption, and the ability to influence dough elasticity, stability and bread volume. Through techniques such as wheat genome sequencing and marker-assisted selection, researchers and breeders are routinely using the potential of disease- and fungal-resistant genes. New generation traits that are being developed, including for coping with climate change, include drought and frost resistance, nitrogen use efficiency, etc. Among the challenges that need to be addressed are: the need to keep the pace of genetic improvement with the speed of climate change; how to transfer the new knowledge and technologies at the farmer's level; to keep the pace and the level of the research in line with the new challenges; identify and harness new technologies to help make real breakthroughs in breeding; ensure the level of investment needed (Horčička, 2015).

Steps are being taken globally and in countries to ensure increased efforts for the adequate conservation and the proper use of genetic resources for food and agriculture. However, stronger and more coordinated efforts should be made to build the necessary collaboration between all the different partners that need to be involved at national and international level, to ensure that genetic resources for food and agriculture make a full and effective contribution to national adaptation planning (FAO, 2015d).

A.3 ECONOMIC AND SOCIAL CONSEQUENCES

Impacts on production directly translate in economic impacts at various scales, on the farm and in the food chain, and with social consequences. The effects of climate change are translated into social and economic consequences through a range of different pathways that can result in changes in agricultural incomes, food markets, prices and trade patterns, and investment patterns. At farm level, they can reduce incomes. They can can impact physical capital. They can force farmers to sell productive capital, for instance cattle, to absorb income shocks. They can reduce the capacity to invest. This directly bears social impacts on farming households, limiting their capacity to face other expenditures, such as health and education. At national level, they can trigger an increase in agricultural commodities' prices (food and feed), which impact the economic and social status of the whole population, particularly in countries where an important part of the household budget is spent on food. This triggers macro-economic effects for agriculture-dependent countries for which agriculture is an important part of GDP, and/or for which agriculture constitutes an important part of employment. Climatic risks can also hinder agricultural development by discouraging investments. Climatic shocks that impact a significant volume of worldwide production or an area of importance in terms of world markets have global consequences on markets: (i) quantity and price effects, with increased tension on markets; and (ii) impacts on bilateral contracts and/or import/export behaviour, with disruption of trade patterns.

These consequences can be expected to unfold over time and the progression of climate change impacts, as well as varying across different locations and sectors of the population. We must consider the effects of increasing intensity and frequency of extreme events and weather anomalies at present, and the near-term as well as longer-term impacts associated with major shifts in global warming. Estimating economic consequences of long-term global warming is difficult as it requires a reliance on the outputs from global climate modelling studies, and there is still relatively limited work in this area. Another issue is that consequences depend very much upon actions that people can take to reduce negative and enhance positive outcomes, and this is uncertain.

Impact on agricultural incomes, observed and projected

Given the high level of dependency of poor and food-insecure people on agriculture for their incomes – including rural labourers as well as family farmers and smallholder producers – the potential impacts of climate change on agricultural incomes is of considerable concern. Likewise, the potential negative impact of climate change on agricultural GDP of poor and highly agriculture-dependent economies is of considerable concern.

Table 2: Analysis of the actual impacts on crop yields

Country	Weather/Climate variable or shock	Impact on the value of crop production
Ethiopia	Rainfall-growing season	+ (7–8) %
	Temperature-growing season	+ (10–60) %
Malawi	Rainfall-growing season	+ (16–20) %
	Dry spells-growing season	– (10) %
Niger	Rainfall-growing season	+ (64–84) %
	Late onset of rains	– (42–51) %
United Republic of Tanzania	Within season rainfall variation	– (8–15) %
	Too hot growing season (>30 °C)	– (14–25) %
Zambia	Rainfall-growing season	+ (5–10) %
	Late/false onset of rains	Decreases the + impact of inorganic fertilizers by 50%
	Too hot growing season (>28 °C)	Nullifies the + impact of improved seed

Source: Arslan *et al.* (2015a); Asfaw, Coromaldi and Lipper (2015a,b); Asfaw, DiBattista and Lipper, (2015); Arslan *et al.* (2015b); Asfaw, Maggio and Lipper, (2015)

Table 2 shows examples of actual impacts on value of crop production associated with a range of climate shocks for five countries for varying years, but all in the past ten years.

Lam *et al.* (2012) have modelled the economic and social implications of climate change-induced modifications in marine fisheries species availability, in terms of landed values of fish and fisheries-related jobs, in 14 West Africa countries by 2050. Using the high range IPCC Special Report on Emission Scenarios (SRES) (IPCC, 2000) A1B scenario, they project a decrease in landed fish value of 21 percent and a total annual loss of USD311 million by 2050 over 2000 values, and a significant loss in fisheries-related jobs of almost 50 percent, down to 390 000 jobs, with Côte d'Ivoire, Ghana, Liberia, Nigeria, Sierra Leone and Togo suffering the most important impacts.

Studies conducted by the EPIC programme at FAO on the impacts of climate and weather shocks across six countries in sub-Saharan Africa show that climatic shocks have significant impacts on household welfare indicators. These studies (based on nationally representative household surveys combined with high-resolution historical data on rainfall and temperatures) use a wide variety of shock variables to characterize both long-term changes in climate variables (i.e. coefficient of variation in season rainfall, or maximum temperatures over 30 years) and short-term weather shocks (e.g. within season distribution of rainfall, within season rainfall/temperature extremes, deviations of the seasonal rainfall/temperature from the long-term averages). They also use a wide set of welfare indicators ranging from total income and agricultural income to daily calorie consumption per capita. In the United Republic of Tanzania, it has been found that an increase in the variability of rainfall in the past five to ten years is associated with about a 35 percent decrease in total income, and increased variability of temperature is associated with about an 11 percent decrease in daily calorie intake. In Malawi, the occurrence of a 1 °C drought shock (i.e. 1 degree more than the upper confidence interval of the comfort zone) induces a negative drop in overall consumption per capita by about 19.9 percent and food caloric intake by about 38.7. In Ethiopia and the Niger, both rainfall and maximum temperature variability appear to exert a negative impact on consumption expenditure, household income and food security, which points towards the absence of income-smoothing behaviour. In Uganda, however, the limited impact of climate shock on household welfare together with highly significant effects of other socio-demographic and wealth indicators could indicate a consumption and income-smoothing behaviour. In most of the countries, the most vulnerable rural households are more adversely affected by a rainfall deficit compared with the households in the top income quantile. Climate shocks affect the variability of incomes as well as its levels. Both in Malawi and in Zambia, it has been found that increased variation in seasonal rainfall (defined over 30 years) not only decreases the expected incomes but also increases its variance.

Ultimately, the impact of climate change on agricultural incomes depends on the effects on production as well as on markets and prices. As documented in above sections, the expected impacts of climate change on agricultural production are generally negative for areas with the highest concentration of poor and food-insecure smallholders and for countries with a high dependence on agriculture in the national economy. Rural poverty and hunger are concentrated in two regions: South Asia, with the greatest number of poor rural people, and Africa south of the Sahara (SSA), with the highest incidence of rural poverty and where population growth rates are still high. Agriculture in these areas is considered highly vulnerable to climate change impacts due to the limited coping capacity of the population as much as to the exposure to increased climate risks (Eriksen *et al.*, 2011). Caldzilla *et al.* (2013) estimated that with no adaptation actions taken, GDP in sub-Saharan Africa would decline by 0.2 percent by 2050 under a moderate climate change scenario (scenario B2 of the special report on emission scenarios of the IPCC), however this could be reversed and a positive growth in GDP attained if adaptation measures that generate a 25 percent increase in crop productivity were implemented.

Climate change has been found to pose risks to producer incomes in other areas as well. Bárcena *et al*. (2014) summarize the results of a series of studies of projected impacts of climate change on agricultural revenues. As shown in Table 3, the projected impacts are generally found to be negative across a wide range of locations, temperature increases and assumptions.

In another recent study modelling the potential effects of climate change on agricultural incomes across a wide range of farming systems in Central Asia, the authors found positive income gains for large-scale commercial farmers in northern Kyrgyzstan, but negative impacts for small-scale producers in arid areas of Tajikistan. The negative impacts could be further aggravated in arid zones of Central Asia if irrigation water availability declines due to climate change and water demand increases in upstream regions. The scenario simulations show that market liberalization and improved commodity exchange between the countries have very good potential to cope with the negative consequences of climate change (Bobojonov and Aw-Hassan, 2014).

Evidence from recent analyses of the impacts of various types of weather anomalies on farm income indicates the impacts are greatest for the poorest farmers.

Summarizing the results on agricultural incomes at farm and national levels, three main factors emerge. First that climate change is already having a negative impact on agricultural incomes and this is likely to continue without broad and effective adaptation measures. The second is that the negative impacts on income are hitting the poorest countries and farmers most due to both higher exposure to climate risks as well as lower adaptation capacity. Finally, effective adaptation in agriculture is expected to be able to reduce much of the negative impact on incomes.

Impact on food prices, trade and investments

Most model projections of food price impacts from climate change indicate future increases, although the magnitude and locations vary considerably across models and climate change scenarios. Food price increases are driven by population growth and rising incomes, giving rise to higher demand, as much as by negative supply impacts from climate change. According to a paper that coupled scenarios for population growth and income growth with climate

Table 3: Changes in agricultural net revenues associated with rising temperatures based on ricardian models

Author	Country	Increase in temperature (°C)	Revenue change (percentages)
Sanghi (1998)	Brazil	2.0	–5 to –11
		3.5	–7 to –14
Mendelsohn *et al.* (2000)	South America	2.0	0.18 to 0.46
Lozanoff and Cap (2006)	Argentina	2.0 to 3.0	–20 to –50
Timmins (2006)	Brazil	2.0	– 0.621
González and Velasco (2007)	Chile	2.5 and 5.0	0.74 and 1.48
Seo and Mendelsohn (2007)	South America	1.9, 3.3 and 5	–64, –38 and –20 (small farms)
			–42, –88 and –8 (large farms)
Mendelsohn and Sen (2007)	South America	1.4 to 5.1	–9.3 to –18.9
		1.3 to 3.2	–5.0 to –19.1
		0.6 to 2.0	41.5 to 49.5
Mendelsohn and Sen (2007)	South America	1.4 to 5.1	Exogenous: –6.9 to –32.9
			Endogenous: –5.4 to –28.0
		1.3 to 3.2	Exogenous: –5.7 to –17.6
			Endogenous: –4.2 to –19.0
		0.6 to 2.0	Exogenous: 4.7 to 0.1
			Endogenous: 9.7 to –1.1
Mendelsohn *et al.* (2007)	Brazil	10	–33
Seo and Mendelsohn (2008)	South America	5.1 to 2.0	–23 to –43
Seo and Mendelsohn (2008)	South America	1.9, 3.3 and 5	–14.2 to –53.0
			–14.8 to –30.2
			2.3 to –12.4
Sanghi and Mendelsohn (2010)	Brazil	1.0 to 3.5	–1.3 to –38.5
Mendelsohn *et al.* (2010)	Mexico	2.3 to 5.1	–42.6 to –54.1
Cunha *et al.* (2010)	Brazil	2.0	–14
Seo (2011)	South America	1.2, 2.0 and 2.6	–26 to 17 (private irrigation)
			–12 to –25 (public irrigation)
			–17 to –29 (dry farming)

Source: Bárcena *et al.* (2014)

change scenarios to look at the potential impacts under 15 different combinations, the mean projected price increases by 2050 are 87 percent for maize, 31 percent for rice, and 44 percent for wheat compared with 2010 levels for an optimistic scenario of low population and high income growth and using mean results from four climate scenarios (Nelson *et al.*, 2010). The lower the level of climate change, the lower the projected price increase due to reduced negative impacts on food supply.

Food price volatility is another potential impact of climate change (Porter *et al.*, 2014). Recent food price spikes often followed climate extremes in major producing countries, and have become more likely as a result of climate trends. Recent experience indicates that climate change effects on food price volatility are greatly influenced by domestic policies, with export bans contributing to price fluctuations. Another threat to the stability of food prices is that food prices are becoming more and more coupled with energy prices. This occurs because biofuel policies create a new source of demand for food, land and water. In addition, modern food systems are heavily reliant on fossil fuel energy, either directly as fuel (for pumping water, field mechanization or processing) or indirectly as a key input into the manufacture of nitrogen fertilizers (Freibauer *et al.*, 2011; Schmidhuber, 2007). This creates new risks. Volatility in energy markets is likely to cause volatility in food markets; energy shocks may become food price shocks too (FAO, 2012a).

Trade is expected to play a major role in adjusting to climate change-driven shifts in agricultural and food production patterns (Nelson *et al.*, 2010; Chomo and De Young, 2015). A study on an ensemble of ten global economic models (six general equilibrium models and four partial equilibrium models of the agriculture sector) ran coordinated scenarios to estimate the likely impacts of climate change and socio-economic drivers on international trade in agrifood commodities (Nelson *et al.,* 2014; Von Lompe *et al.*, 2014). The model results show a general agreement on an increasing role for trade under climate change, but the extent of the changes in trade varies substantially between models. However, most models also show that the net trade status of key exporting and importing countries/regions would remain the same in 2050. However, the results have only focused on a few important traded commodities and major exporters and importers. Valenzuela and Anderson (2011) also address the adaptive role of trade in a study that finds that climate change will cause a substantial 12 percent decline in the food self-sufficiency ratio of developing countries by 2050. They use a static, global computable general equilibrium (CGE) model to analyse the world economy in 2050 under two scenarios.

While trade is expected to play an increasingly important role under climate change, the negative impacts of climate change on infrastructure and transport links, as well as on economic performance of countries with a high agricultural share in the economy, raise questions on how well trade will actually be able to fulfil its role in adaptation. Ultimately, global markets will only be accessible to the poorest countries and the poorest sections of these societies if they have sufficient purchasing power. In a world where population growth, changing diets in middle-income countries and biofuels are creating new demand for food, higher food prices are likely in coming decades. Research shows that the elasticity of food demand is much lower in high-income countries than in poor countries, and that this difference in elasticity is widening over time (HLPE, 2011). In other words, when food prices rise, high- and middle-income consumers continue to purchase regardless, whereas poor consumers are forced to reduce their consumption – the burden of balancing global supply and demand falls mostly on them. In order to compete on world markets, therefore, poor countries and poor consumers will need sufficient income. This makes overall economic growth an essential (if not sufficient) part of building stable food security. In most developing countries, agriculture is the largest sector of the economy and therefore should be a major driver of this growth.

One important economic consequence of climate change may be to change investment patterns in such a way as to reduce long-term productivity and resilience of agricultural systems at household and national levels. Greater uncertainty reduces incentives to invest in agricultural production, potentially offsetting positive impacts from increasing food price trends. This is particularly true for poor family farmers and smallholders with limited or no access to credit and insurance. Greater exposure to risk, in the absence of well-functioning insurance markets, leads to: (i) greater emphasis on low-return but low-risk subsistence crops (Heltberg and Tarp 2002; Sadoulet and de Janvry, 1995; Fafchamps, 1992; Roe and Graham-Tomasi, 1986); (ii) a lower likelihood of applying purchased inputs such as fertilizer (Dercon and Christiaensen, 2011; Kassie *et al.*, 2008); (iii) a lower likelihood of adopting new technologies (Feder, Just and Zilberman, 1985; Antle and Crissman, 1990); and (iv) lower investments (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).

Impacts of extreme events, climate-related disasters.

Agriculture is one of the sectors most affected by natural hazards and disasters. The majority of the people most vulnerable to natural hazards are the world's 2.5 billion small-scale farmers, herders, fishers and forest-dependent communities, who derive their livelihood from renewable natural resources. With climate change, the risks to food and nutrition security are multiplied by the expected increase in the frequency and intensity of climate-related extremes and disasters.

Shocks and crises caused by climate extremes such as drought, floods and hurricanes destroy crops, livestock and fish resources, as well as agriculture, livestock and fishing/aquaculture infrastructure and productive assets such as irrigation systems, livestock shelters, docks, and landing and post-harvest facilities, reducing overall food production capacity. They can interrupt market access, trade and food supply, reduce income, deplete savings, erode livelihoods and increase hunger. At the same time, disasters contribute to ecosystem degradation and loss, including increased soil erosion, declining rangeland quality and salinization of soils. In turn, increasing environmental degradation reduces the availability of goods and services, and shrinks economic opportunities and livelihood options.

The magnitude of impacts of extreme events on agriculture is high. FAO's recent analysis of 78 post-disaster needs' assessments in 48 developing countries spanning the 2003–2013 period shows that 25 percent of all economic losses and damages inflicted by medium- and large-scale climate induced hazards such as droughts, floods and storms in developing countries are affecting the agriculture sector (FAO, 2015e). These figures represent only impacts reported via post-disaster needs' assessments so, while indicative of scale, the actual impact is likely to be even higher. To arrive at a closer estimate of the true financial cost of disasters to developing world agriculture, FAO compared decreases in yields during and after disasters with yield trends in 67 countries affected by medium to larger-scale events that hit 250 000 people or more, between 2003 and 2013. The final tally: USD80 billion in losses to crops and livestock, alone, over that ten-year period.

A.4 VULNERABILITIES DETERMINE THE IMPORTANCE OF THE NET IMPACT ON FOOD SECURITY AND NUTRITION

As shown above, climate change impacts directly agro-ecosystems, which in turn has a potential impact on agricultural production, which drives economic and social impacts, which impact livelihoods and food security. In other words, impact translates from climate to the environment, to the productive sphere, to economic and social dimensions. At each stage of this stress transmission chain, the impact is determined by the shock itself and vulnerability at the stage/level of the stressed system. The transmission of a stress can be amplified or reduced, depending on the vulnerabilities at each level of the system. Vulnerability can increase over time if systems/households face repeated shocks that steadily erode their base/assets. These mechanisms of transmission, and the role played by the various vulnerabilities at each level, are what determine the final impact on food security and nutrition.

The IPCC, in its synthesis report (IPCC, 2014a) notes that exposure and vulnerability are influenced by a wide range of social and economic factors and processes that have been incompletely considered to date, which make quantitative assessments difficult. It notes also that climate-related hazards exacerbate other stressors, with often negative outcomes for livelihoods, especially for people living in poverty. Both biophysical and social vulnerability are thus critical as one considers the impact of climate change on food security. Social vulnerability examines the demographic, social, economic and other characteristics of the population that affect their exposure to risk and their ability to respond to and cope with negative shocks. A social vulnerability lens is essential to understand why certain individuals, households or communities experience differences in impacts even when they are in the same geographic region.

Understanding food-security vulnerability to climate change is key to understanding net climate impacts on food security, but also to framing ways to adapt as when climate risks are given, means to reduce the net climate change impact goes by reducing vulnerabilities.

Food security vulnerabilities to climate change

The food systems on which food security depends are subject to risks of various nature. These risks can impact directly the four dimensions of food security and nutrition: agricultural production (availability), access to food (sufficient income), utilization (nutrition, quality), and stability). They include climatic risks themselves and, as shown above, many other risks that are, in turn, influenced by climate change, or that may combine with climate change-induced risks and have compensative, cumulative or amplifying effects.

The net impact of a climatic shock on food security depends not only on the intensity of the shock but also on the vulnerability of the food system (and its subcomponents, the relationships between them) to the particular shock, i.e. the propensity or predisposition of the system to be adversely affected (IPCC, 2012). Here we focus on the "food security vulnerability" to climate change, meaning the propensity of the food system to be unable to deliver food security outcomes under climate change.

Food security vulnerabilities to climate change encompass the environmental (productive), economic and social dimensions. IPCC (2014a) has further described situations of institutional vulnerability, pointing to the key role of governance to condition vulnerabilities. Table 4 compiles main food security related vulnerabilities to different climate hazards and changes as mentioned in IPCC, 2014b.

Each of these vulnerabilities will directly increase negative impacts, and potentially increase their consequences. In a given system, shocks in one dimension can spread into another dimension: for instance production shocks are transmitted in the economic and social domains. The same is true for vulnerability: vulnerability in one domain is often linked, or can trigger, vulnerability in another domain.

Vulnerability can be defined as vulnerability of "what" (here: the food system and its components) to "what" (here climate risks and all the sets of risks, or a change – such as influenced by climate change in the context that they shape existing risks) (Carpenter *et al.,* 2001). Box 4 provides some examples of vulnerability analysis in the fisheries and aquaculture sector with different focus.

Obviously some characteristics of a system make it more or less vulnerable to a set of risks. A farm relying on a single crop is particularly vulnerable to a pest affecting the crop or to a price drop of the crop. On the contrary, a much diversified system is less vulnerable to both pests and price fluctuations affecting specifically one type of production. An area prone to water scarcity will be more impacted by a drought. A rainfed system in this area is more vulnerable to a drought than an irrigated one. Households totally dependent on rainfed agriculture are more vulnerable from an economic point of view to drought than households having other sources of income. If they have no assets they are more vulnerable to this reduction of income and will be more impacted, especially if there are no social protection systems. In other words, the impacts of a drought are transmitted from the biophysical dimension to the production system and finally households. This transmission can be amplified or reduced, depending on the policies and institutions that are in place.

The majority of the world's poor and food-insecure people are rural, with direct or indirect dependence on agricultural production and income for their livelihoods, and are thus directly exposed to any risk that would impact agricultural production.

Farmers, wage-workers and people working in the agriculture sectors, as well as their relatives, are more exposed to some health hazards such as zoonosis and vector-transmitted diseases as well as heat waves, all of which will be modified in intensity and frequency by climate change (WHO, 2014),

From the economic dimension of food security smallholders are particularly vulnerable because of their limited capacity to smooth consumption in the face of climate shocks, particularly generalized shocks that affect a majority of households in the same location (Prakash, 2011; Dercon, 2004; Dercon, 2006; Vargas-Hill, 2009; Fafchamps, 2009). Any increase in climate extremes will exacerbate the vulnerability of these smallholders. Currently,

Table 4: Some key vulnerabilities relevant to food security

Environmental	Polar systems.
	High exposure to sea-level rise and coastal flooding including storm surge of people, economic activity and infrastructure in low-lying coastal zones, small island developing states (SIDS), and other small islands.
	Mountain areas (landslide, erosion, water cycle perturbation, shift of ecosystems).
	Coastal and SIDS fishing communities depending on ecosystem services.
	Warm water coral reefs and respective ecosystem services for coastal communities.
	Already degraded areas (land degradation, droughts, not having recovered from extreme events).
	Areas facing water scarcity and irregular supplies, or constraints on increasing supplies.
	Poorly endowed farmers in drylands or pastoralists with insufficient access to drinking and irrigation water.
	Areas having suffered diminution of genetic pools.
	Populations and infrastructure exposed to novel hazards and lacking historical experience with these hazards.
	Monoculture-based systems (pests and diseases, drought).
Economic	Populations with limited ability to compensate for losses in rainfed systems and pastoral systems.
	Populations prone to conflict over natural resources.
	Societies susceptible to loss of provisioning, regulation and cultural services from terrestrial ecosystems.
	Undernourished and malnourished populations.
	Poorer populations in urban and rural settings; includes particularly farmers who are net food buyers and people in low-income, agriculturally dependent economies that are net food importers.
Social	Marginalized rural population with multidimensional poverty and limited alternative livelihoods.
	Limited ability to cope and adapt due to marginalization, high poverty and culturally imposed gender roles.
	Limited ability to cope among the elderly and female-headed households.
	Countries in protracted food security crisis.
Institutional	Areas with inadequate water services and infrastructures.
	Lack of capacity and resilience in water management regimes.
	Inappropriate land policy (including lack of tenure systems).
	Misperception and undermining of pastoral livelihoods. Insufficient local governmental attention to disaster risk reduction.
	Overly hazard-specific management planning and infrastructure design, and/or low forecasting capability.

Source: Adapted from IPCC (2014a)

family farmers and smallholders rely to a large extent on increasing labour off-farm where possible (Kazianga and Udry, 2006; McPeak, 2004; Fafchamps, 1999), but also by decreasing both food consumption and non-food expenditures, such as those on education and healthcare (Skoufias and Quisumbing, 2005; CARE, 2000).

Box 4: Vulnerability assessments in the fisheries and aquaculture sector

A number of vulnerability assessments have been implemented to better characterize and understand the broad climate change threats and underlying issues facing fisheries and aquaculture. Depending on the vulnerability questions asked and the purpose of the assessments, different methodologies have been used – ranging from models and indicators to community perception-based assessments.

The first global-level assessment in fisheries, for example, asked how national economies are vulnerable to climate-related changes stemming through their fisheries and used available information to develop indicators of economies' exposure to change (predicted temperature changes), economies' sensitivity to such change (indicators on national dependency on marine and inland fisheries) and economies' adaptive capacities (human development indices) (Allison *et al.,* 2005; 2009). Other assessments have focused on how different aquatic species are exposed to sea surface temperature, air temperature, pH, salinity, precipitation, currents and sea-level rise and the biological attributes of each species that are predictive of their ability/inability to respond to potential environmental changes, such as in the United States of America in order to answer the question of which species have life histories and exposures that may leave them vulnerable to large changes in abundance or productivity (Hare *et al.*, forthcoming; Morrison, forthcoming).

Given the links between the aquatic system and dependent fisheries sector, there have also been vulnerability assessments that look at both the links between ecological vulnerability and the vulnerability of the human systems that depends on the natural systems, such as in Kenya, and the question of what is the social–ecological vulnerability of coral reef fisheries to coral reef bleaching due to increased sea temperatures (Cinner *et al.,* 2013). Another approach to understanding vulnerability within fisheries communities focuses on how people perceive change and their own vulnerability to this change – an example of such a participatory vulnerability assessment can be seen in the Benguela Current small-scale fisheries, where members of fishing communities expressed their perception of changes not only in wind patterns, sea surface temperatures and shifts in fish and other aquatic species but also of other changes (social, economic, etc.) they are experiencing, and evaluated their ability to respond to these changes through the fishers' socio-economic circumstances and the governance setup within which the fishers operate (Raemaekers and Sowman, forthcoming).

Source: Brugère and De Young, (2015)

Furthermore, evidence suggests that poorer households are more likely to reduce consumption, while wealthier households have the capacity to liquidate assets to cover current deficits (Carter and Lybbert, 2012; Kazianga and Udry, 2006; McPeak, 2004; Kurasaki and Fafchamps, 2002). Households currently vulnerable to climate shocks have limited opportunities to smooth these shocks through reliance on informal networks and reallocation of labour, and thin or non-existent credit and insurance mechanisms mean that poor households are faced with difficult choices between consumption and asset smoothing in response to a climate shock. Systems can be defined at various scales. Their vulnerability often depends on the vulnerability of their components or of the system of which they are part (Gitz and Meybeck, 2012). Understanding the complex, cascading, multidimensional and multiscale nature of vulnerabilities is key to build strategies to increasing resilience.

In many cases, there can be amplifying effects of shocks/risks. For example, a drought increases vulnerability to the next drought. By decreasing the strength of the cattle it also increases their vulnerability to diseases. By reducing assets of households it also increases their vulnerability to any kind of shock. From one dimension to another, from one level to another, or from one time scale to another, vulnerabilities can either add themselves, compensate each other, or amplify each other. Food insecurity vulnerability, vulnerabilities due to situations of lack of education and healthcare facilities lead to economic impediments, with long-term effects (Hoddinott, 2006).

These interrelationships have important consequences in terms of strategies to mitigate vulnerability. First, reducing vulnerability to one kind of shock can help also to reduce vulnerability to another kind of shock. Second, the vulnerability of a system can be reduced by finding ways to limit the internal transmission of shocks, such as for example from one level to another. This is why, for instance, monitoring of diseases and plant pests, and early action to avoid their spread, is an essential way to reduce vulnerability at different levels. Third, strategies covering different dimensions, levels and time scales can be mobilized to compensate vulnerabilities in a particular dimension/level/time scale. For instance a climatic shock, reducing yield in one area, can, at household level, be compensated for by trade, provided that trade is not impeded, and provided that households have the means to buy that food, using other sources of income, their own assets or social transfers (safety nets).

Vulnerabilities resulting from gender bias

Vulnerability is often determined by socio-economic factors, livelihoods, and people's capacity and access to knowledge, information, services and support. Vulnerability and adaptation to climate change depend on opportunities governed by the complex interplay of social relationships, institutions, organizations and policies. Vulnerability assessments, which focus on climate and environment variables and macro-level data on poverty and economic activities, are often conducted nationally or regionally. At that level, analyses risk overlooking some of the most vulnerable people and groups and missing the underlying causes of their vulnerability.

Women and men possess and have access to different amounts and combinations of livelihood assets (human, social, financial and natural). For example, family farmers and smallholders everywhere face constraints in accessing credit but in most countries the share of female smallholders who can access credit is 5–10 percent lower than their male colleagues (FAO, 2011c). Men and women tend to participate in different activities with varying levels of decision-making power, each of which influences their vulnerability to climate change. As a result, women in rural areas may experience the effects of climate change more acutely than men.

Experience shows that women typically face different constraints than men and that the feasible climate change adaptation options open to women differ from those open to men (World Bank/FAO/IFAD, 2012). These constraints include formal legal and regulatory issues, for example land tenure. In developing countries, only 10–20 percent of all landholders are women (FAO, 2011c). Moreover, social norms or time constraints may prevent women from seizing off-farm opportunities, which influences women's level of vulnerability, incomes and ability to adjust their agricultural production. In some communities, only men have the right to cultivate certain crops or to access markets. In addition, many adaptation practices require investments in cash, time or labour and thus are costly for households with limited access to credit and with few, mostly female, working-age adults. Gender and social differences between men and women may also affect investment needs and access to weather and climate information. In an FAO-study in India, only 21 percent of women report having access to weather information versus 47 percent of men (Lambrou and Nelson, 2010).

It is also important to note that not all men and women are equally vulnerable to climate change. Women are not necessarily victims of climate change but can be crucial actors in finding solutions on how to cope with climate change. A nuanced understanding of vulnerabilities to climate variability and change for different types of men and women is therefore necessary (World Bank/FAO/IFAD, 2012).

A.5 IMPACTS ON FOOD SECURITY AND NUTRITION

As a result of the cascading impacts and specific vulnerabilities to them described in the previous sections (see also Box 8), climate change impacts food security in its four dimensions, described in Box 5: availability, access, utilization and stability, directly and indirectly. As noted by the IPCC (Porter *et al.*, 2014) there is much less quantitative understanding of how non-production components of food security will be affected. A review of peer-reviewed journal papers on food security and climate change since 1990 showed that they were mainly about availability, 70 percent, access, utilization and stability being represented by 11.9 percent, 13.9 percent and 4.2 percent, respectively, of the papers (Wheeler and von Braun, 2013). The authors propose several causes of this unequal representation: a focus on direct effects of climate change, on areas easier to investigate, including through analysing single factor changes rather than complex systemic interactions.

This section summarizes the main expected impacts of climate change on the four dimensions of food security.

Availability

Impacts on major crop yields is probably the food security-related issue on which there are the most studies, with two decades of work since the global assessment of Rosenzweig and Parry (1994), including major studies by Parry, Rosenzweig and Livermore (2005), Cline (2007), the IBRD/WB (2010) and Rosenzweig *et al.* (2014). Projections vary according to the scenario used, the model and time scale. There is, however, consistency on the main orientations: yields are more impacted in tropical regions than at higher latitudes and impacts are more severe with increased warming. Importantly, many of the areas where crop yields are expected to decrease are also areas that are already experiencing food insecurity (see Box 6). There are important limitations to these studies. As shown above, there are risks that are difficult to factor in such projections, like single weather events and impacts of pests. Moreover, they are limited to major crops and the

Box 5: Food security

"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" (World Food Summit, 1996). This widely accepted definition points to the following four dimensions of food security:

Availability: The availability of sufficient quantities of food of appropriate quality, supplied through domestic production or imports (including food aid).

Access: Access by individuals to adequate resources (entitlements) for acquiring appropriate foods for a nutritious diet. Entitlements are defined as the set of all commodity bundles over which a person can establish command given the legal, political, economic and social arrangements of the community in which they live (including traditional rights such as access to common resources).

Utilization: Utilization of food through adequate diet, clean water, sanitation and healthcare to reach a state of nutritional well-being where all physiological needs are met.

Stability: To be food secure, a population, household or individual must have access to adequate food at all times. They should not risk losing access to food as a consequence of sudden shocks (e.g. an economic or climatic crisis) or cyclical events (e.g. seasonal food insecurity). The concept of stability therefore refers to the availability, access and utilization dimensions of food security.

effects of climate change on many important productions are much less known. Availability of aquatic foods will vary, positively and negatively, through changes in habitats, stocks and species distribution (Barange and Perry, 2009). Marine fish availability in the tropical belt and along coastal regions across the globe is predicted to decrease substantially (Cheung *et al.*, 2010).

Global temperatures of 4 degrees or more, combined with increased food demand, would pose large risks to food security globally and regionally (Porter *et al.*, 2014). They are generally greater in low latitude areas.

Access

There are relatively few models that look at the impacts of climate change on the global number of hungry and malnourished. AgMIP protocols have helped to narrow the uncertainty and understand the reasons for differences in modelling outcomes and projections of climate change impacts on food security (see Box 7). The Fourth Assessment report of the IPCC (2007) estimated that depending on the climate change scenario 200 million to 600 million more people could suffer from hunger by 2080 (Yohe *et al.*, 2007). Nelson *et al.* (2009) developed 15 scenarios for climate change based on three economic development and five climate change scenarios and found that up to 2050 economic growth has a much greater effect on global food security than climate change, although climate change does augment negative impacts. They project increases in the number of malnourished children due to changes in per capita calorie availability driven by varying economic growth and climate change scenarios. They found increases ranging from 8.5 to 10.3 percent over the baseline scenario. Their findings also indicate that, up to 2050, changes in global food trade patterns can mitigate negative effects of climate change. Hertel, Burke and Lobell (2010) use a computable general equilibrium model to analyse food security impacts of climate change, focusing on the tails of the distribution of projected climate change impacts on yields up to 2030. The results highlight the importance of income source in determining food security impacts: scenarios with high impacts on yields also generated increases in food prices, which benefitted net exporters/sellers. Conversely, high productivity growth scenarios lead to reductions in food prices, which had differential impacts on sellers and buyers.

The risks of climate change are not just to the production capacity of food security – but also to the potential growth in incomes and ability to purchase food of poor people, the risk of market disruptions, effects on supply and storage systems, and effects on stability of agricultural and rural incomes as well as nutritional content.

The people at greatest risk are those that are dependent on agriculture and natural resources for livelihoods, especially those most vulnerable, and who depend on systems that are the most impacted, and poor people.

According to the World Bank, in 2015, there are still 836 million people in the world living in extreme poverty (less than USD1.25/day). And according to IFAD, at least 70 percent of the very poor live in rural areas, most of them depending partly (or completely) on agriculture for their livelihoods. It is estimated that 500 million smallholder farms in the developing world are supporting almost 2 billion people, and in Asia and sub-Saharan Africa these small farms produce about 80 percent of the food consumed. Rural poor often depend partly on forests for their livelihoods (World Bank, 2002). It is estimated that between 660 and 820 million people (workers and their families) depend totally or partly on fisheries, aquaculture and related industries as a source of income and support (HLPE, 2014).

Forest-based employment and sale of forest products – including timber, fuelwood and non-wood forest products collected from forests or produced on-farm – provide a main or supplemental source of income that may be used by the rural household to purchase food. The poor tend to have a higher dependence on forest products. A study of the *miombo* woodlands in Southern Africa cites several studies that record high dependence on the woodlands, including forest income from different sites in Zambia ranging from 10–50 percent and in

Box 6: Investigating climate change effects on agriculture production and consumption: results from a recent model intercomparison study

Assessing climate change impacts on agriculture requires integrated use of climate, crop and economic models to take into account the reaction of the sector (including management decisions, land-use choices, international trade, prices) and of consumers to changing conditions. Nelson and colleagues have designed a common protocol to compare results of a set of nine models under the scenario RCP8.5 (see A.1) (which is the highest set of IPCC's concentration pathways), 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 – accounting for about 70 percent of 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 increase associated with the shock both by intensifying management practices, leading to a final mean yield change of –11 percent, and by a mean increase of cropping area by 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 effect is relatively small, the price increases caused by the inelastic nature of global demand are likely to significantly increase food costs for the poor, with especially negative effects for the poor in rural areas who will also see reduced income from production-side effects.

The study shows that a large part of the climate change shock is transferred to production-side and trade responses, not limiting climate change impact to biophysical effects alone.

Source: Nelson *et al.* (2014)

Box 7: The agricultural model intercomparison and improvement project

The agricultural model intercomparison and improvement project (AgMIP) is a framework linking climate, crops, livestock and economics. It includes analyses at field-to-regional scales and includes both crop and economic model intercomparisons and improvement activities, as well as simulations with guided climate sensitivity tests and climate change scenarios. The results have been used by the IPCC.

AgMIP protocols have helped to narrow the uncertainty and understand the reasons for differences in modelling outcomes and projections of climate change impacts on food security. For instance, Von Lampe *et al.* (2014) and Nelson *et al.* (2014) have compared the behaviour of ten of the world's leading global economic models; for the particular climate shock chosen, all models report higher prices for almost all commodities in all regions, with yields down, area up, and consumption somewhat reduced. But the relative size of the adjustments varies dramatically by model. These differences depend on both model structure and parameter choice.

Zimbabwe 15 percent of total income (Dewees *et al.*, 2011). The same article indicates the importance of miombo as a safety net in the areas where poverty rates are high.

In regions with high food insecurity and inequality, increased frequency of droughts will particularly affect poorer households and may disproportionately affect women, given their vulnerability and restricted access to resources (IPCC, 2014b). Climate change will particularly

Box 8: Cascading impacts from climate change on food security in the fisheries sector

Changes in distribution, species composition, productivity, risks and habitats will require changes in fishing practices and aquaculture operations, as well as in the location of fish landing, farming and processing facilities.

Extreme events will impact on infrastructure, ranging from landing and farming sites to post-harvest facilities and transport routes. They will also affect safety at sea and settlements, with communities living in low-lying areas at particular risk.

Water stress and competition for water resources will affect aquaculture operations and inland fisheries production, and are likely to increase conflicts among water-dependent activities.

Livelihood strategies will have to be modified, for instance with changes in fishers' migration patterns due to changes in timing of fishing activities.

Reduced livelihood options, especially in the coastal regions, inside and outside the fishery sector, will force occupational changes and may increase social pressures. Livelihood diversification is an established means of risk transfer and reduction in the face of shocks, but reduced options for diversification will negatively affect livelihood outcomes.

There are particular gender dimensions, including competition for resource access, risk from extreme events and occupational change in areas such as markets, distribution and processing, in which women currently play a significant role.

put at high risk indigenous peoples, who depend on the environment and its biodiversity for their food security and nutrition – specifically those living in areas where significant climate change impacts are expected such as mountain regions, the Pacific islands, coastal and other low-lying areas, and in the Arctic (IPCC, 2014b). Access to aquatic foods will be affected by changes in livelihoods and catching or culture opportunities combined with transferred impacts from other sectors (i.e. increased prices of substitute foods), competition for supply and information asymmetries. Impacts may also arise from rigid management measures that control temporal and spatial access to resources.

As shown above, climate change can also have remote impacts on the food security of people distant from the initial shock, particularly through food price increases and volatility. Without considering effects of CO_2, changes in temperature and precipitation will contribute to increase global food prices by 2050 (Nelson *et al.*, 2014).

Utilization

Potential impacts of climate change on nutrition have been much less studied. Several impact pathways can be identified. As mentioned above, climate change will impact livelihoods and income of small-scale food producers and also, through food price increases and volatility, the livelihoods of poor net food buyers, constraining these populations to reduce their food consumption in quantity and quality. They are also likely to reduce health expenditures with potential effects on nutrition. Using the results of Nelson *et al.* (2009) on undernourishment, Lloyd, Kovats and Chalabi (2011) projected a relative increase in moderate stunting from 1 to 29 percent in 2050, with severe stunting increasing from 23 percent (Central Africa) to 62 percent (South Asia).

There could be a reduction of production and consumption of some foods that play a critical role in the diets of vulnerable rural and indigenous populations, such as fish, fruits and vegetables and wild foods. The impacts of climate change on many of those are not well known. To date, studies mostly focus on cereals. There is a need to better capture all the nutritional consequences of the effects of climate change on other foods and vegetables and wild foods, all of which have an important role in balanced diets and which are at risk (HLPE, 2012a; Barucha and Pretty, 2010). For instance, today capture fisheries and aquaculture provide 3 billion people with at least 20 percent of their average per capita intake of animal proteins, and a further 1.3 billion people with at least 15 percent of their per capita intake. Utilization of aquatic products and the nutritional benefits produced will be impacted by: changes in range and quality of supply; market chain disruptions; greater food safety issues; and reduced opportunities to consume preferred products. This is particularly critical for countries with high per capita fish consumption, like small island states (FAO, 2008).

Studies also point to changes in the nutritional quality of foods (reduced concentration in proteins and in some minerals like zinc and iron), due to elevated CO_2, particularly for flour from grain cereals and cassava (Porter *et al.,* 2014). This effect does not necessarily translate into impacts on nutrition, as it is generally combined with increased yields which themselves can increase food intake, often the main concern (Porter *et al.,* 2014). However, some authors (Myers *et al.*, 2014) note that in some countries populations receive 70 percent of iron or zinc from C3 grains or legumes and that, in countries where proteins are mainly of plant origin, a decrease of protein content could have serious health consequences. Climate change is expected to reduce water quality, posing risks to drinking water quality even with conventional treatment (Jimenez Cisneros *et al.,* 2014). This is likely to exacerbate risks of water-related diseases reducing food absorption. According to WHO (2014) climate change is projected to increase diarrhoeal diseases, impacting mainly low-income populations.

Climate change also has an impact on food safety, particularly on the incidence and prevalence of food-borne diseases. Mycotoxins and pesticide residues have been identified as important issues for climate change effects in Europe (Miraglia *et al.,* 2009). Tirado *et al*. (2010) reviewed the potential impacts on food contamination at various stages of the food chain and described adaptation strategies and research priorities to address food safety implications of climate change. Continuously rising temperatures also support the spreading of the organism responsible for producing the toxin that causes ciguatera fish poisoning (CFP), which occurs in tropical regions and is the most common non-bacterial food-borne illness associated with the consumption of fish (IPCC, 2013). Rising rates of CFP have already been observed in the Lesser Antilles (Tester *et al.,* 2010) and in the Pacific in Tokelau, Tuvalu, Kiribati, the Cook Islands and Vanuatu (Chan *et al.*, 2011). The Food Research International journal recently published a special issue on climate change impacts on food safety (Uyttendaele and Hofstra, 2015), which tackled this topic from various perspectives. Overall, the reviews conclude that climate change could reduce food safety and that more research is required to get a better understanding of the problems and to set up adaptation strategies.

Stability

Increased climate variability, increased frequency and intensity of extreme events, as well as slow ongoing changes, will affect the stability of food supply, access and utilization. Stability of food supply will be impacted by changes in seasonality, increased variance of ecosystem productivity, increased supply risks and reduced supply predictability – issues that may also have large impacts on supply chain costs and retail prices (FAO, 2008). For instance, the UK-US Taskforce on Extreme Weather and Global Food System Resilience report (Global Food Security Programme, 2015) shows that severe “production shocks” caused by extreme weather – whereby global food production is seriously disrupted – of a scale likely to occur once in a century under past conditions, may occur as frequently as once every 30 years as the world’s climate and global food supply systems change in the coming decades.

Irregularity of income of people depending on agriculture for their livelihoods as well as food price increases and volatility will threaten economic access to food. This will be compounded in some regions, particularly in landlocked countries and small island states with reduced physical access, further aggravated in the case of extreme events. Forest foods, including bushmeat and forest plants, are sources of protein and micronutrients that are crucial for peoples' nutrition in many places. These are particularly important in times of food shortage. Dependence on "famine foods" from forests may well increase where climate change negatively impacts the production of crops and livestock. In addition to the impacts on nutrition through the pathways mentioned above, droughts and floods severely impact reliability of drinkable water supply.

A.6 CONCLUSIONS

Climate change is alrady impacting, and will increasingly impact, food security and nutrition. Through effects on agro-ecosystems it impacts agricultural production, the people and countries depending on it and ultimately consumers through increased price volatility. The impacts of climate change on food security and nutrition are the results of climate changes themselves and of the underlying vulnerabilities of food systems. They can be described as "cascading impacts" from climate to biophysical, to economic and social, to households and food security. At each stage vulnerabilities exacerbate effects.

This leads to drawing some important conclusions;

- The first and the worst impacted are the most vulnerable populations (poor), with livelihoods vulnerable to climate change (depending on agriculture sectors), in areas vulnerable to climate change.
- Reducing vulnerabilities is key to reduce final impacts on food security and nutrition and also to reduce long-term effects.
- The first and main impacts on food security and nutrition will be felt through reduced access and stability for the most vulnerable.

From an agronomic perspective, favourable conditions for crops and other species will move geographically. Optimizing these conditions will thus require changing crops and other cultivated species, moving them. Even to benefit from potential positive effects, such as longer growing seasons in some cold regions, would, most of the time, require significant changes in agricultural systems and practices to effectively translate into production growth. Also, these changes of climatic conditions will go with changes of other biotic parameters (like pests and diseases), which can counteract the benefits of climatic changes.

B. ENSURING FOOD SECURITY AND GOOD NUTRITION IN THE CONTEXT OF CLIMATE CHANGE: OPTIONS AND LESSONS LEARNED

In this section we turn to the actions that need to be taken to ensure that global food security can be attained under the new challenges of climate change. As evidenced in the first section of this report, climate change can impact food security and nutrition in many ways, most of which are exacerbated by underlying vulnerabilities. Therefore, a key way to reduce the impacts of climate change on food security and nutrition is to reduce these underlying vulnerabilities and increase resilience of food systems from field to household. Resilience can be described as the capacity of systems, communities, households or individuals to prevent, mitigate or cope with risk, and recover from shocks. At first glance, resilience is simply the opposite of vulnerability, but importantly by encompassing also adaptive capacity it adds a time dimension to the concept of vulnerability: a system is resilient when it is less vulnerable to shocks across time, and can recover from them in a timely manner. Adaptive capacity encompasses two dimensions: recovery from shocks and response to changes. These two dimensions play an essential role in resilience, both to recover from shocks and to adapt to change, thus ensuring the "plasticity" of the system (Figure 3).

Increasing resilience can be achieved by reducing exposure, reducing sensitivity and increasing adaptive capacity, for every type of risk. Actions can be taken across biophysical, economic or social domains. One way to enhance resilience is to reduce transmission of shocks between types of risks, between scales and between domains, and to organize compensation between scales (for instance transport of feed in case of drought) or between domains (for instance safety nets to compensate for bad harvests) to avoid cumulative and long-term effects.

Resilience puts a greater emphasis on the capacity of a system to recover and transform itself in the long term, to adapt to its changing environment, in a dynamic perspective. It therefore implies that it is not only shocks that have to be considered, as a change relative to an

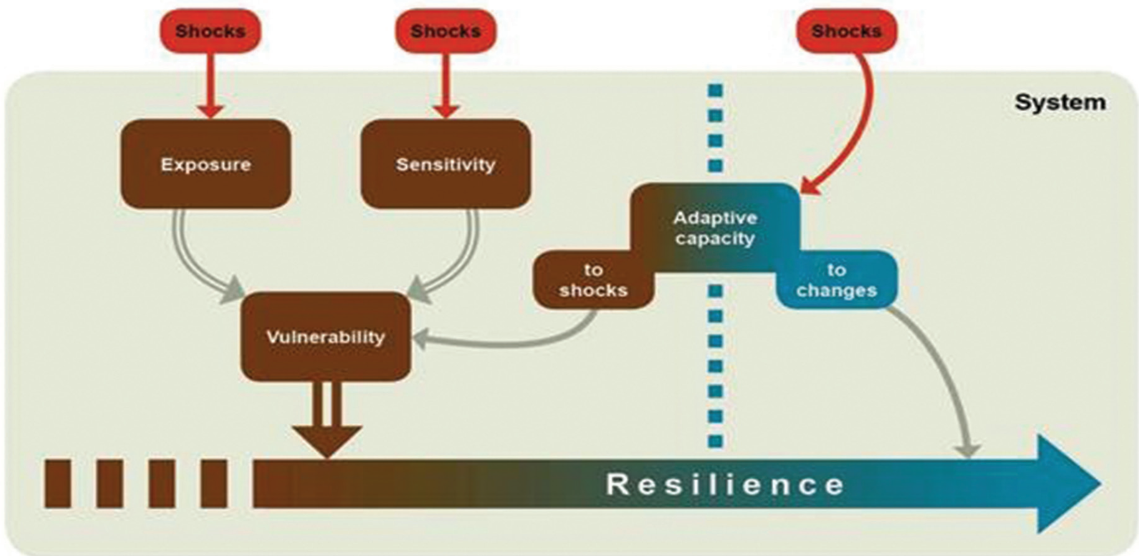


Figure 3. Vulnerability and resilience.
Source: Gitz and Meybeck (2012)

average, but also the change of the average itself. Ultimately the question is the extent to which a system can adapt before changing to another type of system. Building resilience will require actions at multiple scales, in various dimensions, ecological, technical, economic and social, involving various categories of actors and enabling governance environments. Importantly it also requires the integration of different time frames and the time needed for a specific action to produce positive effects at field level.

This chapter describes potential means of addressing risks to food security and nutrition caused by climate change. The point of departure is at household level, considering how extreme poverty and hunger could be eradicated. These efforts need to be supported by efficient disaster risk reduction and management strategies and plans. The chapter then investigates how agricultural systems can be made more resilient. The third section looks at how resilient agricultural development can support these changes and what are the means and tools to be mobilized. The fourth section considers the enabling environment, and the policies and institutions that are needed to realize adaptation to climate change, at national and international levels. The concluding section aims to summarize the actions that need to be taken, now, and by whom – to build resilience of food systems to climate change and ensure food security now and in the future.

B.1 INCREASE RESILIENCE OF LIVELIHOODS

The section starts from food security and nutrition, now, at household level, considering how extreme poverty and hunger could be eradicated and how these efforts need to be supported by efficient DRRM strategies and plans. The focus of this subsection is on building resilience in agriculture-based livelihoods, as this is where a major part of the global food insecurity challenge must be met, as well as a sector highly vulnerable to natural extreme events, climate variability and climate change. Agriculture is the source of employment for about 45 percent of the total labour force (including paid and unpaid workers in formal and informal employment) and women supply approximately 43 percent of the total agricultural labour in low- and middle-income countries (FAO, 2015f). However, agriculture generates only about 10 percent of GDP in these countries – implying low output per worker and low incomes for those employed in the sector. And indeed the highest rates of food insecurity are found in rural areas. Approximately 500 million people who are food insecure are in Africa and Southern Asia (FAO, 2015g): these regions are crucial to reach zero hunger globally not only because of the proportion of food insecure today, but also because they are thought to be among the regions that will be most affected by climate change. In both areas, there is a high dependence on agriculture for livelihoods and a high share of the poor and food-insecure are directly or indirectly dependent on agriculture.

What do we mean by resilient livelihoods in the context of achieving global food security under climate change? Livelihoods that support improvements in their participants' income, access and utilization of food in a way that is able to withstand, recover and adapt to the climate risks they are exposed to. Essentially this requires that the livelihoods of those that are poor and food-insecure today be improved to allow them to escape hunger and poverty, and that these improvement pathways are built so as to enabe a continued capacity to generate benefits even under climate risks.

The Rome-based agencies (FAO, IFAD and WFP) recently stated that it is possible to end poverty and hunger by 2030 by combining public investment in social protection with public and private efforts to raise investment levels in productive sectors – especially in rural areas and particularly in agriculture (FAO/IFAD/WFP, 2015). An average of USD267 billion per year during 2016–2030, i.e. 0.3 percent of world economic output in 2014, is required to fund social protection and additional targeted pro-poor investments, of which rural areas would receive USD181 billion annually. In the longer term, additional investment is required to stimulate and to sustain higher pro-poor, gender-inclusive rural growth of incomes and employment. To be pro-poor and gender-sensitive, investments in urban and rural areas, including in agriculture, should be properly targeted so that the poor could earn enough to overcome poverty. In the longer term, as the incomes of the poor increase because of investments, the need for social protection to close the poverty gap diminishes.

Climate change introduces an additional element of uncertainty in determining what is needed to end hunger, as documented in the earlier sections of this report. Climate change is likely to have mostly negative impacts on agricultural productivity and human well-being in areas of high poverty and food insecurity, and where reliance on agriculture for food and livelihoods is highest. However, as noted in section A, the risks of climate change also affect the potential growth in incomes and poor people's ability to purchase food, the risk of market disruptions, effects on supply and storage systems, effects on stability of agricultural and rural incomes as well as nutritional content, all of which have an impact on food security.

Concern about the climate change-induced impacts on poverty and food security through increased food prices are reinforced by the high share of income that poor consumers, spend on food, thus generating a disproportionately negative effect of price increases on this group (FAO, 2011d). The distribution of net food buyers and net food sellers varies considerably across countries and can be expected to change with the process of economic development (Aksoy *et al*., 2010; FAO, 2011d). The evidence base on potential climate change impacts on consumption patterns and other non-production elements of food security is still relatively thin (IPCC, 2014a). Nonetheless, one would expect that the urban poor and agricultural producers who are net food buyers would remain particularly vulnerable to adverse climate change impacts, which may yet again imply a potential need for increased coverage of social protection in a climate change context. This also indicates that investing now to improve the incomes of these vulnerable categories in a form that is resilient to current and future effects of climate change is essential to achieve resilient livelihoods.

B.1.1 Devise appropriate social protection strategies

To break the vicious cycle of poverty and hunger, people who are extremely poor and hungry have to be assisted through social protection.[5] Adequate, well-designed social protection would enable the people in this category to quickly overcome poverty, hunger and undernutrition, as well as to tackle some of the main vulnerabilities of households to climate risks.

Access to food is the most significant basic need by far. Basic minimal food expenditures can represent, in many countries, the major part of poverty line incomes. Income provided to the poor and hungry through social protection can enable them to afford sufficient food to meet their basic nourishment needs. Social protection covers a wide array of instruments and objectives, encompassing both safety nets and so-called "safety ropes", i.e. mechanisms that enhance income generating abilities and opportunities for the poor and vulnerable. Such actions will be particularly efficient if targeted to the needs of women (HLPE, 2012).

The "Achieving Zero Hunger" report (FAO/IFAD/WFP, 2015) envisions supporting income of the food insecure until 2030 through expanded coverage of safety net programmes while investments are being put in place. Over this period, the projected mean decrease in agricultural production due to climate change is not likely to have a major impact on the cost of these additional safety net expenditures, reported at an average annual cost of USD116 billion. On the other hand, the increased climate-induced agricultural variability in some regions is likely to increase the importance and need for safety nets in reducing hunger. However, it is

[5] Social protection includes three broad components: social assistance, social insurance and labour market protection. Social assistance programmes are publicly provided conditional or unconditional cash or in-kind transfers or public work programmes. Social insurance programmes are contributory programmes that provide cover for designated contingencies affecting household welfare or income. Labour market programmes provide unemployment benefits, build skills and enhance workers' productivity and employability (FAO, 2015f). In this document the focus is primarily on social assistance programmes.

difficult to estimate how much this would increase needed investments in safety nets (Thornton *et al*., 2014).

Social protection can take on a variety of forms, from cash transfers to school meals to public works. When targeted at the poorest and most vulnerable, these policies may be seen as social protection interventions in their own right. Policies promoting agricultural production, such as input subsidies, may also have a social protection function to the extent that they help reduce the vulnerability of smallholder farm households to price volatility. Social protection programmes contribute to resilient livelihoods by enhancing the nutritional, health and educational levels of household members, which in turn increases their capacity to engage in productive activities. Social assistance programmes play an important role in risk management and overall resilience of households and individuals – they have been shown to have positive and significant impacts on risk coping strategies. Participants in social protection programmes are less likely to undertake "bad" coping strategies such are reducing food consumption, or selling off productive assets, that can lead to a long-term decline in income and food security (Asfaw *et al.*, 2014; 2015a,b; Daidone *et al.*, 2014a,b).

According to FAO (2015f), in most regions poor rural households are more likely than urban ones to need social assistance. However, in the rural areas of South Asia and sub-Saharan Africa, for instance coverage of such programmes is low: only about 30 and 20 percent respectively, compared with about 70 percent in Latin America and the Caribbean (FAO, 2015f).

Social protection can improve access to food by providing direct income support to households with an immediate impact on food security and poverty, but also by supporting farmers to overcome liquidity constraints, enhance human capital and stimulate local economic employment (HLPE, 2012b; FAO, 2013a). 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 empowered, but households' welfare is also improved because of women's role in managing household food and nutrition and their children's education and well-being.

Poor households spend most of their income on food and there is broad evidence that social protection interventions improve household food security and child nutrition. A meta review of cash transfer programmes identified 17 out of 20 studies that reported an increase in food intake, diversity and quality, all of which make important contributions to food security (Tirvayi, Knowles and Davis, 2013). Cash transfer programmes have also led to a reduction in child malnutrition, though impact is mediated by other determinants of child nutritional status, including access to health services and potable water, hygiene practices, and household and parental characteristics. Children benefitting from Brazil's Bolsa Familia programme are 26 percent more likely to avoid malnutrition than non-beneficiaries (Paes-Sousa, Santos, and Miazaki, 2011). In Colombia, cash transfers to the poor "greatly increased" total food consumption and particularly increased consumption of food rich in proteins: milk, meat and eggs. Beneficiary families of Malawi's cash transfer programme now eat meat or fish three times a week, whereas before they could only afford to do so once every three weeks (Hanlon, Barrientos and Hulme, 2010). A recent review by Hidrobo *et al.* (2014) assesses the impact of social assistance programmes on household food security. Their review included 48 studies of 39 social protection programmes and found average positive impacts (relative to the baseline) of 13 percent for caloric intake and 17 percent for food consumption/expenditure. They also found evidence that some programmes improved dietary diversity, especially with regard to consumption of animal products (FAO, 2015f).

Social protection programmes have been found to contribute to the resilience of rural livelihoods through several pathways. As mentioned above, one of the most important is the improved capacity for risk coping and avoidance of poverty traps. However, equally important is the impact they can have on the household investment decisions that affect the long-term benefits livelihoods can generate (HLPE, 2012b). Social protection programmes that provide cash can help overcome credit constraints that households, and particularly women, face and which are a common barrier to investment in improved inputs and production methods. Importantly, social protection programmes have been found to have positive spill-over effects in local economies. Additional income is spent on goods, such as livestock products and simple agricultural and household goods and services, which may be produced and provided locally, often by non-beneficiary households. Many of these goods are only traded within a small area, either because they are perishable or because of the costs of transportation, and thus have a strong positive effect on the local economy.

Aside from direct income support, social protection programmes have an important impact on agricultural investment decisions of rural households and thus have a longer-term positive impact on food access. For example, the livelihoods of most social protection beneficiaries in sub-Saharan Africa are predominantly based on subsistence agriculture and rural labour markets, and this will continue to prevail for the foreseeable future. Local labour markets often do not provide many opportunities for overcoming poverty and, as a result, poor households tend to resort to self-employment, whether in or outside agriculture. Moreover, most beneficiaries live in places where markets for credit, insurance, labour, goods and inputs are lacking or functioning poorly. In this context, when social protection is provided in a regular and predictable manner, it helps households to overcome credit and labour constraints and better manage risks. This, in turn, helps induce more productive investments, improves access to markets, stimulates local economic activity and employment creation, and increases adaptive capacity. A recent evaluation of 12 social protection programmes involving cash transfers in sub-Saharan Africa indicates that participation in the programme was effective in increasing household investments in inputs, tools and production systems, although the effect varied by country and programme design (FAO, 2015f).

The risk management function of social protection programmes clearly has an important role to play in the context of increasing risk exposure from climate change (HLPE, 2012b) and because of this social protection has a potentially key role to play in adoptation strategies. By expanding the number of households exposed to risks, as well as deepening risks households already face, climate change can be expected to increase the vulnerability to food insecurity, and thus social protection is likely to become an even more critical tool for food security under climate change.

In addition to the role they play in reducing the vulnerability to climate change related hazards, social protection programes can enhance the households financial and human capacity to invest in adaption and effective natural resource management, as outlined by the 2012 HLPE Report on *Food Security and Climate Change* (HLPE, 2012).

Social protection programmes could also further integrate specific vulnerabilities to climate change by including environmental targeting criteria, and combine income poverty and food security mapping as well as climate-related risks assessment. Especially for predictable hazards, effective linkages could be made between social protection management and information systems with early warning systems, ensuring that the former are able to integrate additional beneficiaries, in the time of crises.

However, social protection alone is not sufficient to generate long-term capacity to reduce poverty and generate secure and stable food access for poor rural households. Investments to support agricultural growth are also necessary to obtain this. At present, social protection, disaster risk management, agriculture, fisheries and forestry and climate change policies are not usually well aligned, and evidence indicates that greater effectiveness across these policy domains could be obtained with better coordination (FAO, 2015f).

B.1.2 Address gender-related vulnerabilities

An increasing body of evidence (World Bank/FAO/IFAD, 2015) emphasizes the need to better take into account gender specificities in order to address the differences in vulnerability and adaptation capacities of men and women. Research implies the importance of collection and analysis of sex-disaggregated data, as well as quantitative and qualitative analyses of the gender-differentiated impacts of climate change and gender-specific adaptation needs, as well as the sharing of benefits from adaptation activities.

Further, understanding men's and women's roles in relation to food security and nutrition, including their roles in producing and processing food and managing agricultural activities, is key. It is also important to identify and document the perceptions and strategies used by men, women and youth to cope with food insecurity related to the climate risks.

Men's and women's participation and benefits from interventions aiming at more sustainable agricultural practices are heavily influenced by social norms and intrahousehold decision-making and bargaining. Conducting analyses at the household level reveals that it is common for men and women within the same household to pursue separate livelihoods. Furthermore, women and men incorporate a wide range of different technology and production management options (World Bank/FAO/IFAD, 2015). When designing policies and programmes in response to climate change, gender equity trade-offs need to be systematically analysed and addressed.

Box 9: Some examples of disaster risk reduction and management (DRRM)

Decentralization of DRRM in agriculture – an example for enhanced tools and capacities in the Philippines

The Department for Agriculture (DA), Bicol Region, established a Technical Unit for DRRM in 2010 with technical advice from FAO. This unit coordinated, with support from FAO and the Central Bicol State University of Agriculture (CBSUA), the development of a Regional Plan of Action in agriculture and 15 community development plans for DRRM formally endorsed by municipalities and barangays in line with the implementation of DRRM Government Act 10121. A partnership agreement between the DA and the meteorological agency (PAGASA) led to the regular issuing of agro-climate information bulletins that inform farmers' crop choices before the agricultural seasons start and provide weather-related management advice on a monthly basis throughout the season. The pilot-testing of good practice technology options for DRRM through farmer field schools raised awareness for the adoption of prevention and mitigation measures – such as the use of newly released submerged and saline-tolerant rice varieties – in recurrently hazard-prone communities. The development of a Web-based software application made it possible to monitor – based on seasonally updated field data and existing plot sizes – the performance of four main commodities (rice, maize, abaca and coconut). It reports on status and value of standing crops at any time during the cropping cycle. The standardized methodology enhances preciseness and speeds up the collection of loss and damage data in agriculture, and thus better informs relief and rehabilitation planning.

Plan of Action for DRRM in agriculture – an example for a participatory planning process in the Lao People's Democratic Republic

The Ministry of Agriculture and Forestry (MAF) has high commitment to shift towards a more proactive approach to disaster risk management and initiated an interactive DRRM stakeholder consultation process in 2013, which led to the development of this Plan of Action for DRRM in agriculture (2014–2016). Drawing upon key priorities embedded in existing policies and regulatory frameworks, the Plan of Action identifies priorities and working mechanisms for enhanced risk reduction in agriculture, livestock, forestry and fisheries. FAO facilitated the DRRM stakeholder consultation and planning process among several technical departments in MAF and its affiliated research institute, the Ministry of Natural Resources and Environment and the National Disaster Management Office, as well as several international organizations. The planning process was informed by a DRRM system analysis in four regions. MAF has endorsed the Plan and implements currently selected priority actions in high-risk provinces with technical assistance from FAO.

There is convincing evidence that when women start to have decision-making responsibilities and control their earnings, a greater proportion of the income is allocated to family nutrition and children's education, therefore the benefits trickle down to the entire household. Consequently, there is now consensus that gender-specific differences in strategies and opportunities must be fully incorporated in the design and implementation of climate change response strategies, programmes and projects.

B.1.3 Conceive disaster risk reduction for food and security and nutrition in the context of climate change adaptation

Building resilience requires a change in the conventional approach to disaster risk reduction and to prioritize the reduction and active management of risks rather than being limited to reacting to extreme events. Field-based evidence shows that DRR is cost-effective: for every USD1 spent on DRR, USD2–4 are returned in terms of avoided or reduced disaster impacts. Yet, investment in proactive disaster risk reduction, and specifically for DRR in agriculture, is extremely low. Less than 5 percent of all humanitarian funding has gone to disaster

Upscaling of a capacity building system for agro-climatic risk management in the territories of the Central American Agricultural Council (CAC)

In the framework of the CAC, a technical group on disaster risk management and climate change is developing – with the support of FAO and other key regional institutions (Center for Tropical Agricultural Research and Higher Education [CATIE], Economic Commission for Latin America and the Caribbean [CEPAL], International Center for Tropical Agriculture [CIAT], Research Program on Climate Change, Agriculture and Food Security [CCAFS], Inter-American Institute for Cooperation on Agriculture [IICA]) – a capacity-building programme for agro-climatic risk management that will be institutionalized and implemented in all the Central American subregion. The objective is to strengthen capacities to promote policies and improve investment programming for risk reduction and resilience building. FAO is specifically supporting the design and piloting of the programme in El Salvador, Guatemala, Honduras and Nicaragua. Lessons learned from the capacity-building pilots in the target countries will provide information for local level implementation. Key activities include the formation of an agro-climatic risk management committee to define the capacity development system and to lead its implementation, the provision of a knowledge management platform, the design of e-learning tools for DRR in agriculture, and training sessions to plan the implementation of the capacity-building system at local level (municipalities, extension services providers, farmers' associations, etc.) in the Dominican Republic, Guatemala, Honduras, El Salvador and Nicaragua.

Partnerships for resilience – an example for investing in drought resilience in the Horn of Africa

The Intergovernmental Authority on Development (IGAD) and FAO have undertaken pioneering work in policy advocacy and strengthening institutional capacities for good governance. This has been in the form of raising awareness on resilience and the IGAD Drought Disaster Resilience and Sustainability Initiative (IDDRSI), which provides a common architecture elaborated in the Regional Programming Paper (RPP) and the Country Programming Papers (CPPs). FAO, through its diverse expertise in the subregion, has been working with IGAD in the preparation of the CPPs as a basis for investment planning and decision-making. High-level policy consultations were organized by IGAD and FAO in Khartoum, Sudan, and Nairobi, Kenya, bringing together ministers, members of parliament, state/county governors, technical experts and civil society organizations, that led to a deeper understanding of the need by all key players to invest in the priority interventions identified in the CPPs. FAO continues to engage with IGAD in the IDDRSI not only in the capacity of a steering committee member but as a technical partner ready to support in the delivery of the various IDDRSI pillars.

preparedness and prevention on a yearly average; and for those countries most in need, it is less than 1 percent. DRR investment from official development aid (ODA) disbursements was in the range of 0.4 percent in 2010 and 2011 (UNISDR/OECD, 2013) across all sectors.

Prevention and preparing for current and future risks of extreme climatic events is a basic prerequisite for climate change adaptation, and for effective and humanitarian and development work – it is not optional but a must when aiming for sustainable development.

FAO has conceptualized and implements DRR action in many countries (see examples in Box 9), which are recurrently exposed to extreme climate (and other) events, through four mutually supportive pillars that correspond to the Sendai Framework for Disaster Risk Reduction (SFDRR), and are addressed in an integrated and demand-responsive way as articulated by country: (i) the enabling environment through strengthened capacities and enhanced legal and planning frameworks for disaster risk and crisis governance; (ii) understanding the risk and informing decision-making through sector-specific risk monitoring and early warnings; (iii) location-specific practices to prevent and mitigate impacts of natural hazards and disasters; and (iv) enhanced capacities, coordination and planning for preparedness, emergency response and building back better as before during rehabilitation.

B.2 BUILD RESILIENCE OF AGRICULTURAL SYSTEMS

The aim of this section is to briefly showcase some examples of adaptation means in agricultural systems that support food security and nutrition, keeping in mind that actual measures to be implemented are very system- and local context-specific. The section investigates how agricultural systems can be made more resilient, starting from the farm, from crops to livestock, then to forestry and fisheries/aquaculture and broader landscape approaches. Increasing resilience of agricultural systems is here considered with two aims: increasing resilience of the food systems and of the households depending on them for their livelihoods. This in turn requires improvements and stabilization of incomes of populations dependent on agriculture.

The literature on adaptation and food production has increased substantially. Adaptation frameworks generally distinguish between those that are incremental or systemic, often associating them to autonomous or planned adaptation, respectively. However, even incremental or autonomous adaptation needs to be facilitated, supported and enabled, which requires appropriate means, institutions and policies. Incremental changes could require specific planning (see sections B.3.2 and B.4.1).

Depending on the types of agro-ecosystems, incremental changes can be introduced more or less easily, at shorter or longer time scales, and impacts of those changes can take more or less time to be effective.

Importantly, adaptation options need also to take into account the need to sustainably increase production in order to address an increasing demand, driven by population growth and changing diets, as well as potential mitigation co-benefits. In so doing there is a need to carefully assess potential trade-offs or synergies between increased efficiency in the use of resources on the one side and resilience on the other side.

B.2.1 Crop systems

A primary means of increasing the resilience of agriculture-based livelihoods is through increasing and stabilizing the benefits producers obtain from their production systems, and increasing and stabilizing productivity is an essential element in this effort.

Individual farmers can adopt a suite of measures to adapt, the details of which will be contingent on individual circumstances. Nevertheless, broad adaptation themes can be identified (Table 5). These adaptation practices at farm level can be complemented and supported by measures in other sectors, such as agricultural R&D and innovation, and at

Box 10: Developing a methodology for assessing irrigation investment needs

FAO has significant expertise in analysing and improving irrigation systems, and has developed a number of analytical tools and approaches to help identify and prioritize improvements to irrigation systems. The Mapping System and Services For Canal Operation Techniques (MASSCOTE) tool mainly consists in a detailed and comprehensive methodology for analyzing canal operation modernization. From diagnosis through the formulation of operational units and the planning of a service, the MASSCOTE methodology allows for developing tailored technical recommendations for optimizing the performance of irrigation canal systems. However, MASSCOTE does not currently cover in detail the assessment of investment needs, the ownership structure of irrigation systems i.e. which parts of the irrigation system are owned/ managed by which entities (e.g. central government, municipalities, irrigation companies, water user associations, etc.), the ability of the entities involved to borrow, nor their creditworthiness. Given the need to scale up investment in irrigation improvements, in 2013 the EBRD and FAO have started joining efforts to developing the MASSCOTE tool further so that it can be used to inform investment activities in the irrigation sector, and identify irrigation investment priorities. EBRD and FAO are working to develop an additional 'financial/investment analysis module' that can help to identify and prioritize the specific investment needs of irrigation systems and opportunities for private sector participation in such investments. This would serve to identify and quantify the investment needs of specific irrigation systems and provide an investment framework for irrigation upgrades. This new module is to be piloted in Egypt in the next coming months.

landscape levels. They very often require farmers to engage with other food producers to share best practices and experience, and participate in risk monitoring systems (inform and be informed), so as to enhance community-based adaptation (see Box 11).

Adaptive changes in crop management – especially planting dates, cultivar choice and sometimes increased irrigation – have been studied to varying extents, and in many regions farmers are already adapting to changing conditions, many of them being changes made to existing climate risk management practices. Müller and Elliott (2015) found that adaptive changes in crop management have the potential to increase yields by about 7–15 percent on average, though these results depend strongly on the region and crop being considered: for instance, according to IPCC (2007), responses are dissimilar between wheat, maize and rice, with temperate wheat and tropical rice showing greater potential benefits of adaptation.

As agro-climatic zones may shift poleward, cropping might be feasible in previously unsuitable places, such as in parts of the Russian Federation, Canada or of the Scandinavian region, albeit with other constraints due to climate extremes, water limitations or other barriers. This might only compensate for some of the losses in tropical latitude areas.

Developing cultivars with appropriate thermal tolerance characteristics (such as to peak temperatures), or resistant to drought, can be a solution, but breeding takes 8 to 20 years to deliver, which selection planning will need to anticipate (Ziska *et al.*, 2012).

Increasing the efficiency of scarce resources, particularly water, is an important aspect of building resilient livelihoods. One of the main effects of climate change is altering rainfall and water availability patterns, and thus a capacity to deal with water scarcity (or overabundance) will be important in order to maintain productivity levels.

Adapting to increasing drought conditions and water scarcity can be enabled by enhanced water management in agriculture (HLPE 2015) with water storage and improved access to irrigation water, improved irrigation technologies and techniques such as water harvesting. Investment decisions need to take into account needs, availability of water on the long term as well as institutional and financial arrangements (see Box 10). Agronomy practices that enhance soil water retention should also be considered, such as minimum tillage, agroforestry

Table 5: Options for adaptation to climate change at farm level

Risk	Response
Changing climate conditions and climate variability and seasonality	Participate in monitoring schemes when available. Optimization of planting schedules such as sowing dates (including for feedstocks and forage). Plant different varieties, species or cultivars of crops. Use of short duration cultivars. Varieties or breeds with different environmental optima may be required, or those with broader environmental tolerances. The use of currently neglected or rare crops and breeds should be considered. Early sowing enabled by improvements in sowing machinery or dry sowing techniques. Increased diversification of varieties or crops to hedge against risk of individual crop failure. Use intercropping. Make use of integrated systems involving livestock and/or aquaculture to improve resilience. Change post-harvest practices, for example the extent to which grain may require drying and how products are stored after harvest. Consider the effect of new weather patterns on the health and well-being of agricultural workers.
Change in rainfall and water availability	Participate in monitoring schemes when available. Change irrigation practices. Adopt enhanced water conservation measures. Use marginal and waste water resources. Make more use of rainwater harvesting and capture. In some areas, increased precipitation may allow irrigated or rain-fed agriculture in places where previously it was not possible. Alter agronomic practices. Reduced tillage to lessen water loss, similarly the incorporation of manures and compost, and other land use techniques such as cover cropping increase soil organic matter and hence improve water retention.
Increased frequencies of droughts, storms, floods, wildfire events, sea level rise	Participate in monitoring schemes with available General water conservation measures are particularly valuable at times of drought. Use flood, drought and/or saline resistant varieties. Improved drainage, improved soil organic matter content and farm design to avoid soil loss and gullying. Consider (where possible) increasing insurance cover against extreme events.
Pest, weed and diseases, disruption of pollinator ecosystem services	Participate in risk monitoring and preventing schemes when available. Use expertise in coping with existing pests and diseases. Build on natural regulation and strengthen ecosystem services.

or increase in soil carbon and organic matter, among others. New tillage practices can reduce the exposure of topsoil to the air, reducing evaporation, improving soil moisture characteristics and reducing sensitivity to drought and heat. Breeding can lead to new cultivars that send roots down faster and deeper, increasing access to water in the soil profile, or that are more robust to underwater submergence conditions that could become more common in a future climate.

Building resilience in the agro-ecosystems is key to ensure their capacity to provide ecosystem services. Agro-ecology has been defined as: *The discipline that provides the* *basic ecological principles for how to study, design and manage agroecosystems that are both productive and natural resource conserving, and that are culturally sensitive, socially just and economically viable* (Altieri, 1995). This approach can play a critical role to better understand and value ecosystem services provided by interactions inside a specific system. It also enables strengthening them in order to improve the efficiency and resilience of the system. However, as shown above, climate change is modifying relationships between species inside ecosystems. There is therefore an acute need for more research on how climate change is impacting agro-ecosystems, grounded on local specific observation and monitoring, and to establish knowledge-sharing mechanisms enabling farmers to get prepared for projected changes. The International Symposium on Agroecology for Food Security and Nutrition[6] organized by FAO in September 2014 underscored the importance of agroecology for climate change adaptation and resilience.

An essential aspect of adaptation to climate change will be that of increasing the diversity within production systems. This can take many forms: combining different types of production (crop, forest, fish and animal) in different ways; increasing the numbers of different species, populations, varieties or breeds; and increasing the use of materials that are themselves genetically diverse such as crop multilines. These different approaches will help provide the complementarity, option values and risk minimizing strategies that will become increasingly important in the future. Finding ways to combine diversity-rich strategies with the production demands of the future is one of the major challenges for the future and the improved maintenance and use of genetic resources for food and agriculture will lie at the heart of meeting this challenge (FAO, 2015c).

A crucial point to consider in building resilient farm livelihoods is the costs involved in undertaking actions and in particular the implications for financial flows at the household level as this is a key determinant of whether or not households can adopt such measures, and whether or not they can contribute to poverty reduction and food security. For example, for many sustainable land management techniques an increase in labour is required, and this may not be adequately offset by benefits obtained. In some cases, the issue is that the costs are experienced at the initial stages of making a change, while the benefits can be considerably delayed. Restoration of degraded ecosystems can involve even longer periods before positive returns are gained, and involve very significant opportunity costs in the form of foregone income from the ecosystem during restoration. A classic example is restoration of degraded grazing lands, which involves reduction (or even elimination) of grazing for extended periods.

B.2.2 Livestock and pastoral systems

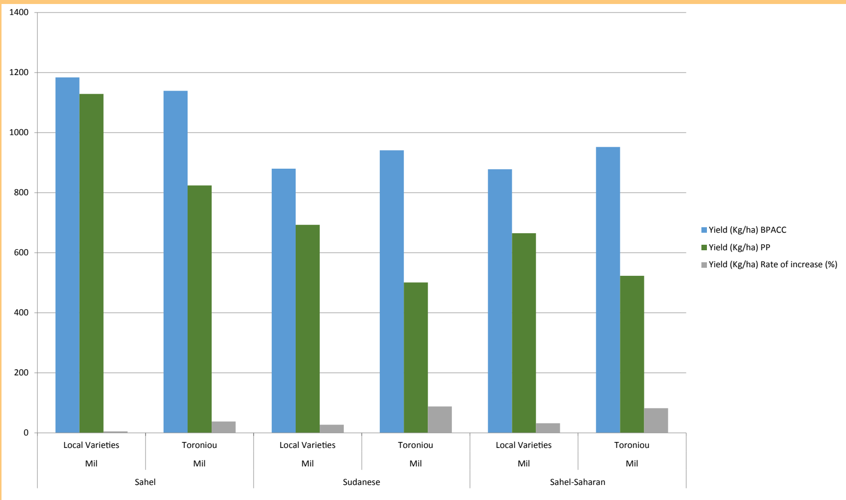
Regions identified as the most vulnerable to climate change, such as sub-Saharan Africa and South Asia, are also regions where farmers and rural communities rely the most on livestock for, income and livelihood, and where livestock is expected to contribute more to food security and better nutrition. Traditionally, livestock keepers have been capable of adapting to livelihood threats and, in some situations, livestock keeping is itself an adaptation strategy, in particular in pastoral communities where livestock have always been the main asset to face harsh climatic conditions (IUCN, 2010; Scoones, 1996; Ashley and Carney, 1999). Livestock can be used as a diversification and a risk management strategy in case of crop failure. Moreover, in some regions, switching from crop to mixed crop–livestock or to livestock systems will be a key adaptation strategy (Jones and Thornton, 2009). Assessing the resilience of livestock production systems, their potential for future growth, and the combined need for long-term investments and timely policy interventions is essential for informing the planning

[6] http://www.fao.org/about/meetings/afns/en/

Box 11: Farmer field schools to integrate climate resilience in Mali

Launched in 2012, the Mali project "Integrating climate resilience into agricultural production for food security in rural areas" builds on some 15 years of field expertise of the Integrated Pest Management Programme (IPPM) on farmer field schools (FFS) and sustainable agriculture supported by FAO and implemented by governments and national stakeholders.

The FFS approach is a community-education approach based on the principles of experimentation, learning by doing and cooperation. Through weekly field learning sessions, groups of 20–25 farmers from the same village are provided with a risk-free environment to test innovations and build their capacity to adapt to climate change throughout the season. Learning is facilitated by a facilitator who underwent the same learning cycle over a season to understand the principles of non-formal education while learning about existing climate change adaptation practices. Therefore, FFS provide ideal learning platforms for farmers to adapt existing climate change adaptation practices from research, extension and traditional practices to their own needs and contexts, as necessary for effective locally-adapted climate change adaptation to take place (FAO, 2013c, Winarto *et al.*, 2008).

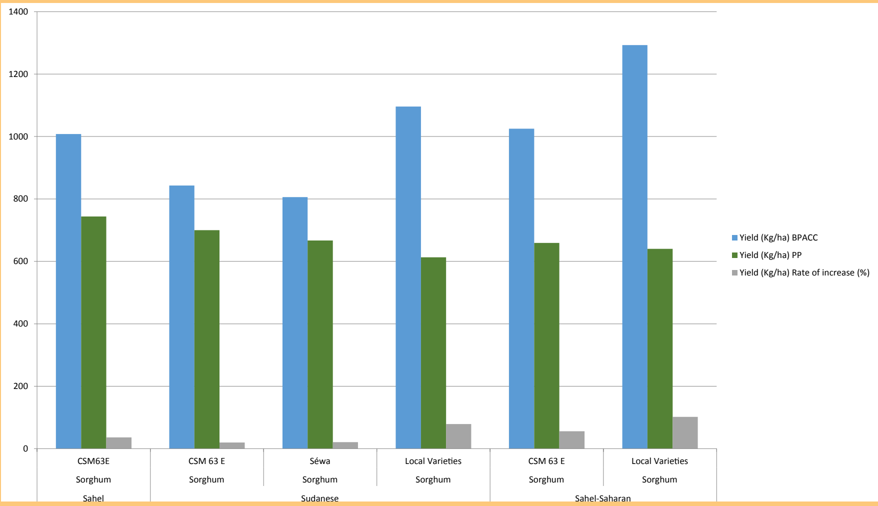


Comparison of sorghum yields for different tested varieties. The comparison is between local seed and ameliorated varieties and between ancestral farmers' technical knowledge (local tradition PP) and techniques introduced via FFS by the climate change adaptation project (BPACC).

of policy-makers, as well as the international community – to better enable them in carrying out efficient and coordinated actions for climate change adaptation.

In the dry lands of sub-Saharan Africa, FAO has collaborated with the World Bank, the International Center for Cooperation in Agricultural Research for Development (CIRAD), IFPRI and the french NGO Action Contre la Faim to assess livestock production under climatic constraint and proposed interventions to increase productivity and reduce the impact of climate variability on livestock outputs. Volume and quality of feed supplies were assessed as well as the degree to which they could meet the animal requirements under different climatic and intervention scenarios, for the period 2012–2030. Results show that 2.5 times more feed resources are needed in a baseline 2012–2030 scenario with similar climate than in the past (1998–2011), and 3.5 times more feed is needed in case of drought. They also show that there is a potential for livestock's growth if feed resources are made accessible, which calls for interventions in animal mobility (corridors, security, border regulations, health, tenure), feed management (storage, processing, transport) and stratification of production to reduce grazing pressure in arid areas. Interventions

The project in Mali aimed to strengthen farmers' capacities to adapt to climate change, building upon an expanding network of FFS initiatives already supported by FAO and the Malian Government. Thanks to the full involvement of the national and local authorities, the project was able to scale up the FFS/climate change adaptation approach from 9 communes (2012) to more than 134 communes (2014). It resulted in the capacity building of 16 237 producers of which 5 321 women, the adoption of improved seeds in 242 villages within 134 communes, with the dissemination of 13 improved/adapted varieties of sorghum, cowpea, rice, millet and maize in three agro-ecological zones; the implementation of four new agroforestry perimeters managed and maintained by four farmers organizations, of which 75 percent of the members are women. It also included the preparation of a facilitators' training guide embedding more than 30 modules on FFS/climate change adaptation best practices (FAO, 2014b).



Comparison of millet yields for different tested varieties in 2014. The comparison is between local seed and ameliorated varieties and between ancestral farmers' technical knowledge (local tradition PP) and techniques introduced via FFS by the climate change adaptation project (BPACC).

can significantly increase the output of livestock products in the African drylands (5 to 20 percent) if accessibility to feed is improved. Shocks brought by climate-driven variability on livestock production can be buffered through animal movements, adjustments in feed baskets, health interventions and animal offtake for market: while interannual variability in biomass reaches 16 percent in the baseline scenario, variability in animal intake is brought down to 7 to 14 percent, depending on the interventions considered, and variability of animal product is brought down to 1 to 8 percent. Results therefore confirm that livestock is a strong asset for adaptation in pastoral areas.

Livestock's adaptive capacity depends on the production system, including choice of species and breeds, the availability/adaptability of alternative feed resources, the accessibility of animals (health/extension services), the type/efficiency of response to outbreaks (surveillance, compensation schemes, etc.) and the household wealth status (ICEM, 2013).

A range of adaptation options is available for livestock production (Table 6). They exist at different scales: animals, feeding/housing system, production system and institutions. They

Table 6: Climate change adaptation options in the livestock sector

Animals	Forage and feed crops	Labour force and capital
• Water management (e.g. boreholes) • Breed on resistance to drought, heat and harsh environments • Shifts in species, breeds and/ or production system (e.g. small ruminants, poultry) • Disease control and animal health • Cooling (indoor systems) or provide shade (e.g. trees)	• Irrigation • Purchase feed, supplementation • Breed feed crops and forages for water use efficiency and for resistance to drought, salinity and waterlogging • Grazing management • Changes in cropping calendar • Agroforestry • Increase mobility for resources	• On- and off-farm diversification • Insurances • Reconversion (in the context of national/regional production zoning) • Institutional changes (e.g. trade, conflict resolution, income stabilization programmes

also differ between small-scale livestock production with low market integration and large-scale production with high market integration.

In particular, breeding livestock but also feed crops and forages is a major component of building resilience to climate change. Many livestock breeds are already well adapted to high temperatures and harsh environments (see Box 13), but the wider diffusion of such breeds or their incorporation into breeding programmes is restricted by the limited extent to which they have been characterized and improved in structured breeding programmes (Madalena, 2008) and by trade constraints (Gollin, Van Dusen and Blackburn, 2008). Adaptation traits are more difficult to study and to record than production traits, have lower heritability, higher levels of non-additive genetic variation and phenotypic variance, and are more susceptible to genotype-by-environment interaction (Frankham, 2009).

The speed of climate change may outstrip the ability of breeds to adapt genetically or that of their keepers to adjust their management strategies. In places, this may break the link of adaptation between local livestock and their production environments (see Box 3 on Kenyan Kamba cattle). If such effects occur, adapting production systems and animal genetic resources management will be a major challenge and may increase the need for moving better-suited species and breeds into new areas. It will be critical to ensure that plans to introduce new breeds take into account climatic and other agro-ecological and socio-economic conditions and their predicted future trends. Breeds introduced to new geographical areas should have a range of advantageous traits, as introductions of breeds considering only one trait have not been successful (Blackburn and Gollin, 2008). Furthermore, access to inputs and livestock services relevant to climate change adaptation needs to be improved. Specifically for animal genetic diversity, this requires: better characterization of breeds, production environments and the associated knowledge; the compilation of more complete breed inventories; improved mechanisms to monitor and respond to threats to genetic diversity; genetic improvement programmes targeting adaptive traits in high output and performance traits in locally adapted breeds; more effective *in-situ* and *ex-situ* conservation measures; increased support for developing countries in their management of animal genetic resources; and wider access to genetic resources and associated knowledge.

While irrigation of feed crops and grasslands as well as purchasing feed are immediate farm-level coping mechanisms for short-term adaptation to climate change, there exist long-term options such as breeding feed crops and forages for water use efficiency, resistance to drought, salinity and waterlogging. More systemic, longer-term adaptation options include grassland restoration or diversification in composition; agroforestry with fodder trees and legume shrubs to provide alternate feed resources, shade and retain water; or animal and feed mobility. In grazing production systems, these long-term adaptation strategies addressing variability of already scarce feed resources while providing other types of environmental

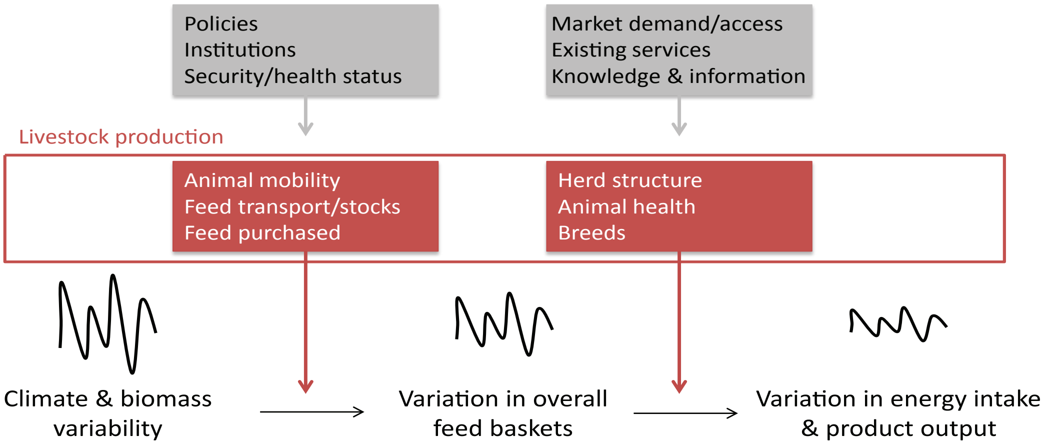


Figure 4. Attenuation of climate variability effect on herd performances.
Source: Mottet *et al.* (2015)

services, such as mitigation of greenhouse gas emissions or biodiversity conservation, are particularly relevant and should be supported by public policies.

Impact assessments are a prerequisite to the development of adequate policy response to climate change in the long term (IPCC, 2007; 2014a). Havlík *et al.* (2015) have noted the need for impact assessment frameworks that could be used to estimate costs and benefits of adaptation options. Such frameworks should pay specific attention to forages and feed resources, which are critical to better assess adaptation needs in livestock. Developments in satellite imagery could also contribute to this effort through monitoring of soil moisture, leaf area index, infra-red imaging of drought or even pasture and water points monitoring for seasonal adjustments of stocking density and mobility. They represent important potential for early warning systems.

Finally, better information is needed on adaptive responses to not only climate stress but also other interwoven stresses such as nutrition and diseases.

B.2.3 Forests

Forests contribute to the resilience of agricultural systems in many ways. At landscape level, they contribute to water and temperature regulation and provide habitats for important species such as pollinators. At household level, forests and trees play important roles in livelihood resilience in the face of climate change, including:

- as safety nets in times of emergency;
- as sources of products important for production and income diversification for farm households and rural families;
- as sources of employment (particularly important where farming and other rural livelihoods are no longer viable).

The importance of forests as safety nets in times of natural disasters (e.g. floods and droughts) or civil unrest is well documented (e.g. Angelsen and Wunder, 2003). During these times, forests are often relied upon to provide food for the household or products to sell for survival. They also fill gaps in other times of difficulty. While heightened dependence on forest foods and products generally drops off when times return to normal, it is important to keep the safety net option open (i.e. not restricting access of vulnerable people to forests when needed for survival), particularly where relief services and social services are not adequately developed to meet emergency needs.

Maintaining forest ecosystems in a healthy state is the most straightforward action to retain their resilience. Healthy forests are better able to cope with stress, recover from damage and adapt autonomously to change. Healthy ecosystems are more resilient to negative biotic and

Box 12: The state of animal genetic resources with regard to climate change adaptation

According to FAO (2006), 1 074 breeds were identified as adapted to drylands. In the Near East, 90 percent of all the region's breeds are kept in the drylands. In Africa, 56 percent of all breeds are adapted to drylands, 42 percent in Asia and only 19 percent in Latin America. On average, 46 percent of the breeds in the four regions are adapted to drylands, and many of them are transboundary. More than 70 percent of breeds of ass, around 50 percent of sheep and goat breeds and 30 percent of cattle and horse breeds reported are adapted to arid areas (FAO, 2006).

Of the 135 populations said to be kept in arid/semi-arid areas, steppe or marginal areas, 81 percent are described to be adapted to a dry or hot climate, or hot summers and cold winters; 53 percent of 108 populations adapted to high mountains, highlands and mountainous areas are said to be adapted to cold and hot-and-cold climates.

The ability to cope with extreme weather conditions will become increasingly important. Breeds occur in impressive temperature ranges, for example 158 populations can continue to function at average monthly temperatures ranging from –9 °C to 39 °C, and the temperature range of 104 populations spans from 0 °C to 44 °C. Obviously, average monthly climate data at national level, especially in large countries or countries with long north–south axes, mask considerable local variation. The ability to resist temperatures below –20 °C is pronounced for populations in high mountains, mountains, arid/ semi-arid areas and steppe. On the other side of the temperature range, many populations adapted to arid/semi-arid areas and mountains, marginal areas and harsh environments are able to resist temperatures higher than 40 °C.

A temperature humidity index (THI) of higher than 70 is commonly assumed to be the onset of physiological heat stress (Bohmanova, Misztal and Cole, 2007; Dikmen and Hansen, 2009). A total of 9 748 national breed populations (79 percent) of studied species live in countries where the average THI of the hottest month exceeds 70; in Africa and Asia there are even 64 populations in countries with average THI exceeding 90. More than 80 percent of populations described as hardy, locally adapted, drought-resistant and rustic occur in countries with a THI between 70 and 95, implying that they are able to cope with high THI.

It needs to be kept in mind that the country-level THI of the hottest month used for the analysis, derived from average temperature and humidity, can only be considered a rough approximation, as it masks daily and regional variation. Despite the methodological imperfection, the results imply that countries with high THI offer potential for selection of heat-resistant animals. So far, only a few countries with well-developed breeding institutions, research, extension and artificial insemination services have commercially relevant tropical cattle breeds, tropically adapted taurine, indicine or composites (e.g. Australia, Brazil, Kenya, South Africa and the United States of America), and even fewer countries have commercially significant breeding programmes for adapted breeds of the other species (Madalena, 2008). Most selection relevant to climate adaptation is undertaken in developed countries with commercial breeds, most of which are of temperate origin. Considerable genetic variance caused by heat stress was related to high daily THI in Jersey and Holstein Friesian dairy cattle (Ravagnolo and Misztal, 2002; Hayes *et al*., 2009). Therefore, selection for heat tolerance in high-output breeds based on rectal temperature measurements and inclusion of a THI in genetic evaluation models is promising. Hayes *et al.* (2009) also identified genetic markers associated with sensitivity of milk production to feeding level, a trait that may become important assuming that future dairy systems become more reliant on pasture than grain feeding.

abiotic influences than are ecosystems under stress whose ecological processes are impaired. Best practices include integrated pest management, disease control, forest fire management, employment of reduced impact logging in production forests, limitation of gathering of non-wood forest products or livestock grazing in forests at sustainable levels, and forest

With increasing milk yield in dairy cattle, growth rates and leanness in pigs or poultry, metabolic heat production has increased and the capacity to tolerate elevated temperatures has declined (Zumbach *et al.*, 2008; Dikmen and Hansen 2009). In beef cattle, the genetic antagonisms between adaptation to high-temperature environments and high-production potential seem to be less pronounced than in dairy. Breeding goals may have to be adjusted to account for the effects of climate change such as higher temperatures, lower-quality diets and greater disease challenge. Several Latin American cattle breeds with very short, sleek hair coats were observed to maintain lower rectal temperatures, and research in the major "slick hair" gene, which is dominant in inheritance and located on Bovine Chromosome 20, is ongoing (Olson *et al.*, 2003; Dikmen *et al.*, 2008). This gene has now been introgressed in some Holstein populations.

It is therefore very important to develop methods for characterizing adaptive traits relevant to climate change adaptation and comprehensively evaluate performance and use of animals in specific production environments, and for describing these production environments in a standard way. Such techniques should be included in phenotypic characterization studies and breed surveys. As management (e.g. night grazing) influences exposure, relevant local and indigenous knowledge needs to become a topic of research. Local knowledge of how to cope with harsh and fluctuating production environments also needs to be integrated within climate change adaptation strategies. Breeding strategies to improve animals' abilities to cope with several climate change-related problems are possible and are likely to become increasingly important in the future.

Number of national breed populations with information on specific adaptation traits reported by countries in the Domestic Animal Diversity Information System (DAD-IS)

	Total number of breeds with information	Highest frequency of mention	Second highest frequency of mention	Third and subsequent frequency
Climate adaptation	664	38% are adapted to dry, hot and hot dry climates	20% are adapted to hot humid climates	16% are adaptable to changing temperatures and humidity or to both hot and cold temperatures, 14% are adapted to cold climate, either dry or wet, and another 8% support hard continental climate with hot summers and cold winters
Fodder and feeding adaptation	413	40% cope well with poor fodder quality or coarse vegetation	26% deal well with walking and selecting poor quality vegetation or thriving on pastures	15% withstand irregular or long feeding or watering intervals
Habitat	834	45% are adapted to high mountains, mountains, highlands and hills	16% are adapted to arid/semi-arid areas or steppe	

Source: Hoffmann (2013)

law enforcement. Restoring degraded forests to healthy states, thereby re-establishing ecosystem functions, is a major strategy for increasing resilience. An estimated two billion hectares of land have the potential to be restored or reforested.[7] Biodiversity is a key factor

[7] See: *A world of opportunity for forest restoration* http://pdf.wri.org/world_of_opportunity_brochure_2011-09.pdf

underlying the resilience of forest ecosystems and trees to existing stresses and is a basic ingredient for building their adaptive capacity in the face of future stresses. Thompson *et al.* (2009) highlight some actions that may be taken to maintain or increase resilience in forests through management and use of biodiversity, at all scales. Table 7 provides examples of forest management measures consistent with these. A more complete set of management options is available in the publication *Climate change guidelines for forest managers* (FAO, 2013d).

While broad regional and national patterns of climate change can be predicted with some certainty using climate models, making accurate predictions of the dimensions and character of changes at local level is problematic. The uncertainties associated with projections of climate change at local level, coupled with uncertainties about how impacts will reverberate in complex natural systems, make it difficult for resource managers to decide which adaptation actions would be most appropriate and cost effective to take. The fact that forest resources are generally managed on medium- to long-term time cycles, in which the ability to make rapid changes is constrained, adds to the challenge. Measures that respond to expected trends in climate and that are consistent with sustainable forest management practices, represent "no regrets" options (Seppälä, Buck and Katila, 2009). These are the logical starting point. Actions, for example, to reduce the risk and control against wildfires and pest outbreaks, where they exist, would convey benefits in any case.

Implementing best practices for forest management and implementing "no regrets" options that will help forests cope with change and recover from disturbance will not be sufficient, however. Forest managers will need to take additional measures to increase the adaptive capacity of forests. Adaptive management is particularly relevant in environments where the future is uncertain (Robledo and Forner, 2005). Adaptive management involves a systematic

Table 7: Examples of measures to increase forest resilience to various impacts of climate change

Risks/impacts	Implications (social, economic, environmental)	Response measures for risk reduction and increased resilience
Decreased forest vitality and productivity	Reduced revenue from wood and non-wood forest products; reduced forest ecosystem services	Adjust silvicultural practices, change composition of species and varieties; increase forest biodiversity; implement forest restoration measures
Increased forest pests and diseases	Reduced forest revenue; reduced forest ecosystem services	Implement and intensify pest and disease management measures; adjust silvicultural practices
Increased wildfires	Loss of life; damage to infrastructure; reduced forest revenue and ecosystem services; wildlife losses	Implement and intensify wildfire management; adjust silvicultural practices
Increased water erosion and landslides	Damage to forest and to infrastructure (towns, roads, dams); reduced water quality	Undertake watershed management measures (including protecting and increasing vegetation cover; reducing intensities of harvesting and other uses)
Drought-induced forest/tree dieback and land degradation	Reduced availability of forest products; increased wind damage; reduced grazing values	Plant windbreaks; maintain tree cover; change composition of species and varieties
Increased storm damage	Reduced forest revenue and ecosystem services; increased risk of pests and disease	Change species and adjust tree spacing to reduce risk; salvage harvesting; pest/disease control
Reduced extent and vitality of mangroves and coastal forests	Increased exposure of land to storm damage; reduced productivity of coastal fisheries	Increase protection, restoration and enhancement of mangroves and other coastal forests
Changes in species ranges and species extinctions	Reduced forest ecosystem functions; loss of forest biodiversity	Restore/increase forest connectivity and wildlife corridors; assist migration; take *ex-situ* conservation actions

process for continually adjusting and improving management practices by monitoring, analysing and learning from the outcomes (Seppälä, Buck and Katila, 2009). This process of observation, analysis, planning, implementing, monitoring and taking corrective action for further improvement is in itself a valuable adaptation tactic, particularly where the speed, direction and impacts of climate change are difficult to predict. Setting up systems for forest management conducive to adaptive management can help keep improvements in resilience in step with climate changes.

B.2.4 Fisheries and aquaculture systems

There are a range of risks for fisheries and aquaculture that are associated with oceanic acidification climate variability and climate change and these will involve direct physicochemical and bioecological impacts, as well as social, economic and political consequences (FAO, 2009b; IPCC 2013 and 2014a). Effective and well-measured protection against these outcomes will be a major challenge. There may also be positive opportunities in fisheries and aquaculture, as changing conditions may improve ecosystem functions and increase productivity. However, in most scenarios, even if net outputs across an ecosystem, region or globally are relatively stable, changing spatial and economic distributions of supply and demand will create an additional development burden and this burden will be particularly felt by poorer or more vulnerable groups.

In a number of contexts, interactions between fisheries, aquaculture and other sectors affected by climate change, are also likely to be important. Inland fisheries are particularly sensitive to policies and actions outside the sector that impact freshwater quality, quantity and flows. In the same vein, many coastal environments are also increasingly subject to changes in freshwater runoff, agricultural intensification, growth in the industrial and energy sector, expanded urbanization, transport and tourism development. For aquaculture, there are similar issues of interaction and trade-offs with other sectors, particularly regarding land and water use, aquatic and terrestrially-derived feeds, and the negotiation of coastal and riverine space (HLPE, 2014).

Vulnerability to climate change in fisheries and aquaculture is experienced across a range of productive, social and political dimensions and will also depend on timing and locations of changes. For example, climate risks may be felt at a very specific location and in a targeted manner (e.g. through increased storm events in a small fishing location), or at a broader scale, as in the impacts of a shift in temperature and freshwater balances across a major river delta and its associated coastal system, or as a range of risks impacting on a range of people and communities with different capacities to cope with and adapt to the potential impacts. As with other sectors, vulnerability is also highly connected with other factors, such as the availability of human, social and political capital, access to services and other resources, and options for alternative livelihoods. Options for reducing vulnerability are commonly defined by the nature and severity of the risks involved, the comparative costs of physical and other responses required to reduce impacts by definable amounts, and the capacity of individuals, communities and organizations to analyse, prioritize and implement the appropriate actions.

There is increasing knowledge on how to build and maintain resilience of the natural and human systems and in the fisheries and aquaculture sector. The 1995 Code of Conduct for Responsible Fisheries (FAO, 1995) contains the principles and standards applicable to the conservation, management and development of the world's fisheries, including aquaculture, such as the prevention of overfishing, the minimization of negative impacts to aquatic ecosystems and local communities, and the protection of human rights to a secure and just livelihood. The ecosystem approach to fisheries and aquaculture (EAF/EAA)[8] provides the approaches, strategies and tools for implementing the Code and implies a holistic, integrated

[8] See FAO 2003, 2009b, 2010 and FAO, 2015h

Table 8: Overview of practical options for reducing vulnerability in fisheries and aquaculture

Impact area	Potential responses
Capture fisheries	
Reduced yield	Access higher-value markets; shift/widen targeted species; increase fishing capacity/effort*; reduce costs/increase efficiency; diversify livelihoods, exit fishery
Increased yield variability	Diversify livelihoods; implement insurance schemes; promote adaptive management frameworks
Change in distribution	Migrate fishing effort/strategies and processing/distribution facilities; implement flexible allocation and access schemes
Sea-level change, flooding, and surges	New/improved physical defences; managed retreat/accommodation; rehabilitation and disaster response; integrated coastal management; early warning systems and education
Increased dangers of fishing	Weather warning systems; improved vessel stability/safety/communications
Social disruptions/new fisher influx	Support existing/develop new local management institutions; diversify livelihoods
Aquaculture	
Extreme weather events	Improve farm siting and design; individual/cluster insurance; use indigenous or non-reproducing stocks to minimize biodiversity impacts
Temperature rise	Better water management, feeds, handling; selective breeding/genetic improvements; adjust harvest and market schedules
Water stress and drought conditions	Improve efficacy of water usage; shift to coastal aquaculture, culture-based fisheries; select for short-cycle production; improve water sharing; improve seed quality, efficiency,
Sea-level rise and other circulation changes	Shift sensitive species upstream; introduce marine or euryhaline species (wide salinity tolerance); use hatchery seed, protect broodstock and nursery habitats
Eutrophication/upwelling, harmful algal blooms	Better planning; farm siting; regular monitoring; emergency procedures
Increased virulence of pathogens, new diseases	Better management to reduce stress; biosecurity measures; monitoring; appropriate farm siting; improved treatments and management strategies; genetic improvement for higher resistance.
Acidification impact on shell formation	Adapt production and handling techniques; move production zones, species selection
Limits on fish and other meal and oil supplies/price	Fish meal/oil replacement; better feed management; genetic improvement for alternative feeds; shift away from carnivorous species; culture of bivalves and seaweeds
Post-harvest, value addition	
Extreme event effects on infrastructure/ communities	Early warning systems and education; new or improved physical defences; accommodation to change; rehabilitation and disaster response
Reduced/more variable yields, supply timing	Wider sourcing of products, change species, add value, reduce losses, costs; more flexible location strategies to access materials; improve communications and distribution systems; diversify livelihoods
Temperature, precipitation, other effects on processing	Better forecasting, information; change or improve processes and technologies
Trade and market shocks	Better information services; diversify markets and products

Source: adapted from Daw *et al.* (2009); De Silva and Soto (2009)
*Note: Some autonomous adaptations to declining and variable yields may directly risk exacerbating overexploitation of fisheries by increasing fishing pressure or impacting habitats.

and participatory way to managing fisheries and aquaculture systems, from precautionary and adaptive management frameworks to low-impact and efficient production systems to improve human and ecological well-being. Tools and best practices for reducing vulnerability in specific conditions are still being developed and validated within the fisheries and aquaculture sector. However, in addition to the general resilience-building and "no regrets" approaches, a number of practical options across the production chains can be identified as shown in Table 8. Some autonomous adaptations to declining and variable yields may directly risk exacerbating overexploitation of fisheries by increasing fishing pressure or impacting habitats. Box 13 describes an example of adaptive regional management of tuna fisheries.

Application of the Code of Conduct and the EAF/EAA will help to ensure that effective stakeholder involvement in both monitoring changes and adaptation planning becomes the default approach to ensuring resilience of the socio-ecological systems and to minimize unintended consequences of adaptation and mitigation actions. Integrated adaptation planning and implementation within a systems' approach will allow for the specificity needed within each sector but also for addressing issues shared across sectors within a broader system. Efforts are needed to improve and downscale our understanding of current vulnerabilities and adaptation strategies of the sector to prepare the sector for its own climate change planning but also to enable the sector to participate in national climate change planning, including providing feedback on the impacts of adaptation and mitigation actions from other sectors. Technological innovation, public and private insurance schemes and disaster risk management will also provide necessary adaptation options, but putting into place robust and effective management now will be the key to ensuring and enhancing the benefits derived from fisheries and aquaculture.

B.2.5 Building resilience at landscape level

In most areas, agricultural production is embedded within a broader landscape influenced by a range of biophysical, social and institutional forces. Many ecosystem services relevant for agricultural production, such as pollination, pest and disease resistance, watershed protection and erosion control, occur over landscape scales. These services are directly related to resilience of agricultural livelihoods through their impacts on reducing environmental risks and improving coping capacities (FAO, 2007; McCarthy *et al.,* 2010).

Adopting a landscapr approach to management includes taking into consideration the physical and biological features of an area as well as the institutions and people who influence it. The interconnectiveness of these factors underlines the value of working across sectors and addresses environmental, social and economic issues in an integrated way. The landscape is a useful unit on which to work in an integrated manner. Working at the landscape level is conducive to building resilience of land-use systems, natural resources and people's livelihoods in a cohesive way and supported by effective institutional and governance mechanisms. It is more likely to optimize their contributions to the stability and vitality of ecosystems and their ability to support societal needs in a sustainable manner. Understanding the dynamics between the different elements (biophysical, social, economic and institutional) and engaging local stakeholders in decisions will help in the development of strategies and actions to increase resilience (Braatz, 2012).

Two examples of integrated approaches within a wider landscape context are provided below (taken from FAO, 2012b):

- Watershed management has been successfully used to restore and maintain the agro-ecological viability and production potential of various watersheds throughout the world, using land-use management techniques that integrate across sectors and also address socio-economic concerns of local populations. Decades of strong technical support and lessons learned in the process have led to increased awareness by decision-makers of the importance of supporting integrated watershed management programmes and projects that engage local stakeholders in participatory planning and management (FAO, 2006).

Box 13: Adaptive regional management of tuna fisheries

The industrial fisheries for skipjack and yellowfin tuna in the equatorial waters of the western Pacific Ocean make important contributions to the global supplies of fish and to the economies of Pacific island countries (PICs). The 1.3 million tonnes of tuna caught each year from the exclusive economic zones (EEZs) of PICs supply 25 percent of the world's canned tuna; licence fees from foreign fishing fleets contribute up to 10–40 percent of government revenue for several small island nations; and locally based tuna fishing vessels and canneries account for as much as 20 percent of the GDP of some PICs. But the effects of the *El Niño* -Southern Oscillation (ENSO) on the distribution and abundance of these two species of tuna make it difficult to know when and where these important benefits will occur. During *La Niña* events, tuna catches are greatest in the western part of the region. During *El Niño* episodes, the best catches are made further east.

To keep catches within sustainable bounds, and optimize the distribution of economic benefits, the eight PICs where most of the tuna are caught control and distribute fishing effort by the purse-seine fishery through the 'vessel day scheme' (VDS). These eight countries are known as the Parties to the Nauru Agreement (PNA)* The VDS sets a total allowable effort within PNA waters. This total effort is allocated among the EEZs of PNA members, based on historical average patterns of fishing. Members are able to trade fishing days between themselves to cater for situations where the fish, and hence fishing vessels, are unusually concentrated either in the west or east due to the influence of ENSO events. The trading component aims to ensure that all PNA members continue to receive some level of benefits from the fishery, regardless of where tuna are concentrated. The VDS not only allows the purse-seine fishery to deal with climatic variation, it has the flexibility to allow the fishery to adapt to climate change. Allocation of vessel days to PNA members based on fishing effort history is adjusted regularly. Therefore, as the projected redistribution of tuna to the east occurs under the changing climate, the periodic adjustment of allocated vessels days will reduce the need for members to trade fishing days.

* PNA members are: Federated States of Micronesia, Kiribati, Marshall Islands, Nauru, Palau, Papua New Guinea, Solomon Islands and Tuvalu [www.pnatuna.com].

Source: Bell, Johnson and Hobday (2011)

Watershed management is also increasingly recognized as an appropriate approach in disaster risk management, particularly related to landslides, avalanches and floods.

- Fire management has recently undergone a transition away from a forestry approach to a broader landscape approach, in which agriculture, forestry and rangeland concerns are considered simultaneously in order to better identify the causes and ultimately prevent destructive vegetative fires that often cross the boundaries of different land-use systems. An integrated approach of fire management supports building higher resilience and adaptive capacity of communities and ecosystems to the effects of vegetation fires.

Landscape approaches are also quite well developed in arid zones – such as the "gestion de terroirs" approach in West Africa, dating to the early 1990s, in which natural resource management at the village or community level links technical interventions, socio-economic factors and the legal and administrative functions. Sustainable land management for soil and water conservation is increasingly being planned and managed with the scale and principles of the landscape approach in mind. Sustainable mountain development and integrated coastal zone management are other examples of the landscape approach in action.

Recognition of the importance of cross-sectoral approaches at the landscape level is growing as well as political support. Institutions, networks and partnerships have emerged in recent years aiming to improve rural livelihoods, land-use planning and management by adopting integrated approaches to land use. Examples include:

- The Global Partnership on Forest and Landscape Restoration,[9] that aims to catalyse support for the restoration of forests and degraded lands to ensure that forests, trees and the functions that they provide are effectively restored, conserved and employed to help secure sustainable livelihoods and ecological integrity for the future.
- The International Model Forest Network (IMFN),[10] which supports the establishment of model forests, based on an approach that combines the social, cultural and economic needs of local communities with the long-term sustainability of large landscapes in which forests are an important component. By design they are voluntary, broad-based initiatives linking forestry, research, agriculture, mining, recreation, and other values and interests within a given landscape.
- The Landscapes for People, Food and Nature Initiative,[11] a collaborative three-year process of research, discussion, knowledge-sharing and advocacy that aims to develop action agendas for policy, investment, capacity building and research and to support their implementation through action and advocacy within UN conventions and key regional platforms.
- The Global Partnership for Climate, Fisheries and Aquaculture (PACFA)[12], a voluntary partnership comprising 20 international organizations and sector bodies, with a common concern for climate change interactions with global waters and living resources and their social and economic consequences. The partnership was borne from a mutual desire to draw together potentially fragmented and redundant climate change activities through a multi-agency global programme of coordinated actions and to address the pressing need to raise the profile of fisheries and aquaculture in the global climate change discussions.

B.3 MANAGING GENETIC RESOURCES

Crops, livestock, forest trees and aquatic organisms that can survive and produce in future climates will be essential in future production systems (FAO, 2015a, Galluzzi *et al.*, 2011). This will require revising the goals of breeding programmes (HLPE, 2012a), and in some places it is likely to require the introduction of varieties and breeds, even species, that have not previously been raised in the local area. Breeding programmes take time to reach their goals and therefore need to start many years in advance. Genetic resources for food and agriculture are among the keys to efficiency, adaptability and resilience in production systems. They underpin the efforts of local communities and researchers to improve the quality and output of food production (FAO, 2015a).

It is vital to preserve the genetic diversity we have today, as it will be key to adapt agriculture and food production to future changes (FAO, 2015a; Jarvis *et al.*, 2010). Improvements to *in-situ* and *ex-situ* conservation programmes for domesticated species, their wild relatives and other wild genetic resources important for food and agriculture, along with policies that promote their sustainable use, are therefore urgently required.

FAO, the Consultative Group on International Agricultural Research (CGIAR) and other actors in this field are working to improve the knowledge needed to better use the potential of genetic resources to cope with climate change and increase the resilience of future production systems. Information is being gathered on the resources, where they are found, what characteristics they have (e.g. resistance to drought or disease) and how they can best be managed. Unfortunately, many locally adapted varieties and breeds of crops and livestock are poorly documented and may even be lost before their potential roles in climate change adaptation are recognized (Beed *et al.*, 2011; Cock *et al.*, 2011; Jarvis *et al.*, 2010; Loo *et al.*, 2011; Pilling and Hoffmann, 2011; Pullin and White, 2011).

---

9 http://www.ideastransformlandscapes.org/
10 http://www.imfn.net
11 http://www.landscapes.ecoagriculture.org/
12 http://www.fao.org/pacfa/en/

Box 17: Community-based management of genetic resources

The need to replenish diversity in agricultural systems has encouraged the community management of genetic resources. This has resulted in the establishment of community seed banks to facilitate the revival and distribution of traditional and stress-tolerant crops and varieties. In Uttar Pradesh, India, the establishment of seed banks to facilitate the diversification of local food systems is one of the flood coping mechanisms (Wajih, 2008).

In Honduras, farmers organized community-based agricultural research teams to diversify their plant genetic resources and develop hardier plant varieties that grow well on their soils. Responding to the higher occurrence of hurricanes, farmers were able to produce, through a participatory breeding process, improved maize varieties that are shorter and capable of withstanding the physical trauma brought by the hurricanes, with a higher yield and yet still adapted to high-altitude conditions. The selection process was accompanied by a conservation effort, as the seeds of the selected species are stored in a community seed bank, assuring availability of healthy and resistant plants (USC Canada, 2008).

In Colombia, Panama, Peru, Bolivia, Ecuador, Thailand, India and other countries, indigenous organizations are actively involved in the protection of traditional knowledge and reintroduction of indigenous crop varieties of vegetables, tubers, grains, beans and fruit. The Potato Park in Cusco, Peru, was created in 2005 to protect the genetic diversity of local potato varieties and associated indigenous knowledge. The project demonstrates the link between the protection of agrobiodiversity and the protection of indigenous people's rights, livelihoods and culture. Indigenous Quechua communities involved in the project have brought back from a gene bank into their fields over 400 potato varieties to ensure the adaptation to changing climatic conditions (Argumedo, 2008).

The roles of invertebrates and micro-organisms in food and agriculture are even less well studied (Beed *et al.*, 2011; Cock *et al.*, 2011). The same is true of many forest trees and aquatic organisms (Loo *et al.*, 2011; Pullin and White, 2011). Characterization studies for genetic resources are therefore a priority.

In crop production, maintaining genetic diversity has long been an essential element of strategies to reduce the effects of crop diseases and abiotic stresses such as drought. While it is difficult to predict the precise effects that climate change will have on the distribution and severity of diseases and unfavourable climatic conditions, the availability of greater genetic diversity is likely to increase the resilience of crop production systems in the face of new climatic and disease challenges. Community based initiatives can be particularly effective in that respect (see Box 17). Improving collections of crop wild relatives is important, as they are likely to have genetic traits that can be used in the development of well-adapted crops for use in climate change-affected production systems (FAO, 2015a).

Genetic diversity is also a vital resource for the livestock sector. Most livestock diversity is maintained *in-situ* by farmers and pastoralists. Breeds developed in harsh production environments (e.g. hot, drought-prone or disease-infested areas) are often well adapted to conditions that may become more widespread as a result of climate change. However, rapid changes to the livestock sector are threatening many locally adapted breeds and the production systems in which they are raised. Measures to promote the sustainable use and development of these breeds, and where necessary *in-situ* and *ex-situ* conservation measures to prevent their loss, are urgently needed (Pilling and Hoffmann, 2011). The genetic diversity of the world's livestock provides a range of options (see Box 18) that are likely to be valuable in climate change adaptation, including resistance and tolerance to specific diseases, adaptation to poor-quality diets or to feeding in harsh conditions, and tolerance of climatic extremes. Most locally adapted breeds are, however, not well characterized. The Domestic Animal Diversity

Box 18: Genetic diversity of the world's livestock: options for adaptation

Native breeds such as the Red Maasai sheep are valued by local farmers for their tolerance of harsh climatic conditions and disease resistance, but exotic breeds such as the Dorper breed from South Africa have been introduced because of their higher productivity during non-drought periods. As a result the Red Maasai sheep is threatened by extinction due to uncontrolled cross-breeding with the exotic Dorper breed. This is a concern as there is an anticipated rise in the frequency of droughts. Conserving the ability of Red Maasai sheep breed to withstand drought and disease and simultaneously increasing productivity in this extensive low-external input system is thus a main breeding goal (Audho *et al.*, 2015).

The Mediterranean region is a global "hot-spot" of climate change. Global warming and its impacts on the environment and people will be more pronounced than elsewhere. For example, in the coming decades, the Mediterranean climate will extend inland, reaching the areas of the Massif Central. The GALIMED Project – Genetic Adaptation of Bovine Livestock and Production Systems in the Mediterranean region – is aimed at genetically characterizing the local adaptation of Mediterranean breeds to their agroclimatic conditions, to provide solutions for breed conservation, to better define the breeding goals, to evaluate livestock practices and exploit them to cope with the consequences of global climate change (Audho *et al.,* 2015).

Information system of FAO[13] lists numerous breeds, particularly from mountainous and arid areas, that are adapted to extreme ranges in temperature and such breeds may merit further research (Hoffmann, 2013).

Species diversity tends to increase the resilience of natural and planted forests in the face of climate change and variability, because it increases the likelihood that some of the species present will be able to cope as conditions change. Genetic diversity within individual species similarly increases the likelihood that the species will be able to adapt to the new environmental conditions driven by climate change (FAO, 2015a). In planted forests, tree species and populations can be moved into new areas as climatic conditions change. Assisted migration of trees is recognized as a potentially important response to climate change, but has rarely been put into practice. The role that natural forests and tree planting can play in mitigating climate change through carbon sequestration is widely recognized. However, the significance of genetic diversity within species is less well appreciated. Trees can only provide mitigation services if they are well adapted to their surroundings and have the potential to adapt to future changes (Loo *et al.,* 2011). Best practice calls for the use of native species to avoid the risk of a species becoming invasive.

Among wild and farmed aquatic organisms, most adaptation to the stressors associated with climate change is occurring through natural selection as their environments change. The most important traits in this respect include fecundity, tolerance to lower water quality (lack of available oxygen, acidification, increased or reduced salinity, increased turbidity and siltation, and increased levels of pollutants) and resistance to diseases, parasites and toxic blooms. Climate change means that aquaculture and fisheries will have to rely on species, stocks and genetic strains that can live and perform adequately in a wide range of environments. For ecological and economic reasons, this will favour the use of fish that feed at lower trophic levels and that have relatively short production cycles. In warmer waters of variable quality, air-breathing species will have increased potential, especially in aquaculture. Aquatic ecosystems will also better contribute to mitigation services through

[13] http://dad.fao.org

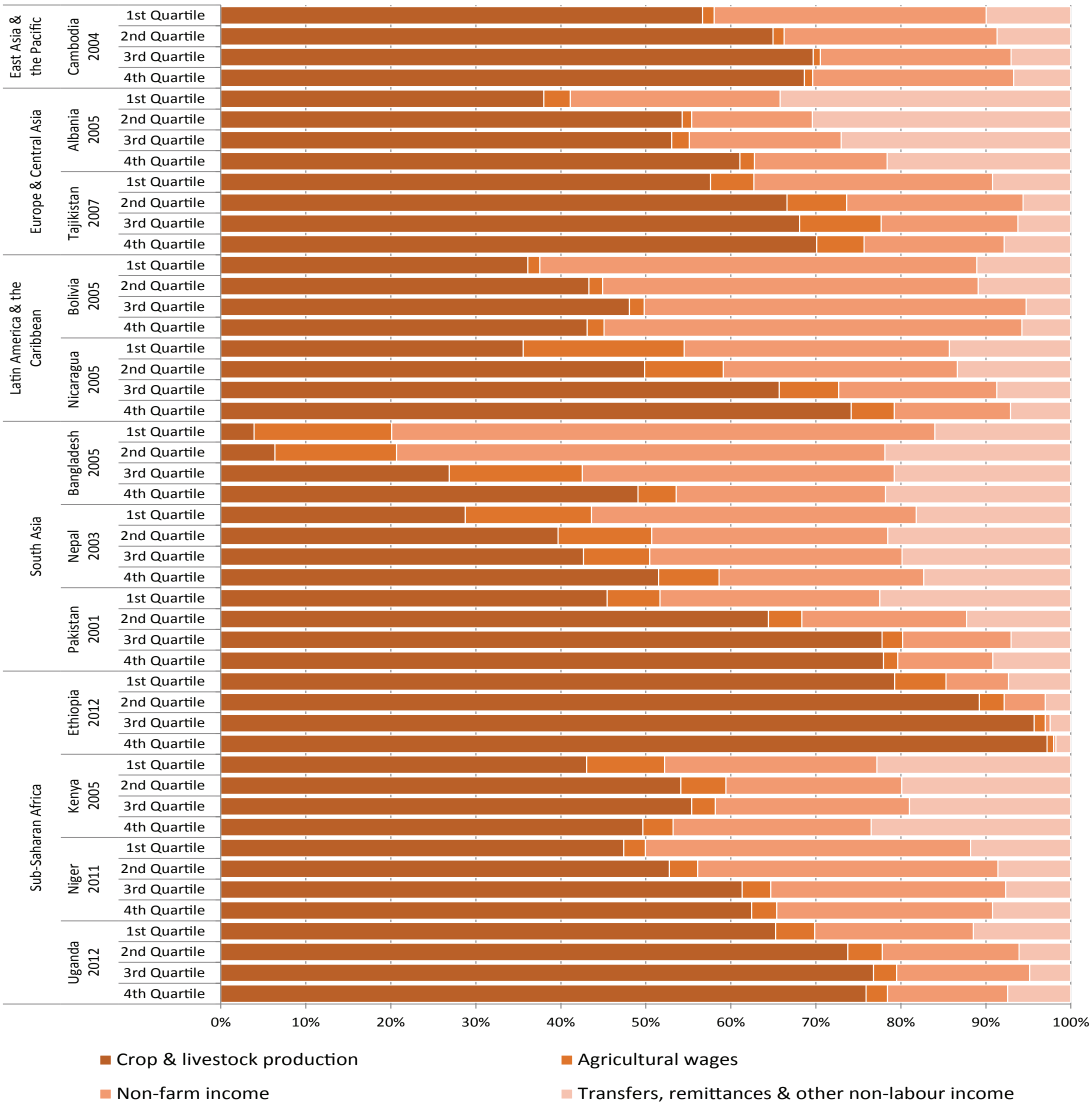


Figure 5. Average shares of household income, by source and farm size.
Source: FAO (2014c)

their roles as carbon sinks if they are able to adapt successfully to climate change (FAO, 2015a; Pullin and White, 2011).

Conservation of invertebrate and micro-organism genetic resources useful to agriculture and food production is necessarily based on maintaining whole organisms in situ. This requires both ensuring that management practices do not threaten the survival of these organisms in agricultural systems and avoiding the destruction of natural habitats that provide refuges for them or serve as potential sources of species that will be useful in the future (e.g. to provide biological control of emerging pest problems). Because of the important roles of invertebrates and micro-organisms in the cycling and retention of carbon in the soil, managing these organisms appropriately may serve as a means of increasing carbon sequestration and thereby reducing atmospheric carbon dioxide levels (FAO, 2015a; Beed *et al.*, 2011; Cock *et al.*, 2011).

B.4 INVESTING IN RESILIENT AGRICULTURAL DEVELOPMENT

For farmers, fishers, livestock keepers and foresters to take actions for building resilience in their livelihoods, at system as well as at landscape level, an enabling environment is needed,

Box 14: Incorporating climate change considerations into agricultural investment programmes

FAO has developed a set of guidance and learning materials based upon practical investment formulation experience at country level. The guidance materials provide practitioners with pertinent information from FAO and other sources, as well as options and good practices on rapid assessments, climate change adaptation and mitigation, and disaster risk reduction, and step by step guidance on questions to address and information to take into account at identification, design, supervision and evaluation stages.

The guidelines are available in English, French, Spanish and Chinese (http://www.fao.org/investment/tci-publications/publications-detail/en/c/165267/). An e-learning programme based upon the core elements of the guidelines is available on the FAO E learning platform (http://www.fao.org/elearning/#/elc/en/course/FCC2). The face-to-face learning materials which include practical examples were piloted, adapted and upgraded in partnership with the China Agricultural University (CAU). These training modules have been included into the CAU postgraduate education programme as a special course and are included in China's South-South Cooperation (SSC) training programme.

which in turn requires actions and coordination by government, civil society and the private sector. Significant progress in addressing climate change in the agricultural sectors can only be achieved if climate concerns are considered in the context of all agricultural investment decisions, rather than in climate change specific projects. This requires careful analysis ahead of any investment decision (see Box 14). Also, it requires proper consideration of the potential to mainstream climate change responses into proper agricultural development strategies (Box 15).

The section looks at how resilient agricultural development, and related investment, can support these changes and what are the means and tools to be mobilized. It starts by showing the types of investments to increase the resilience of agricultural development efforts to eradicate hunger and poverty. It then focus on two priority categories for investment to build resilient development: systems to assess risks, vulnerabilities and adaptation options and then genetic resources. These two categories of means are of major importance not only in themselves as enabling adaptation but also as conditioning further investments, including at farm level.

B.4.1 Promoting agricultural development for economic growth, alleviation of poverty and reduction of vulnerabilities in rural areas, focusing on smallholder agriculture.

Over past decades we have seen how reductions in poverty have led to a reduction in vulnerability to food insecurity, via improvements in food access (FAO, 2015f). As households move out of poverty, they have sufficient income, savings and assets to secure their access to food, even in the wake of adverse events such as food price increases or production failures. Non-poor households also have greater access to financial instruments such as credit and insurance that help maintain adequate and stable access to food.

A primary means of increasing the resilience of agriculture-based livelihoods is through increasing the benefits producers obtain from their production systems, and increasing productivity is one important aspect of this. Furthermore, investments in agriculture (World Bank, 2008), and especially in smallholder agriculture (HLPE, 2013) have been shown as being a vital tool for sustainable development and poverty reduction, with implications for reducing food security vulnerabilities. Three out of four poor people in developing countries live in rural areas and most depend on agriculture directly or indirectly for their livelihoods. In many countries where agriculture is still the major economic sector, agriculture and associated industries are essential to reducing mass poverty and food insecurity. As shown by the World Bank (2008),

Box 15: Mainstreaming climate responses within pro-poor development strategies

Combatting climate change goes hand in hand with alleviating poverty, which requires mainstreaming climate responses within pro-poor development strategies. Consequently, there is increasing support for mainstreaming climate change responses within human development and poverty alleviation rather than pursuing separate climate and poverty tracks and risking potentially negative outcomes for one or the other of these goals. Such mainstreaming would require policies that can achieve co-benefits for poverty alleviation, climate adaptation and greenhouse gas emission reduction. Mainstreaming involves the integration of information, policies and measures to address climate change in ongoing development planning and decision-making. Mainstreaming should create "no regrets" opportunities for achieving development that are resilient to current and future climate impacts for the most vulnerable groups, and avoid potential trade-offs between adaptation and development strategies, which can result in maladaptation.

growth in agricultural GDP from investments in agriculture is three times more effective than growth in any other sector in reducing poverty in countries highly dependent on agriculture.

The vast majority of the world's farms are small or very small, and in many lower-income countries farm sizes are becoming even smaller (HLPE, 2013). Worldwide, farms of less than 1 hectare account for 72 percent of all farms but control only 8 percent of all agricultural land. As shown by the HLPE (2013), a food security oriented agricultural development strategy should put smallholder farming at the centre, to devise context-dependent pathways for a productivity revolution, including through a shift to higher-value agriculture, diversification of rural-based non-farm economic activity, better connection to markets, creation of a vibrant rural economy including the downstream and upstream sectors connected to farming.

In the "Achieving Zero Hunger" report, an annual average of USD105 billion of additional rural investment up to 2030 is estimated to be needed to build enabling conditions for agricultural development to support the eradication of hunger by 2030. Of this amount, 62 percent is spent on investments that will improve the functioning of markets and market access; USD16.5 billion annually for improving agro-processing operations, by investing in rural and wholesale market facilities. An estimated USD34 billion annually is needed for improvements in infrastructure such as rural road and rural electrification. Finally, investing in institutions would account for an additional USD14.5 billion annually, which would improve land titling, access to credit through rural finance, and improve food safety measures.

Previous sections of this report have highlighted the important role of trade in limiting the negative impacts of climate change. By improving market infrastructure, the above-mentioned investments will be crucial in smoothing the effects of climate change by enabling shifts of food supplies from food surplus regions to regions facing food deficits. Trade is expected to play a crucial role in smoothing regional effects of climate change and thus investments in the physical infrastructure, as well as an enabling regulatory framework, are essential.

Although the above-mentioned investments amounts laid out as necessary to end hunger by 2030 in the "Achieving Zero Hunger" report are not classified as investments in adaptation to climate change per se, if designed to take into account climate change effects, they can effectively contribute to adaptation mechanisms. Similarly the funds planed for R&D (USD17.6 billion annually), even though not specifically for adaptation, can be oriented to take potential climate change into account.

The analysis carried out in the "Achieving Zero Hunger" report focuses on reaching this goal by 2030. In this respect, since the most dramatic impacts of climate change are projected to occur after 2030, the analysis can be viewed as setting the preconditions for successful

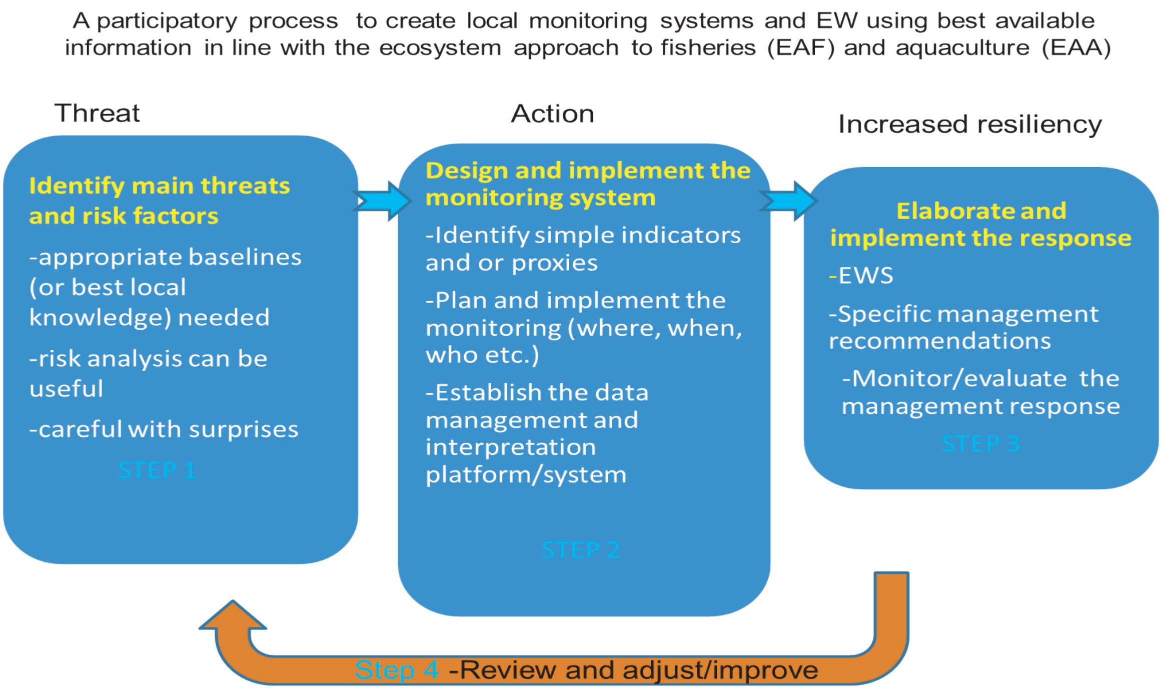


Figure 6. Schematic representation of the process and steps to implement local monitoring and early warning systems.

adaptation to climate change. Studies show that the bulk of climate change impacts and thus adaptation costs will occur after 2030. For example, the annual costs for Africa in 2030, based on current policy projections, is expected to be 15 USD 2012 billion, but it is expected to grow to 35 USD 2012 billion in 2040, and to 70 USD 2012 billion in 2050. Agricultural production and wages provide a large share of household income for all farm sizes, as can be seen in Figure 5. Thus increasing the returns to smallholder agricultural production is an important, but not sole, means of increasing household incomes and reducing poverty.

B.4.2. Enabling in-farm and off-farm diversification

For most farming families, agriculture is only one of several sources of income (HLPE, 2013), and smaller size households often have higher shares of non-agricultural incomes than larger ones. It is also important to recognize that an important strategy for increasing resilience among agricultural based populations is to diversify to non-agricultural sources of income and in many cases to exit from agriculture for employment opportunities in other sectors. In many microlevel studies of agricultural household welfare, the access to off-farm income sources from labour diversification is generally positively associated with welfare levels. For example, labour migration is a common strategy in the face of climate risk and environmental degradation, and remuneration from these migrants plays an important role in maintaining household resilience. In other cases, permanent migration of entire households through resettlement programmes or individual relocation is an attempt on the part of households to move to new and more resilient livelihoods outside the agriculture sector. Of course, there is considerable variation in how well these strategies actually do contribute to livelihood resilience. In addition, evidence indicates that the poor and most vulnerable to climate risks are the least capable to undertake effective migration, since they lack the assets and social networks required. Non-agriculture-based livelihoods are likely to play an increasingly important role in building resilience among agricultural populations due to projected population growth patterns as well as potential climate change impacts. Thus it is important to consider how to improve pathways for low-income and food-insecure people in both the agriculture and non-agriculture sectors to access resilient livelihoods.

Diversification, both on-farm with increased number of varieties, species and breeds, including through mixed systems such as crop/livestock, crop/fish or processing products, and off-farm, by getting a non-agricultural job, is an important element of climate change adaptation (Thornton and Herrero, 2014). It is, however, very context-dependent, operates at farm level and requires overcoming constraints of access to information and initial cost of investment. Household income diversification is not restricted to developing economies (Kurukulasuriya and Rosenthal, 2013) and can be observed in countries like Canada and Ireland. It requires policies that provide the opportunities to pursue alternative livelihood options, including training, information dissemination and support services.

B.5 INVESTING IN SYSTEMS TO ASSESS RISKS, VULNERABILITIES AND ADAPTATION OPTIONS

A correct understanding of local climatic risks, potential impacts on agriculture and food security, characterized vulnerabilities, and effectiveness of adaptation options, is needed to form a solid evidence-base for enabling climate change adaptation.

A careful strategic assessment needs to evaluate the benefits and trade-offs in various social, economic and environmental conditions. Assessments can determine how local climate conditions and their impact on agriculture, the natural resource base, food security and livelihoods have been changing and are projected to change in the future. They also can identify the most vulnerable locations and contexts that require adaptation actions. Knowing which agricultural systems and livelihood activities may be more sensitive to a changing climate, for example, will help practitioners choose more resilient crops, livestock, aquaculture and forestry species and adopt more diversified livelihoods. Informing stakeholders of the changing amounts of rainfall and the spatial distribution of precipitation will help them to better allocate resources for the management of water resources. In addition, given the multiple environmental changes driven by climate change, it may be necessary to develop environmental monitoring systems, focusing on key parameters.

Assessment of impact and vulnerability need to be completed by assessments of effectiveness of adaptation options. These are necessary to know more about which changes in agricultural and commercial practices and in the institutional and policy environment are effective and efficient measures to achieve climate change adaptation objectives. Such assessments can determine whether certain measures indeed help farmers, pastoralists, fisherfolk and forest users adapt to climate change in a particular context. Effective adaptation options can be explored based on historical, current and projected climatic impacts on agriculture and the vulnerability of livelihoods and food security. It is also possible to simulate the adaptation activity that is more suitable for adapting to a changing climate.

Any assessment should be linked to concrete development objectives and actions that result in the robust adaptation of food-insecure vulnerable populations, taking into account uncertainties in climate change scenarios. The information needs of stakeholders, as well as key risk and vulnerability questions that contribute to policy and development objectives, should be clearly defined as well as the methodologies to be employed, and the tools, data and information necessary for the assessment to be conducted. As such, assessment frameworks should account for the different needs of end-users.

Finally, early warning systems are essential to reduce impacts of changes, and particularly of extreme events.

Climate risk and impact assessment and tools

A better understanding of the influence of a changing climate on agriculture is a first step to climate change adaptation. Climate impacts on agriculture are highly location-specific.

Local perception of how climate has been changing in the recent past, and how agricultural production systems are affected by changes, can be validated by an analysis of past climate variability and characteristics of extreme events from an agronomic perspective. Such an analysis forms a robust evidence-base for adapting farming, fishing practices and forestry to climate variability and climate change, and for identifying needs for further research and development (e.g. new varieties resistant to increasing climate risks).

A common climate impact assessment of agricultural productivity (e.g. crop/fish yield) follows a top-down approach. Past climate conditions can be associated with past agricultural productivity to establish causal links and calibrate models. Global climate models can provide future climate projections, based on socio-economic and emission scenarios, and they can be downscaled using appropriate methods. The calibrated models can simulate future impacts of climate change on agriculture with projected climate as an input (FAO, 2012a for general methodology). Climate change can bring opportunities as well as risks. Analyses can also help identify conditions in which opportunities may (or may not) be taken advantage of, or identify cases where risks will affect systems (sectors, dependent communities, economies, natural systems, etc.) differently.

UNFCCC (2010) provides a review of available agricultural models, including: agroclimatic indices with geographic information systems (GIS); statistical models and yield functions and process-based crop models; and economic models, such as economic cross-sectional models, farm-level micro-economic models, household and village models, and macro-economic models. All of these models may be useful for climate impacts assessment and for adaptation planning.

Aquacrop, for example, is a FAO crop model to simulate yield response to water of major crops. The Modelling System for Agricultural Impacts of Climate Change (MOSAICC) is an integrated package of tools for facilitating an interdisciplinary assessment of impacts of climate change on agriculture.

Assessments should be based on the best available scientific information (methodologies, tools, models and data), making use of model-based methodologies as well as participatory, perceptions-based methodologies. In order to ensure accountability, replicability and transparency, established and robust methodologies should be selected, while allowing for uniqueness inherent to each context.

Developing environmental monitoring systems

As described above, climate change will profoundly affect ecosystems, directly and indirectly, through modifications of physical and biological characteristics, including water quality (temperature, salinity, acidity) and distribution of species. Environmental monitoring systems should follow a risk-based approach recognizing that increased risks require increased monitoring efforts. The involvement of local actors and the value of locally collected information is particularly important for farmers and fisherfolk to better understand the biophysical processes and become part of the solution, e.g. rapid adaptation measures and early warning, long-term behavioural and investment changes.

Fisheries and aquaculture are sensitive to sudden climate changes and climatic variability (as well as to long-term trends/changes). There are, however, few cases of integrated monitoring systems providing information and interpretation of the information that fishers and fish farmers can use to make decisions. One such example is the early warning system for US Pacific shellfish hatcheries as shown in Box 16. Even though information on meteorological conditions can reach fishermen and fish farmers and they may have some experience interpreting this information and the potential consequences for the farm and/or fishing operations, simple information collected on a permanent basis can provide a particularly relevant tool for decision-making, especially when changes can produce dramatic consequences. For example, temperatures above or below average can trigger diseases in farmed animals; sudden water movements or internal circulation can bring anoxic water to the surface or trigger toxic algal blooms. Changes in temperature, pH or salinity can affect farmed fish and can drive away fish that are normally captured by coastal fishermen. Changes in monsoon patterns can generate different freshwater delivery and therefore fisheries and fish farming needs to be prepared. In the case of aquaculture, the monitoring of environmental variables such as oxygen and water transparency can also indicate excessive nutrient output from farms and so on.

FAO is promoting pilot development and implementation of participatory environmental monitoring (aquatic environment, target farmed species systems) and early warning systems to improve fishers and farmers preparedness and resilience to climatic variability and climate change. Pilots following the participatory process described in Figure 6 are been developed or initiated in Nicaragua and in the countries of the Lower Mekong Basin (Thailand, Viet Nam and Cambodia).

Vulnerability assessment and tools

Impacts on agricultural productivity and other aspects of the sector can lead to different repercussions in household income and food security. Vulnerability of livelihoods depends on the capacity of local communities to substitute a negatively affected production system with an alternative that could prevent losses in agricultural income, provide subsistence production, or supply food to urban markets. Vulnerability assessments characterize and identify areas, households or subpopulations that have particularly low livelihood resilience. This helps adaptation planners prioritize their actions and target vulnerable communities (e.g. youth, the elderly, land-less people and women). Vulnerability assessments also provide the basis for the development of strategies to increase the resilience of systems and livelihoods to climate change.

With the potential impacts of climate change identified from previous assessments, vulnerability can be assessed by evaluating the adaptive capacity of the system in a top-down approach. It is also necessary to acknowledge and improve the knowledge of social-ecological climate drivers and vulnerabilities of agriculture, forest and fisheries systems (e.g. indirect impacts on livestock through natural vegetation; direct impacts on fish species; indirect

Box 16: Early warning system for US Pacific shellfish hatcheries

Shellfish along the West Coast is an USD111 million industry, supplying thousands of jobs in Oregon and Washington. Less than a decade ago, shellfish hatcheries in Oregon and Washington, essential to shellfish growers all along the West Coast, were on the verge of collapse. In 2012, scientists in Oregon found evidence that higher levels of carbon dioxide in the Pacific Ocean were responsible for the failure of oyster larvae to survive in 2005 at Whiskey Creek Shellfish Hatchery on Netarts Bay (Barton *et al.*, 2015). The marine waters of the Pacific Northwest US are particularly vulnerable to ocean acidification. Regional marine processes including coastal upwelling exacerbate the acidifying effects of global carbon dioxide emissions. Coastal upwelling brings deep ocean water, which is rich in carbon dioxide and low in pH, up into the coastal zone. Federal and state investments in monitoring of coastal seawater have helped to provide shellfish hatchery managers with real-time data on the seawater coming into their hatcheries. The data provide an early warning system, signalling the approach of cold, acidified seawater one to two days before it arrives in the sensitive coastal waters where shellfish larvae are cultivated. The data help hatchery managers schedule production when water quality is good, anticipate the need to buffer or adjust the chemistry of the water coming into their hatcheries, and avoid wasting valuable energy and other resources if water quality is poor.

Source: The Northwest Association of Networked Ocean Observing Systems (NANOOS) Web site http://www.nanoos.org/home.php impacts on forest-dependent communities; and direct impacts on production and post-harvest infrastructure, safety at sea, access to markets).

The bottom-up approach, on the other hand, focuses more on collecting different indicators that would characterize the vulnerability of agriculture sectors to various risks, including climate change. There are a wide variety of possible indicators, including socio-economic resources, technology, infrastructure, information and skills, institutions, biophysical conditions and equity (Desai and Hulme, 2004; Brugère and De Young, 2015). Climate change is one among many risks and drivers of change for food insecurity and may be an amplifier of existing vulnerabilities. Vulnerability to climate change should be seen in the context of existing broader socio-economic and environmental conditions. Contextual conditions of the society and environment clarify their adaptive capacity and vulnerability to potential threats.

Adaptation options assessment and tools

Following climate impact, risk and vulnerability assessments, adaptation options assessments examine the extent to which different adaptation measures may achieve the objectives of increasing productivity, enhancing climate change adaptation and improving food security, given the expected impacts of climate change. This helps practitioners identify effective adaptation options.

The tools to support adaptation range from quantitative climate and crop models at various levels (global, regional, national, subnational) and statistical analyses at household level, to qualitative assessments of policies and institutions. Whereas global models provide an important understanding of the climate patterns and projected changes, their resolution tends to be very low to enable local action. Downscaled models of the impacts of climate change on food security dimensions are necessary to better understand localized impacts and relevant options to support adaptation. Local institutions need to develop their capacities to sustain the use of such high-resolution models and adapt them to local needs (as is done by the MOSAICC project).

A complementary set of tools includes statistical analyses that combine relevant climate data as provided by the above with large-scale household data on agricultural and other income-generating activities, adaptation strategies and food security outcomes to understand barriers to adoption and impact on livelihoods. Given that climate change brings both extreme and slow-onset change, such analyses need to be institutionalized and regularly conducted to track change in the system (both agro-ecological and socio-economic). National statistical institutions can incorporate the regular collection of data relevant to climate change and adaptation into their already existing efforts (Agricultural Census or Living Standards Measurement Surveys) to ensure that site-specific relevant information is regularly collected to support evidence-based policy-making.

Quantitative analyses can be complemented with qualitative analyses on local institutions and policies to support adaptation. Policy mapping and harmonization analyses are instrumental in making sure that the strategies outlined above are adapted and can be sustained by households/communities. Scenario analysis is another tool that can be used to combine qualitative analyses with quantitative modelling to assist policy planning for different futures that are possible under predicted climate change and social development paths.

Assessments of adaptation options for effectiveness are an extension of climate impact and vulnerability assessments. Having gained an understanding of potential impacts of climate change and of vulnerabilities, the best adaptation practices for local conditions can be reviewed and identified. Ideally, stakeholders are involved in undertaking and validating the findings of the assessment and help to define and select suitable and workable adaptation options. Process-based crop growth models at the farm level could be used to suggest better management practices to improve yields. Economic models could simulate, for example, the effect of a fertilizer subsidy on productivity, market prices and farm income. A screening analysis is a simple method in which the assessor answers yes or no questions about options. Those options with the most yeses can be given the highest priority or be further assessed using more quantitative analytical methods. In multicriteria assessments, stakeholders identify the criteria to be used in assessing adaptations. Common metrics are defined to measure the criteria. Assessors rank each adaptation option against each criterion by giving scores. In cost-effectiveness analysis, the relative costs of different adaptation options that achieve similar outcomes are compared (UNFCCC, 2010).

Analytical assessments should be complemented by a bottom-up approach in which the local community is fully engaged, and where local men and women farmers and other rural dwellers discuss and agree on the best adaptation interventions that they would be willing to adopt, given the local climatic, socio-economic and environmental conditions (community-based adaptation). This provides an opportunity to link local traditional knowledge with scientific knowledge. In addition, it gives the affected populations an opportunity to identify possible unintended consequences of interventions and discuss how to resolve them. When the comparative advantage of different adaptation options is not clear, an assessment of the costs and benefits of adaptation measures can be done using economic analysis or non-economic evaluation method. In either way, some metrics of costs and benefits need to be estimated (World Bank, 2009).

An overall adaptation strategy should enhance the food security of agricultural producers and of the overall population, which often requires achieving sustainable increases in productivity. Additional assessment criteria that address a specific food security concern may need to be added to vulnerability and adaptation assessments. Adaptation strategies should be able to address many different plausible climates and outcomes, given the large uncertainties in climate projections. For example, scenario-based assessments allow the outcomes of different adaptation options under different climate change scenarios to be explored to guide the robust adaptation of food-insecure, vulnerable populations, considering uncertainties in climate change scenarios. Tools elaborated and developed must be accompanied by training and extension to ensure their utilization and the consequent adoption and maintenance of identified suitable agricultural solutions with tools to facilitate and support their efficient and effective utilization.

Early warning systems

The development of early warning systems is essential to strengthen proactive decision-making at all levels in order to reduce the impacts of extreme weather events such as dry spells, droughts, frosts and tropical cyclones. For example, FAO's Agricultural Stress Index System (ASIS) monitors vegetation indices and detects hotspots where crops may be affected by drought, using data on vegetation and land surface temperature. The system contributes greatly to the food security monitoring work of the Global Information and Early Warning System on Food and Agriculture (GIEWS). Analysis of meteorological data, together with information on phenology, soil and agricultural statistics, also allows the provision of near real-time information about the crop state (crop forecasting), in quality and quantity, with the possibility of early warning so that timely interventions can be planned and undertaken. While such agrometeorological monitoring systems are becoming available, timely and effective delivery of information to the users remains a significant challenge. Beyond hydrometeorological events that progress over days and months, warning systems for very short-term events such as flash floods, landslides and storm surges are not yet readily available in many developing countries.

At national and local levels, risk and opportunity management can be enhanced by weather/climate information systems tailored to the needs of farmers, fishers and foresters, alongside improved outreach to agricultural support services. Seasonal climate forecasts have varying predictive skills depending on the location and lead time. Where predictability is found, farming advice can be provided according to the forecast. The predictability of weather forecasts up to one week has steadily improved over many years (Bauer, Thorpe and Brunet, 2015). Short-term forecasts can be used to inform farmers of better timing of planting, weeding, fertilizing, managing pests, harvesting and drying (Salinger, Stigter and Das, 2000). Irrigation schedules can be managed to increase efficiency, based on agrometeorological monitoring and short-term forecasts. Experiences from FAO's localized climate information systems indicate the need to link information providers and users and customize information products with impact outlooks and management options for use in the agriculture sectors.

The accuracy of weather/climate forecasts and early warning systems rely, among others, on the availability and accessibility of data, including hourly/daily/monthly weather data; data on extreme weather events, their anomalies and impacts; satellite-based weather monitoring; vegetation characteristics; crop prospects, the food situation and food prices. Support to the monitoring and observation at weather stations has steadily decreased over the past decades, mainly as a result of discontinuation of a number of regional and country support programmes. There is an urgent need to invest in continued operational observations and data collection, and in strengthening institutional capacities.

Such systems shall be developed not only for climate shocks but also for other variables of interest like pests and diseases or water quality. FAO's desert locust early warning system monitors weather, ecological conditions and the global locust situation, and provides forecasts and warnings of potential breeding and invasions to affected countries. Box 16 provides an example developed for shellfish hatcheries in the US Pacific.

Information needs to be communicated in a format that is understandable and is relevant to the end-users in their own local context in a timely and accessible way (Winsemius *et al.*, 2014). Information and communication technologies provide considerable opportunities to establish two-way communication systems in which farmers, fishers and forest dwellers are an integral part of surveillance both communicating and receiving information. In order for agrometeorological information to be used for appropriate responses, sufficient support for developing capacities of relevant institutions and personnel needs to be provided. This is true on both sides of information flow: development of the capacity of national meteorological services and agricultural line agencies on the information provider side, and of the farmers and extension service personnel on the information user side. Climate-smart farmer field schools can integrate topics such as weather and climate information products and sources, and how to interpret and incorporate forecasts into farmers' decision-making process.

Farmers can hedge against extreme weather risks with financial insurance (crop insurance, livestock insurance). Insurances based on weather indices have been increasingly explored in the last ten years as an option in developing countries. Payout is not triggered by damage to the crop, but by the level of a weather index that is correlated to crop yield. The main advantage is that insurers do not need to assess damages, which can be costly and long, delaying payments when they are the most needed. Indices can be based on rainfall, water stress, drought or other meteorological variables. Weather index-based insurance has a potential as an adaptation tool and further research on quantification of benefits, improved indices using satellite data, etc. is necessary (Leblois and Quirion, 2011; de Nicola, 2013).

B.6 ENABLING ADAPTATION THROUGH POLICIES AND INSTITUTIONS

The economic and technical options presented above need to be enabled, supported and complemented by appropriate policies and institutions where bridges are built to integrate climate change concerns in food and agricultural policies, coupled with better recognition of the specificities of agriculture and of its key role for food security and nutrition in climate policies.

Several types of policies and institutions can be distinguished to enable adaptation of food producers to climate change, at national and international levels:

- Policies and institutions to support food producers, especially small-scale food producers, in their efforts to adapt.
- Policies and institutions that facilitate and support collective elaboration and implementation of adaptation actions either in a space (for instance a watershed, a forest) or sector.
- Policies and institutions dedicated to the prevention and management of specific risks and vulnerabilities that can be modified by climate change, such as plant pests, animal diseases, invasive species, wild fires, etc.

This section describes these enabling policies and institutions at national level. It then considers the potential role of international trade and the importance of strengthening international cooperation.

B.6.1 Building institutions and policies to support the transition to more resilient systems

Support food producers, especially small-scale food producers, in their efforts to adapt.

To adopt new and more resilient livelihoods, farmers, herders, fishers and foresters need to be operating in an institutional environment that supports such change. At present this type of enabling policy and institutional environment is often lacking 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 very important roles in supporting or hindering farmers and fishers in transitioning to systems with higher resilience (McCarthy *et al.*, 2010; Asfaw, Coromaldi and Lipper, 2015; Asfaw *et al.,* 2015c; Asfaw, DiBattista and Lipper, 2014; Arslan *et al.,* 2014; 2015b; Arslan, Belotti and Lipper, 2015).

In order for food producers to get the material and immaterial inputs needed to adapt, and for them to be able to sell the products resulting from their diversification activities, it will be even more important, under climate change, to better link smallholder farmers to local, national and regional markets. Developing these market linkages also requires investment in small- and medium-size food processors, and small-scale traders at the retail and wholesale levels. Price volatility is a major disincentive for smallholder investment. Government intervention is important to reduce transaction costs in accessing markets and to establish regulatory instruments to bridge gaps in economic and political power that can exist between smallholders and their organizations on the one side, and the other contracting organizations on the other side.

Policies will be needed to reduce financial risks, lower transaction costs, facilitate monetary transactions, enable access to financial services and facilitate long-term investments, such as safe savings deposits (with incentives to save), low-priced credit (such as through joint-liability group lending), and insurance (such as index-based weather insurance). Smallholders and family farmers' financial needs for both working capital expenditures (fertilizers, seeds), medium- and long-term investments, have to be addressed and supported. Civil society and the private sector can play important roles in the effort to build enabling institutions to reduce risks.

Support and facilitate collective action

Climate change gives rise to new and increased demands for collective action. This requires appropriate policies and institutions that facilitate and support collective elaboration and implementation of adaptation actions either in a space (for instance a watershed, a forest) or sector, for instance along the food chain, including to increase and adapt storage facilities. This can be done by improving inclusiveness and transparency of decision-making and providing means to incentivize actions that provide public and collective adaptation benefits in the long term. This is particularly important for management of natural resources (Place and Meybeck, 2013).

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

The real action in building resilience is on the ground. Building or reinforcing local governance mechanisms that engage local stakeholders is essential. These must exist to support appropriate and timely decision-making and action to develop and sustain resilient systems. They can provide the flexibility and responsiveness to react quickly and effectively to respond to climate change. The need for flexible access to resources is likely to increase, with important implications for the design of land tenure security programmes. Multistakeholder dialogue to support improved governance of land and water tenure systems under climate change, taking into account the interests of women, the poor and marginalized groups, is a promising option.

For instance, lessons from experience over the past decades have shown that forests can be well managed and degradation can be reversed by involving local communities, supported by legitimate decentralized institutional arrangements developed through consultative processes (FAO, 2013d). There are many examples of farm foresters' producer groups (FAO/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 that can help provide for effective responses to climate change. Traditional forms of reciprocal and mutual work (e.g. in soil and water conservation work, in labour in shifting cultivation systems) have been partially or totally abandoned in many areas owing to social and economic changes (FAO, 2013d). Encouraging the perpetuation or reactivation of these where appropriate for restoration work may be beneficial. Encouraging informal social networks for sharing information and experience on adaptation options may also help to build social resilience to climate change. Such networks can play a key role in the establishment of surveillance, monitoring and early warning systems.

Manage risks

Climate change is bringing new risks and changing existing ones (FAO/OECD, 2012). Better managing actual risks has been highlighted by the IPCC as a key adaptation action. It requires appropriate institutions and policies. Most of the time, these are sector- and/or risk-specific. There are, however, some broad orientations common to all of them.

For instance, mutualized systems to assess risks, vulnerabilities and adaptation options can help orient individual decisions and actions (see B.3.3). Weather stations, weather and climate projection tools, yield response models, environmental monitoring tools and vulnerability assessments can help determine how local climate conditions will change in the future, and what will be their impact on production. They are key to ground the set-up of early warning systems and of adaptation option assessments.

National public, private and civil society stakeholders have key roles in reducing information costs and barriers. In addition to strengthening the capacities of extension systems to disseminate site-specific information, tools such as radio programmes and information and communications technologies (ICTs) can be used. Real-time weather information via ICTs is already being deployed by public and private sector actors in agricultural value chains in many countries, and could be greatly extended to include information relevant to other risks, including for instance pests and diseases.

Comprehensive risk management strategies require a better understanding of the robustness of different risk management instruments under climate uncertainty, and coordination of actions by public, private and civil society actors from the international 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 incentives for private sector participation in risk coping. Social protection programmes that guarantee minimum incomes or access to food also have potential through their effects on production choices and prices.

Last but not least, adequate policies and institutions are also vital for allowing the diversification of livelihood strategies. Livelihood diversification is, indeed, among the most effective risk management strategies for smallholders and family farmers. Depending on the specific context being considered, these might refer to land-use diversification as well as to income or labour diversification. Agricultural development policies need to integrate diversification as a main component, and local institutions need to facilitate it by providing incentives through improved access to credit and insurance as well as information/training.

Integrate climate change concerns in all agricultural and food security strategies and policies

Numerous instruments and policies need to be mobilized for adaptation, to build resilience of agriculture and food systems to climate change.

This requires the elaboration of an integrated strategy covering, first of all, agriculture and food security policies and measures, as well as those related to water management, land and natural resource management, rural development and social protection, among others. Such an approach can be part of broad, economy-wide adaptation strategies and plans at national or subnational levels.

It calls for holistic approaches considering agricultural development for food security and nutrition in the context of climate change, combining practices, enabling policies and institutions as well as financial resources. It is with such objectives that FAO proposed in 2010 the concept of climate-smart agriculture (Box 19), an approach than can help decision-makers in the agriculture sectors, from farm to national authorities, integrate food security and climate change concerns in their actions and policies.

Ensure the integration of the agriculture sectors as well as food security and nutrition concerns in climate change strategies and policies

The agriculture sectors are the most impacted by climate change of all economic sectors with, as this report shows, a range of food security implications. This calls for better recognizing, in climate policies and tools, the importance and the specificities of the agriculture sectors and of food security. Specific national climate-related instruments like adaptations plans, national

Box 19. Climate-smart agriculture

Climate-smart agriculture (CSA) is a recent concept, initially proposed by FAO in 2010 at The Hague Conference on Agriculture, Food Security and Climate Change, to address the need for a strategy to manage agriculture and food systems under climate change. CSA is an approach aiming at identifying and implementing changes in practices, policies and institutions, in specific systems, towards three main objectives: (i) sustainably increasing agricultural productivity to support equitable increases in incomes, food security and development; (ii) adapting and building resilience to climate change from the farm to national levels; and (iii) developing opportunities to reduce GHG emissions from agriculture compared with past trends. It requires an appropriate evidence-base as well as the inclusive engagement of all concerned stakeholders. CSA does not define a priori which practices are climate smart, as it depends on context. There is already considerable information on the types of practices within agricultural systems and more broadly in agricultural food chains that can contribute to the three objectives of CSA. There is a need to provide the enabling environment and incentives for stakeholders to adopt changes.

adaptation plans of action (NAPA), prepared by least developed countries (LDCs), as well as the national adaptation plans under preparation aim to identify vulnerabilities to climate change and ways to address them.

The criteria to rank priority actions for the NAPAs included the identification of the most urgent needs, taking into account the vulnerability of sectors, vulnerability of groups, the contribution to food security and to poverty reduction, and economic cost. Such criteria, and the way they have been used, made food security, agriculture and natural resources management issues particularly prominent within the NAPAs. And in fact an analysis of the priority projects shows that the great majority are related to the agricultural sectors and food security (Meybeck *et al.,* 2012). As these are the priority measures selected by the countries themselves, after an evidence-based process involving stakeholders, it shows without doubt that adaptation to climate change in LDCs is first and foremost adaptation of agriculture. Although country-specific, these projects, taken all together, cover the broad range and various ways to increase the resilience of agriculture. As such, they constitute an extremely valuable base to identify priority areas of work and of research in order to better answer the needs of the most vulnerable. They also provide, when taken together, a database of measures that can be extremely useful for the preparation of the national adaptation plans.

The Convention of the Parties (COP) of the UNFCCC invited all parties to communicate ahead of COP21 their Intended Nationally Determined Contributions (INDCs[14]) towards achieving the objective of the UNFCCC as set out in its Article 2.[15] Most countries that included adaptation in their INDCs referred to developing national plans and strategies, some of them indicating that they are in the process of preparing a National Adaptation Plan (NAP), most of them foreseeing its development by 2020. Specific policies, measures and initiatives were often mentioned, with water, agriculture, health, ecosystems, forestry and infrastructures as priority areas. Some of the actions mentioned the need to address transboundary dimensions (UNFCCC, 2015).

The national adaptation plan (NAP) process was established under the Cancun Adaptation Framework (CAF). It enables countries to formulate and implement NAPs as a means of identifying medium- and long-term adaptation needs and developing and implementing strategies and programmes to address those needs. It is a continuous, progressive and iterative process which follows a country-driven, gender-sensitive, participatory and fully transparent approach.[16] This a key opportunity to integrate the concerns and needs of the agricultural sectors and actors in broad national strategies and policies. Facilitating consideration and integration of food security and agriculture concerns and perspectives into the NAP process requires at the same time to provide elements for non-agriculture specialists to understand what are the issues and to enable agriculture stakeholders to better identify and understand the issues at stake in a mid/long term perspective and to empower them to participate efficiently in the process. FAO and UNDP are supporting countries in this process.

B.6.2 Enhance markets and trade's contribution to stability of food security

Global markets and trade can play a stabilizing role for prices and supplies and provide alternative food options for negatively affected regions by changing conditions or by finding regions where food can be produced more efficiently (both in terms of environmental and

[14] http://unfccc.int/focus/indc_portal/items/8766.php

[15] As stated by the COP, the information to be provided in the INDCs may include, as appropriate, inter alia, quantifiable information on the reference point (including, as appropriate, a base year), time frames and/or periods for implementation, scope and coverage, planning processes, assumptions and methodological approaches including those for estimating and accounting for anthropogenic greenhouse gas emissions and, as appropriate, removals, and how the Party considers that its INDC is fair and ambitious, in light of its national circumstances, and how it contributes towards achieving the objective of the Convention as set out in its Article 2.

[16] See http://unfccc.int/adaptation/workstreams/national_adaptation_plans/items/6057.php

economic costs). However, trade alone is not a sufficient adaptation strategy, owing to several trade-offs. Dependence on imports to meet food needs may increase the risk of exposure to higher market and price volatility that is expected under climate change. As an example, the extreme heat and wildfires in western parts of the Russian Federation in the summer of 2010 reduced by one-third that country's wheat production, and the subsequent ban on exported grain contributed to a rise in the price of wheat worldwide, with consequences on low-income urban populations in countries such as Pakistan and Egypt.

To date, the empirical evidence linking climate change and trade is incomplete and is fraught with the usual caveats related to uncertainty vis-à-vis future climate outcomes and developments in climate and trade policy. More robust trade analyses in the context of climate change should integrate direct climate impacts on agricultural productivity, demand-side drivers (e.g. consumer diets, labelling, subsidies), resource constraints (such as climate-induced irrigation water shortages), as well as climate policies (e.g. carbon taxes, standards, ecolabelling). Moreover, the two-way linkage between climate and trade is not a settled issue as there remain a number of unanswered questions related to the environmental impact of increased trade (such as indirect land-use change from biofuel trade expansion).

Climate change fundamentally alters global food production patterns and, given the fact that impacts are expected to be worse in low-latitude regions, climate change is likely to exacerbate existing imbalances between the developed and developing world. Spatial differences are also observed at regional and subregional scales, particularly where there are substantial differences in elevation. The impacts of climate change (and of climate mitigation policies) thus have a major impact on patterns of global trade (Elbehri, Elliott and Wheeler, 2015). In addition to the direct impact of climate change on primary production, changing socio-economics can alter comparative advantages and trade flows, and potentially alter future international competitiveness and agrifood trade patterns (Ahammad *et al.*, 2015).

Climate impacts on future food supply strongly suggest an enhanced role for trade with expanded flows from the mid-to-high-latitude regions to the low-latitude regions, where production and export potential could be reduced. Climate change is also projected to cause wide variations in the net global food supply as the result of a higher frequency of droughts and extreme weather events. Climate change can transform trade flows by altering the comparative advantages of countries, while more frequent extreme weather patterns have an adverse impact on trade by disrupting transportation, supply chains and logistics (Elbehri, Elliott and Wheeler, 2015).

Due to their nature, agricultural commodity markets are bound to experience a certain amount of variability, with occasional upward price spikes more likely than severe price troughs. However, the imperfect functioning of global markets has undoubtedly magnified price volatility in the period since 2006. This has had devastating effects on the world's poor (HLPE, 2011), while also creating fiscal and monetary problems for governments. As a result, there has been much recent study on possible ways to improve the functioning of global food markets with the aim of reducing volatility.

After considerable debate, there is now consensus that many of the proposals put forward to control food prices on global markets are unlikely to be effective. International buffer stocks are expensive and vulnerable to speculative attack, and historical examples indicate that they do not work. "Virtual" reserves – created by governments participating in the futures markets – may be counterproductive and hand more profits to speculators. Attempts to limit the flow of speculative money into the futures market are widely seen as unworkable and may weaken the legitimate role of speculators in smoothening out market volatility. There is also a suite of national policies that can be used to control volatility – tariffs, export and import restrictions, price controls, intervention buying, rationing, user subsidies, deficiency payments – but all come at an economic cost and many can create unintended consequences (FAO *et al.*, 2011; Tangerman, 2011). Instead, attention has focused on three possible measures that could help reduce market volatility, namely: limiting trade restrictions, widening and deepening markets, and improving the flow of information.

Limiting trade restrictions

There is four times more trade protection on agricultural products than on other products (FAO *et al.,* 2011). The trade and subsidy policies of large countries are pro-cyclical, depressing world prices further when prices are low and pushing world prices up even further when they are high. The imposition of export restrictions – by developing as well as developed countries – can be particularly damaging, leading to panic on world markets and extracting a significant cost from food importers.

While stability in international food markets is a global public good, it is a collective action problem. It is only rational if everyone cooperates and achieving global cooperation is not easy. In a joint paper for the G20 (FAO *et al.*, 2011), a number of multilateral agencies urged countries not to impose food export restrictions without carefully considering the consequences for global food security and called for the strengthening of existing World Trade Organization (WTO) rules on the use of export restrictions in times of emergency. At a minimum, it was proposed that emergency food aid, as needed by the World Food Programme (WFP) for example, be made exempt from export restrictions. These agencies also called for the gradual reduction of trade barriers on food and agricultural products through completion of the Doha Round of the WTO (FAO *et al.*, 2011). However, it is equally important to recognize the need for special and differential treatment of least developed countries (HLPE, 2011). It makes sense for many developing countries to be more active in developing their domestic agriculture sectors, but this may need to be supported by tariffs and other trade policy measures.

Widening and deepening markets

Food markets in many developing countries do not function smoothly, because of poor infrastructure, weak institutions and a lack of appropriate regulation. Improving the functioning of domestic markets will smooth variability, facilitating the transfer of food surpluses across geographies and the management of price fluctuations over time. In particular, it will be important to develop agricultural markets and value chains that allow smallholders and family farmers to participate. This may mean lowering transaction costs through aggregation (FAO, 2011c).

Developing countries should also be helped to set up functioning local commodity exchanges, including derivatives or futures markets (Tangerman, 2011). For agricultural commodity derivatives markets to function well, in terms of hedging and price discovery, appropriate regulation needs to be in place. In particular, there is need for greater transparency in transactions across futures markets and especially across over-the-counter (OTC) markets, where transactions take place off the regulated commodity exchanges (FAO *et al.,* 2011).

New instruments for mitigating commodity price risk exposure might be explored. A market approach to price volatility involves setting up structures and institutions that allow governments and supply chain intermediaries to cope with price volatility instead of attempting to reduce or eliminate this volatility (Gilbert and Tabova, 2011). For example, a global wheat contract that would specify export delivery points in the major producing regions has been proposed. This would identify "cheapest to deliver" sources by designating delivery points all over the world and act as a global signalling system of both price and regional supply availabilities. Developing countries could enter into futures contracts, or purchase options on the basis of this instrument, which would allow them to lock in a price for future food imports and therefore manage fiscal risks. As part of this, an international grain clearing arrangement could be set up to eliminate counterparty risk for developing countries. It would hold a certain amount of food in reserve and ensure that physical delivery of food could be made in a crisis (FAO *et al.*, 2011; Tangerman, 2011). Such proposals, which require further study, could help ensure that global commodity derivatives markets work to the advantage of low-income, food-importing nations.

Information and transparency

A lack of reliable and up-to-date information on crop supply, demand, stocks and export availability contributed to recent price volatility on food markets. An agricultural market information system (AMIS) has been approved by G20 Ministers of Agriculture and the Committee on world Food Security (CFS) in 2011 with a view to reducing the likelihood of food price volatility. AMIS is an interagency platform to increase transparency and policy coordination in global grain markets. The participating countries are G20 Members plus Spain and seven invited countries selected for their importance as exporters or importers of cereals (Viet Nam, Philippines, Egypt, Ukraine, Kazakhstan, Nigeria, Thailand). Hosted by FAO, AMIS unites the main players of global markets and covers around 85 percent of the world use of cereals.

AMIS monitors global markets of wheat, maize, rice and soybeans in order to detect situations that require international policy action and, if necessary, bring together the main exporting and importing countries to identify and implement appropriate solutions. With a focus on production, utilization, stocks and trade, AMIS provides regular, accurate and timely information on the grain market situation. This information and the analysis of the world market situation are shared by all the participating countries thanks to regular exchanges between FAO-based AMIS market analysts and the countries. These exchanges and the dissemination of good information make it possible to weaken the rumours, to reduce speculation based on wrong facts and to avoid hasty and inappropriate policy measures. In that sense, market transparency and international policy coordination contribute to trade on a fair basis and to food security.

Climate science, supported by satellite data, can also help provide early warning of food security crises and humanitarian crises (Selvaraju, Gommes and Bernardi, 2011).

B.6.3 Strengthen regional and international cooperation

With climate change many productions will have to move, including from one country to another. This calls for strengthened regional and international cooperation to facilitate exchanges of knowledge, manage fish stocks, and exchange and valorize genetic material and practices. This section presents two examples of international instruments that can play a major role to support adaptation efforts, in two very different areas: risk management and genetic resources valorization.

Policies and institutions dedicated to the prevention and management of specific risks and vulnerabilities that can be modified by climate change, such as plant pests, animal diseases, invasive species, wild fires, etc., are mainly local and national, but they can be effectively supported by international cooperation and tools. There is a need for increased international cooperation to prevent and manage transboundary risks, such as plant pests and animal diseases. For instance, global cooperation to combat plant pests is organized through the International Plant Protection Convention (IPPC).

It is likely that climate change will necessitate more international exchanges of genetic resources as countries seek to obtain well-adapted crops, livestock, trees and aquatic organisms. The prospect of greater interdependence in the use of genetic resources in the future underscores the importance of international cooperation in their management today and of ensuring that mechanisms are in place to allow fair and equitable – and ecologically appropriate – transfer of these resources internationally (FAO, 2015a).

International Plant Protection Convention

Global cooperation to combat plant pests is organized through the International Plant Protection Convention (IPPC). The IPPC is an international plant health agreement that aims to protect cultivated and wild plants by preventing the introduction and spread of pests. It has now 182 contracting parties. The IPPC is recognized by the World Trade Organization's (WTO) Agreement on the Application of Sanitary and Phytosanitary Measures (the SPS Agreement) as the sole international standard-setting body for plant health. The IPPC is also one of the seven biodiversity-related conventions that work to implement actions at the national, regional and international levels in order to reach shared goals of conservation and sustainable use. The IPPC is based in Rome under the auspices of FAO and has the following objectives:

- to protect sustainable agriculture and enhance global food security through the prevention of pest spread;
- to protect the environment, forests and biodiversity from plant pests;
- to facilitate economic and trade development through the promotion of harmonized scientifically-based phytosanitary measures;
- to develop phytosanitary capacity for members to accomplish the preceding three objectives.

The Convention stipulates Contracting Parties adherent to the IPPC shall make provisions for a National Plant Protection Organization (NPPOs) to undertake phytosanitary activities. That first concretely translates as national phytosanitary laws and of officers implementing them.

Plants and plant products may be contaminated by a pest. The safe trade of these commodities is ensured through the issuance of a phytosanitary certificate, issued by officers from NPPOs and attesting that these commodities are free of pests. NPPO officers have the task to ensure that the plants and plant products produced in their country are free of quarantine pests. NPPO officers perform inspections of plants and plant products imported at points of entry such as ports and airports. They also perform pest surveillance and pest control activities within their countries. Climate change may require that further verification, inspections, surveillance and control activities be undertaken to prevent new pests from being introduced. In addition to the work being done by NPPO officers, NPPO technical experts work to assess the risks of new pests and how they can be addressed. Risks are anticipated as much as possible through the conduction of pest risk analysis, considering which new pests could be introduced and how to prevent their establishment. GIS tools and methods are used to determine the distribution range of such species under climate change scenarios. The IPPC encourages contracting parties to work together to understand the best actions to take in order to facilitate trade, with special emphasis on assisting developing countries to implement the IPPC standards.

The role of the International Treaty on Plant Genetic Resources for Food and Agriculture

The International Treaty on Plant Genetic Resources is a legally binding international instrument for the management and exchange of plant genetic resources for food and agriculture, and for ensuring the fair and equitable sharing of the benefits arising from the use of these resources (FAO, 2009a). The 136 Contracting Parties to the Treaty undertake to conserve genetic resources, exchange information, transfer technology, build capacity to conserve and sustainably use plant genetic resources, and share the benefits arising from the use of these resources (FAO, 2012c).

The Treaty recognizes the high degree of interdependence among countries with respect to plant genetic resources for food and agriculture (PGRFA), and contains provisions providing guidance to countries regarding the measures and activities to be undertaken at the national level for the conservation and the sustainable use of crop diversity, including for the characterization and evaluation of crops for their potentially useful traits as well as

Box 20: Some results from the Benefit-sharing Fund-sponsored projects

BSF funded projects have facilitated farmers' access to crop genetic resources, either by transferring crop varieties from gene banks to farmers, or between farmers (see http://www.planttreaty.org/content/benefit-sharing-fund-crop-diversity-food-security). Partners in India, Morocco, Peru and Tunisia engaged in seed multiplication in order to distribute large quantities of seed among farming communities (FAO, 2014d).

BSF made available funding for community and scientific efforts to characterize more than 3 200 traditional and wild crop genetic materials, to identify specific traits and breeding new high-performing varieties that are adapted to changing local conditions and tolerant to climate-induced stresses, including pests and diseases. In the second cycle projects, around 28 NGOs have joined forces with 24 national genebanks and research institutions to enhance local diversity through the individuation and development of high-performing local varieties that are resistant to biotic and abiotic stresses. Funded projects have helped identify rice varieties with high drought tolerance in India, drought-tolerant sorghum in the United Republic of Tanzania and rice with good flood adaptability in Indonesia (INPARA 1, INPARA 2 and INPARA 3). In Kenya, two particularly high-yielding finger millet varieties (P224 and U15) that exhibited resistances to blast disease were selected for multiplication and on-farm promotion. The project managed to multiply more than nine tonnes of seeds and distribute them to over 1 000 farmers (FAO, 2013e). In Morocco, partners have identified the best three accessions for both durum wheat (*Triticum durum*) and bread wheat (*Triticum aestivum*) from among the various accessions characterized for resistance to biotic stresses. Selection and evaluation activities carried out by farmers and scientists have resulted in the identification of 14 faba bean varieties tolerant to chocolate spot disease. In Malawi, three varieties of sorghum (*Pirira 1, Acc 947* and *Acc 1065*) have been identified as exhibiting good tolerance to drought. A variety of cowpea (*Sudan 1*), one of pearl millet (*Nyankhombo*) and one of finger millet (*Dopalopa*) have exhibited high yields and tolerance to drought and will be subject to further testing and multiplication in farmers' fields in the coming seasons (FAO, 2014d).

Partners in Morocco and Tunisia engaged in targeted breeding for specific stresses, crossing resistant varieties with farmers' preferred landraces and working to incorporate Septoria disease tolerance identified in a durum wheat landrace into improved lines. Such targeted hybridization, especially when accompanied by full documentation, is a key way to add value to PGRFA.

Under the Peru project, five new "biocultural" products based on local potato varieties were developed and are now commercialized in the Potato Park and on local markets, under the trademark of the Potato Park. Thanks to a local benefit-sharing agreement signed among six indigenous communities, a percentage of the sales of any of the products that carry the Potato Park trademark label goes into a communal fund for Potato Park activities.

In the United Republic of Tanzania, India, Guatemala and Nepal a total of 24 community seed banks storing a total of 1 120 varieties of rice, maize and beans have been created as a platform for offering multiple channels of access and availability of seeds at community level, conserving and restoring local varieties as well as sharing agricultural biodiversity, knowledge and expertise.

As part of the projects implemented in India, farmers have been supported to register their own varieties with the Plant Variety Authority. A total of 55 applications were submitted, for rice, millet, wheat, chickpea and sesame varieties. Moreover 259 farmers were trained in the process of registration, a fundamental precondition for their participation in the improvement of crop genetic resources, and value addition.

the complementarity between on-farm management of genetic diversity and conservation in genebanks, and on farmers' rights, which aim at supporting farmers and indigenous peoples in conserving crop diversity on their farms.

The Multilateral System of Access and Benefit-sharing established a global genepool for food crops and facilitates access to this gene pool for agricultural research and breeding of new crop varieties. This genepool contains 2.3 million accessions of the 64 staple crops that account for more than 80 percent of human calorie intake from plants. The samples come from Contracting Parties to the Treaty, from international institutions, such as international gene banks of the CGIAR, and from natural and legal persons. They are administered under a common set of rules that regulate not only how to obtain access to the plant genetic material but also how to share the results of research and breeding on that material. It facilitates the access and exchange of genetic material by, inter alia, eliminating the transaction costs associated with bilateral case-by-case negotiations and legal contracts (see http://www.planttreaty.org/node/5851).

The "Leading the Field" initiative and its Benefit-sharing Fund (BSF)[17] supports high-impact projects for the conservation and the sustainable use of crop diversity in developing countries, with a focus on helping ensure sustainable food security by assisting farmers adapt to climate change (see Box 20). Since its establishment and the launch of its project cycles, the Benefit-sharing Fund contributed to ongoing research activities that facilitated the characterization and evaluation of 4 679 accessions of different crops (rice, beans, barley, sorghum, citrus, finger millet, lablab beans, maize, potato, sorghum, tomato, wheat, etc.). Through such activities, 178 accessions with a strong potential for different resistances to biotic and abiotic stresses, as well as 26 specific candidate genes of high value to climate change adaptation, were identified, and the development of 96 new breeding lines was supported. In particular, resistance traits and accessions with high resistance levels to six major crop diseases have been studied in addition to accessions with high tolerance levels to heat, drought and cold.

All the executed activities are envisaged to have the potential to be scaled up across agro-ecological zones and replicated in other areas, ensuring maximum positive impact and best use of current scientific knowledge and data.

[17] http://www.planttreaty.org/content/training_edm3

CONCLUSION

As the report has shown, climate change brings a cascade of risks from physical impacts to ecosystems, agro-ecosystems, agricultural production, food chains, incomes and trade, with economic and social impacts on livelihoods and food security and nutrition.

The people who are projected to suffer the earlier and the worst impacts from climate change are the most vulnerable populations, with livelihoods depending on agriculture sectors in areas vulnerable to climate change. Understanding the cascade of risks, as well as the vulnerabilities to these risks, is key to frame ways to adapt. Reducing vulnerabilities is key to reducing the net impacts on food security and nutrition and also to reducing long-term effects.

Increasing resilience of food security in the face of climate change calls for multiple interventions, from social protection to agricultural practices and risk management.

The changes on the ground needed for adaptation to climate change in agriculture and food systems for food security and nutrition will require to be enabled by investments, policies and institutions in various areas. To be the most effective such interventions need to be part of integrated strategies and plans. The strategies should be gender-sensitive, multi-scales, multi-sectors and multi-stakeholders. They should be elaborated in a transparent way and consider the different dimensions (social, economic, environmental) of the issues and different time scales by which the changes will need to be implemented and supported. They should be based on assessments of risks and vulnerabilities, learn from experience and progresses, and be regularly monitored, assessed and updated. Middle- and high-income countries are increasingly carrying out regular assessments but countries without this capacity will need specific support. The National Adaptation Plan process set up under the UNFCCC provides the opportunity to integrate food security and nutrition as a key objective. Such national strategies and plans need also to be supported by enhanced regional and international cooperation.

Actions by different stakeholders are needed in the short term to enable responses in the short, medium and long term. Some medium- and long-term responses will need immediate enabling action and planning, and immediate implementation of investments, especially those investments that require longer time frames to be developed and arrive in the field: forestry, livestock breeding, seed multiplication, R&D, innovation and knowledge transfer to enable adaptation.

REFERENCES

Ahammad, H., Heyhoe, E., Nelson, G., Sands, R., Fujimori, S., Hasegawa, T., van der Mensbrugghe, D., Blanc, E., Havlík, P., Valin, H., Kyle, P., Mason d' croz, D., can Meijl, H., Schmita, C., Lotze-Campen, H., von Lampe, M. & Tabeau, A. 2015. The role of international trade under a changing climate: insights from global economic modelling. *In* A. Elbehri, ed. *Climate change and food systems: global assessments and implications for food security and trade*. Rome, FAO.

Aksoy, A., Beverinotti, J., Covarrubias, K. & Zezza, A. 2010. Household income structures in low-income countries. *In* M. Aksoy & B. Hoekstra, eds. *Food prices and rural poverty,* pp. 89–112. Washington, DC, World Bank.

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.

Allison, E.H., Andrew, N.L. & Oliver, J. 2007. Enhancing the resilience of inland fisheries and aquaculture systems to climate change. *Journal of SAT Agricultural Research*, 4(1).

Allison, E.H., Adger, W.N., Badjeck, M.-C., Brown, K., Conway, D., Dulvy, N.K., Halls, A., Perry, A. & Reynolds, J.D. 2005. *Effects of climate change on the sustainability of capture and enhancement fisheries important to the poor: analysis of the vulnerability and adaptability of fisherfolk living in poverty*. Final technical report. Fisheries Management Science Programme MRAG/DFID, Project no. R4778J. London.

Allison, E.H., Perry, A.L., Badjeck, M-C., Adger, W.N., Brown, K., Conway, D., Halls, A.S., Pilling, G.M., Reynolds, J.D., Andrew, N.L. & Dulvy, N.K. 2009. Vulnerability of national economies to the impacts of climate change on fisheries. *Fish and Fisheries,* 10(2): 173–196.

Altieri, M.A. 1995. *Agroecology: the science of sustainable agriculture*. Boulder, USA, Westview Press. 433 p.

Angelsen, A. & Wunder, S. 2003. *Exploring the forest – poverty link: key concepts, issues and research implications*. CIFOR Occasional Paper No. 40. Bogor, Indonesia, Center for International Forestry Research.

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.

Argumedo, A. 2008. *Association ANDES: conserving indigenous biocultural heritage in Peru*. IIED Gatekeeper Series/International Institute for Environment and Development, Sustainable Agriculture Programme No. 137a. London, IIED, Natural Resources Group and Sustainable Agriculture and Rural Livelihoods Programme.

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., Belloti, F., Asfaw, S. & Lipper, L. 2015a. Welfare Impact of Climate Shock in Tanzania. *Journal of Environment and Development*. Under review.

Asfaw, S. & Lipper, L. 2011. *Economics of PGRFA management for adaptation to climate change: a review of selected literature.* Commission on Genetic Resources for Food and Agriculture. Background Study Paper No. 60. Rome, FAO (available at http://www.fao.org/docrep/meeting/023/mb695e.pdf).

Arslan, A., Belotti, F. & Lipper, L. 2015. *Smallholder productivity under climatic variability: Adoption and impact of widely promoted agricultural practices in Tanzania*. To be revised and resubmitted in *Food Policy*.

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

Asfaw, S., Coromaldi, M. & Lipper, L. 2015a. Welfare cost of weather fluctuations and climate shocks in Ethiopia. *Journal of Climate Change Economics*, Under review.

Asfaw, S., Coromaldi, M. & Lipper, L. 2015b. *Adaptation to climate change and food security in Ethiopia*. FAO-ESA Working Paper. Rome, FAO.

Asfaw, S., DiBattista, F. & Lipper, L. 2014. *Food security impact of agricultural technology adoption under climate change: micro-evidence from Niger*. FAO-ESA Working Paper 14-12. Rome (also under review for the *Journal of African Studies*).

Asfaw, S., DiBattista, F. & Lipper, L. 2015. Effects of weather fluctuations and climate shocks on household welfare: evidence from Niger. *Empirical Economics*. Under review.

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

Asfaw, S., Davis, B., Dewbre, J., Handa, S. & Winters, P. 2014a. Cash transfer programme, productive activities and labour supply: evidence from randomized experiment in Kenya. *Journal of Development Studies*, 50(8): 1172–1196.

Asfaw, S., Pickmans, R., Alfani, F. & Davis, B. 2015a. *Productive impact of Ethiopia's Social Cash Transfer Pilot Programme.* PtoP project report, FAO, Rome.

Asfaw, S., Carraro, A., Pickmans, R., Daidone. S. & Davis, B. 2015b. *Productive impacts of the Malawi Social Cash Transfer Programme.* PtoP project report. Rome, FAO (forthcoming).

Asfaw, S., McCarthy, N., Cavatassi, Cavatassi, R., Paolantonio, A. Amare, A. & Lipper, L. 2015c. *Diversification, climate risk and vulnerability to poverty: evidence from rural Malawi.* Forthcoming FAO-ESA Working Paper (Also contributed Paper Submitted for Oral Presentation at the IAAE Conference, Milan). (Also under review for *World Development*)

Ashley, C. & Carney, D. 1999. *Sustainable livelihoods: lessons from early experience.* London, Department for International Development.

Audho, J.O., Ojango, N.E., Oyieng, E., Okeyo, A.M. & Ojango, J.M.K. 2015. Milk from indigenous sheep breeds: an adaptation approach to climate change by women in Isinya, Kajiado County in Kenya. *In* J.M. Ojango, B. Malmfors & A.M. Okeyo, eds. *Animal genetics training resource*. Kenya, Nairobi, International Livestock Research Institute and Uppsala, Sweden, Swedish University of Agricultural Sciences.

Baker, M.B. Venugopal, P.D. & Lamp, W.O. 2015. Climate change and phenology: *Empoasca fabae* (Hemiptera: Cicadellidae) migration and severity of impact. *PLOS ONE*. DOI: 10.1371/journal.pone.0124915.

Barange, M. & Perry, R.I. 2009. Physical and ecological impacts of climate change relevant to marine and inland capture fisheries and aquaculture. *In* K. Cochrane, C. De Young, D. Soto & T. Bahri**.** *Climate change implications for fisheries and aquaculture: overview of current scientific knowledge.* FAO Fisheries and Aquaculture Technical Paper No. 530. Rome, FAO. 212 p. (available at ftp://ftp.fao.org/docrep/fao/012/i0994e/i0994e.pdf).

Bárcena, A., Prado, A., Samaniego, J. & Pérez, R. 2014. *The economics of climate change in Latin America and the Caribbean: paradoxes and challenges*. United Nations, Economic Commission for Latin America and the Caribbean (available at http://repositorio.cepal.org/bitstream/handle/11362/37056/S1420806_en.pdf?sequence=4).

Barton, A., Waldbusser, G.G., Feely, R.A., Weisberg, S.B., Newton, J.A., Hales, B., Cudd, S., Eudeline, B., Langdon, C.J., Jefferds, I., King, T., Suhrbier, A. & McLaughlin, K. 2015. Impacts of coastal acidification on the Pacific Northwest shellfish industry and adaptation strategies implemented in response. *Oceanography*, 28(2): 146–159.

Barucha, Z. & Pretty, J. 2010. The roles and values of wild foods in agricultural systems. *Philosophical Transactions of the Royal Society B-Biological Sciences,* 365: 2913–2926.

Bauer, P., Thorpe, A. & Brunet, A. 2015. The quiet revolution of numerical weather prediction, *Nature,* 525: 47-55.

Beed, F., Benedetti, A., Cardinali, G., Chakraborty, S., Dubois, T., Garrett, K., & Halewood, M. 2011. *Climate change and micro-organism genetic resources for food and agriculture: state of knowledge, risks and opportunities.* Commission on Genetic Resources for Food and Agriculture. Background Study Paper No. 57. Rome, FAO (available at http://www.fao.org/docrep/meeting/022/mb392e.pdf).

Bell, J.D., Johnson, J.E. & Hobday, A.J. 2011. *Vulnerability of tropical Pacific fisheries and aquaculture to climate change*. Secretariat of the Pacific Community, Noumea, New Caledonia.

Blackburn, H. & Gollin, D. 2008 Animal genetic resource trade flows: the utilization of newly imported breeds and the gene flow of imported animals in the United States of America. *Livestock Science*, 120 (3): 240–247.

Bobojonov, I. & Aw-Hassan, A. 2014. Impacts of climate change on farm income security in Central Asia: an integrated modeling approach, *Agriculture, Ecosystems & Environment,* 188: 245–255.

Bohmanova, J., Misztal, I. & Cole, J.B. 2007. Temperature-humidity indices as indicators of milk production losses due to heat stress. *Journal of Dairy Science,* 90: 1947–1956.

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. *Building resilience for adaptation to climate change in the agriculture sector*. Proceedings of a joint FAO/OECD Workshop. Rome, FAO.

Brander, K.M. 2007. Global fish production and climate change. *PNAS,* 104(50): 19709–19714, doi: 10.1073/pnas.0702059104.

Brugère, C., & De Young, C. 2015. *Assessing climate change vulnerability in fisheries and aquaculture: available methodologies and their relevance for the sector*. FAO Fisheries and Aquaculture Technical Paper No. 597. Rome, FAO.

Caldzilla, A., Zhu, T., Rehdanz, K., Tol, R.S.J. & Ringler, C. 2013. Economywide impacts of climate change on agriculture in sub-Saharan Africa. *Ecological Economics,* 93: 150–165.

CARE. 2000. *Operationalizing household livelihood security: a holistic approach for addressing poverty and vulnerability*. T.R.Frankenberger, M. Drinkwater & D. Maxwell. USA.

Carpenter, S.R., Walker, B.H., Anderies, J.M. & Abel, N. 2001. From metaphor to measurement: resilience of what to what? *Ecosystems*, 4: 765–781.

Carter, M.R. & Lybbert, T.J. 2012. Consumption versus asset smoothing: testing the implications of poverty trap theory in Burkina Faso. *Journal of Development Economics,* 99: 255–264.

Chakraborty, S. & Newton, A.C. 2011. Climate change, plant diseases and food security: an overview. *Plant Pathology*, 60: 2–14.

Chan, W.H., Mak, Y.L., Wu, J.J., Jin, L., Sit, W.H., Lam, J.C.W., Sadovy de Mitcheson, Y., Chan, L.L., Lam, P.K.S. & Murphy, M.B. 2011. Spatial distribution of ciguateric fish in the Republic of Kiribati. *Chemosphere*, 84(1): 117–123.

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.

Christensen, J.H., Krishna Kumar, K., Aldrian, E., An, S.-I., Cavalcanti, I.F.A., de Castro, M., Dong, W., Goswami, P., Hall, A., Kanyanga, J.K., Kitoh, A., Kossin, J., Lau, N.-C., Renwick, J., Stephenson, D.B., Xie, S.-P. & Zhou, T. 2013. Climate phenomena and their relevance for future regional climate change. *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 I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, UK, and New York, USA, Cambridge University Press.

Chomo, V. & De Young. C. 2015. Towards sustainable fish food and trade in the face of climate change. *BIORES*, 9(2) (available at http://www.ictsd.org/bridges-news/biores/news/towards-sustainable-fish-food-and-trade-in-the-face-of-climate-change).

Church, J.A., Clark, P.U., Cazenave, A., Gregory, J.M., Jevrejeva, S., Levermann, A., Merrifield, M.A., Milne, G.A., Nerem, R.S., Nunn, R.D., Payne, A.J., Pfeffer, W.T., Stammer, D. & Unnikrishnan, A.S. 2013. Sea level change. *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 I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, UK, and New York, USA, Cambridge University Press.

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.

Cinner, J., McClanahan, T., Wamukota, A., Darling, E., Humphries, A., Hicks, C., Huchery, C., Marshall, N., Hempson, T., Graham, N., Bodin, Ö., Daw, T. & Allison, E. 2013. *Social–ecological vulnerability of coral reef fisheries to climatic shocks*. FAO Fisheries and Aquaculture Circular No. 1082. Rome, FAO (available at www.fao.org/docrep/018/ap972e/ap972e00.htm).

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

Cock, M.J.W., Biesmeijer, J.C., Cannon, R.J.C., Gerard, P.J., Gillespie, D., Jiménez, J.J., Lavelle, P.M. & Raina, S.K. 2011. *Climate change and invertebrate genetic resources for food and agriculture: state of knowledge, risks and opportunities.* Commission on Genetic Resources for Food and Agriculture. Background Study Paper No. 54. Rome, FAO (available at http://www.fao.org/docrep/meeting/022/mb390e.pdf).

Crescio, M.I., Forastiere, F., Maurella, C., Ingravalle, F. & Ru, G. 2010. Heat-related mortality in dairy cattle: a case crossover study. *Preventive Veterinary Medicine*, 97(3): 191–197.

Cressman, K. 2013. Climate change and locusts in the WANA Region. *In* M.V.K Sivakumar, R. Lal, R. Selvaraju & I. Hamdan, eds. *Climate change and food security in West Asia and North Africa*, pp. 131–143. Springer. DOI 10.1007/978-94-007-6751-5_7.

Daidone, S., Davis, B., Dewbre, J. & Covarrubias, K. 2014a. *Lesotho Child Grants Programme: 24-month impact report on productive activities and labour allocation*. PtoP Project Report. Rome, FAO.

Daidone, S., Davis, B., Dewbre, J., Gonzalez-Flores, M., Handa, S., Seidenfeld, D. & Tembo, G. 2014b. Zambia's Child Grant Programme: 24-month impact report on productive activities and labour allocation. PtoP Project Report Rome, FAO.

Daw, T., Adger, W.N., Brown, K. & Badjeck, M.-C. 2009. Climate change and capture fisheries: potential impacts, adaptation and mitigation. *In* K. Cochrane, C. De Young, D. Soto & T. Bahri, eds. *Climate change implications for fisheries and aquaculture: overview of current scientific knowledge*, pp. 107–150. FAO Fisheries and Aquaculture Technical Paper No. 530. Rome, FAO. 212 p. (available at www.fao.org/docrep/012/i0994e/i0994e00.htm).

De Nicola, F. 2013. Weather insurance as a means of supporting vulnerable agriculture, and impacts of climate change. *CAB Reviews*, 8(027).

De Silva, S.S. & Soto, D. 2009. Climate change and aquaculture: potential impacts, adaptation and mitigation. *In* K. Cochrane, C. De Young, D. Soto & T. Bahri, eds. *Climate change implications for fisheries and aquaculture: overview of current scientific knowledge,* pp. 151–212. FAO Fisheries and Aquaculture Technical Paper No. 530. Rome, FAO.

Dercon, S. 2004. Growth and shocks: evidence from rural Ethiopia. *Journal of Development Economics*, 74: 309–329.

Dercon, S. 2006. Economic reform, growth and the poor. Evidence from rural Ethiopia. *Journal of Development Economics*, 81(1): 1–24.

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

Dessai, S. & Hulme, M. 2004. Does climate adaptation policy need probabilities? *Climate Policy*, 4(2): 107–128.

Dewees, P., Campbell, B., Katerere, Y., Sitoe, A., Cunningham, A., Angelsen, A. & Wunder, S. 2011. *Managing the miombo woodlands of Southern Africa: policies, incentives, and options for the rural poor*. Washington, DC, Program on Forests (PROFOR).

Dikmen, S. & Hansen, P.J. 2009. Is the temperature-humidity index the best indicator of heat stress in lactating dairy cows in a subtropical environment? *Journal of Dairy Science*, 92: 109–116.

Dikmen, S., Alava, E., Pontes, E., Fear, J.M., Dikmen, B.Y., Olson, T.A. & Hansen, P.J. 2008. Differences in thermoregulatory ability between slick-haired and wild-type lactating Holstein cows in response to acute heat stress. *Journal of Dairy Science*, 91(9): 3395–3402.

Eggert, H., Greaker, M. & Kidane, A. 2015. Trade and resources: Welfare effects of the Lake Victoria fisheries boom. *Fisheries Research*, 167: 156–163.

Elbehri, A. & Burfisher, M. 2015. Economic modelling of climate impacts and adaptation in agriculture: a survey of methods, results and gaps. *In* A. Elbehri, ed. *Climate change and food systems: global assessments and implications for food security and trade*. Rome, FAO.

Elbehri, A., Elliott, J. & Wheeler, T. 2015. Climate change, food security and trade: an overview of global assessments and policy insights. *In* A. Elbehri, ed. *Climate change and food systems: global assessments and implications for food security and trade.* Rome, FAO.

Ericksen, P., Thornton, P., Notenbaert, A., Cramer, L., Jones, P. & Herrero, M. 2011. *Mapping hotspots of climate change and food insecurity in the global tropics*. CCAFS Report 5. Copenhagen, CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) (available at www.ccafs.cgiar.org).

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

Fafchamps, M. 1999. *Rural poverty, risk and development*. Economic and Social Development Paper No. 144. Rome, FAO. 131 p.

Fafchamps, M. 2009. Vulnerability, risk management, and agricultural development. *In* Working Paper Series No. AfD-0904, pp. 1–29. Berkeley, USA, Agriculture for Development, Center for Effective Global Action, University of California (available at http://ageconsearch.umn.edu/bitstream/156662/2/4%20%20Fafchamps%20-%20FINAL.pdf).

FAO. 1995. *Code of Conduct for Responsible Fisheries*. Rome (available at ftp://ftp.fao.org/docrep/fao/005/v9878e/v9878e00.pdf).

FAO. 2003. *Fisheries management – 2. The ecosystem approach to fisheries*. Rome (available at http://www.fao.org/docrep/005/y4470e/y4470e00.htm).

FAO. 2006. *Breed diversity in dryland ecosystems*. Information Document 9, Fourth Session of the Intergovernmental Technical Working Group on Animal Genetic Resources for Food and Agriculture. Rome. 13 p.

FAO. 2007. *The State of Food and Agriculture 2007. Paying farmers for environmental services.* Rome.

FAO. 2009a. *International Treaty on Plant Genetic Resources for Food and Agriculture* (available at ftp://ftp.fao.org/docrep/fao/011/i0510e/i0510e.pdf).

FAO. 2009b. *Climate change implications for fisheries and aquaculture*. FAO Fisheries and Aquaculture Technical Paper. No. 530, Rome (available at http://www.fao.org/docrep/012/i0994e/i0994e00.htm).

FAO. 2010. *Report of the FAO workshop on climate change and fisheries in the African Great Lakes*. Bujumbura, 20–21 April 2010 (available at http://www.academia.edu/12458723/Report_of_the_FAO_workshop_on_climate_change_and_fisheries_in_the_African_Great_Lakes).

FAO. 2011a. *Adapting to climate change: the ecosystem approach to fisheries and aquaculture in the Near East and North Africa Region.* FAO Fisheries and Aquaculture Circular No. 1066, Rome (available at: http://www.fao.org/docrep/014/i2146e/i2146e00.htm).

FAO. 2011b. *Potential effects of climate change on crop pollination*, by M. Kjøhl, A. Nielsen & N.C. Stenseth. Rome.

FAO. 2011c. *The State of Food and Agriculture 2010-2011. Women in agriculture: closing the gender gap for development*. Rome.

FAO. 2011d. *The State of Food Insecurity in the World. How does international price volatility affect domestic economies and food security*. Rome.

FAO. 2011e. *Save and grow: a policymaker's guide to the sustainable intensification of smallholder crop production*. Rome.

FAO. 2012a. *Greening the economy with agriculture*. Rome (available at http://www.fao.org/docrep/015/i2745e/i2745e00.pdf).

FAO. 2012b. *Forests, trees and people together in a living landscape: a key to rural development.* Committee on Forestry Paper COFO/2012/6.2 (available at http://www.fao.org/docrep/ meeting/026/me435e.pdf).

FAO. 2012c. *Conservation and sustainable use under the International Treaty* (available at http://www.planttreaty.org/sites/default/files/edm2_full_en.pdf).

FAO. 2013a *Report of the First Meeting of the Plenary Assembly of the Global Soil Partnership* (Rome, 11-12 June 2013). Hundred and Forty-eighth session, Rome, 2-6 December 2013, CL 148/13, Rome.

FAO. 2013b. *Climate-smart agriculture sourcebook* (available at http://www.fao.org/3/i3325e.pdf).

FAO. 2013c. *FAO Statistical Yearbook 2013*. World food and agriculture. Rome.

FAO. 2013d. *Climate change guidelines for forest managers*. Rome.

FAO. 2013e. *Report on the execution of the first round of the project cycle of the Benefit-sharing Fund*. Secretariat of the International Treaty on Plant Genetic Resources for Food and Agriculture (available at http://www.planttreaty.org/sites/default/files/Report_BSF.pdf).

FAO. 2014a. *The State of World Fisheries and Agriculture: opportunities and challenges*. Rome (available at http://www.fao.org/3/d1eaa9a1-5a71-4e42-86c0-f2111f07de16/i3720e.pdf).

FAO. 2014b. *Conduire des Champs Ecoles des Producteurs : Guide du Facilitateur*. Rome, FAO (avaliable at: http://www.fao.org/3/a-i3948f.pdf).

FAO. 2014c. *The State of Food and Agriculture*. *Innovation in family farming.* Rome (available at http://www.fao.org/publications/sofa/2014/en/).

FAO. 2014d. *Enabling farmers to face climate change. Second cycle of the benefit sharing fund projects*. Secretariat of the International Treaty on Plant Genetic Resources for Food and Agriculture (available at http://www.planttreaty.org/sites/default/files/BSF_2nd_cycle-booklet.pdf).

FAO. 2015a. *Coping with climate change – the roles of genetic resources for food and agriculture.* Rome (available at http://www.fao.org/3/a-i3866e.pdf).

FAO. 2015b. *International Standards for Phytosanitary Measures, ISPM 5, Glossary of Phytosanitary Terms*. International Plant Protection Convention (available at https://www.ippc.int/static/media/files/publication/en/2015/05/ISPM_05_En_2015-05-29_CPM-10.pdf).

FAO. 2015c. *The Second Report on the State of the World's Animal Genetic Resources for Food and Agriculture*. B.D. Scherf & D. Pilling, eds. FAO Commission on Genetic Resources for Food and Agriculture Assessments. Rome (available at http://www.fao.org/3/a-i4787e/index.html).

FAO. 2015d. *Voluntary guidelines to support the integration of genetic diversity into national climate change adaptation planning*. In press. Rome.

FAO. 2015e.*The impact of natural hazards and disasters on agriculture and food security and nutrition. Rome* (available at http://www.fao.org/3/a-i4434e.pdf).

FAO. 2015f. *The State of Food and Agriculture.* Rome.

FAO. 2015g. *The State of Food Insecurity in the World*. *Meeting the 2015 international hunger targets: taking stock of uneven progress* (available at http://www.fao.org/3/a-i4646e.pdf).

FAO. 2015h. *Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Eradication* (available at http://www.fao.org/3/a-i4356e.pdf).

FAO/AgriCord. 2012. *Strength in numbers – effective forest producer organizations*. Rome (available at http://www.fao.org/docrep/016/ap452e/ap452e00.pdf).

FAO/IFAD/WFP. 2015. *Achieving zero hunger: the critical role of investments in social protection and agriculture*, Rome (available at http://www.fao.org/3/a-i4777e.pdf).

FAO/IFAD/IMF/OECD/UNCTAD/WFP/World Bank/ WTO/IFPRI/UN HLTF. 2011. *Interagency Report to the G20 on food price volatility*.

FAO/OECD. 2012. *Building resilience for adaptation to climate change in the agriculture sector*. Proceedings of a joint FAO/OECD Workshop. A. Meybeck, J., Lankoski, S., Redfern, N., Azzu & V., Gitz. Rome, FAO.

Faurès, J.M., Bernardi, M. & Gommes, R. 2010. There is no such thing as an average: how farmers manage uncertainty related to climate and other factors. *International Journal of Water Resources Development*, 26(4): 523–542.

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

FeedInfo. 2015. *Lallemand animal nutrition warns of heat stress in cows all over Europe* (available at http://www.feedinfo.com/console/PageViewer.aspx?page=5050311&str=lallemand).

Frankham, R. 2009. Genetic architecture of reproductive fitness and its consequences. *In* J. Van der Werf, H.U. Graser & R. Frankham, eds. *Adaptation and fitness in animal populations: Evolutionary and breeding perspectives on genetic resource management*, pp. 15–40. Springer.

Freibauer, A., Mathijs, E., Brunori, G., Damianova, Z., Faroult, E., Girona i Gomis, J., O'Brien, L. & Treyer, S. 2011. *Sustainable food consumption and production in a resource-constrained world*. European Commission – Standing Committee on Agricultural Research (SCAR). 149 p.

Frieler, K., Levermann, A., Elliott, J., Heinke, J., Arneth, A., Bierkens, M.F.P., Ciais, P., Clark, D.B., Deryng, D., Döll, P., Falloon, P., Fekete, B., Folberth, C., Friend, A.D., Gellhorn, C., Gosling, S.N., Haddeland, I., Khabarov, N., Lomas, M., Masaki, Y., Nishina, K., Neumann, K., Oki, T., Pavlick, R., Ruane, A.C., Schmid, E., Schmitz, C., Stacke, T., Stehfest, E., Tang, Q., Wisser, D., Huber, V., Piontek, F., Warszawski, L., Schewe, J., Lotze-Campen, H. & Schellnhuber, H.J. 2015. A framework for the cross-sectoral integration of multi-model impact projections: Land use decisions under climate impacts uncertainties. *Earth Syst. Dyn.,* 6: 447–460. doi:10.5194/esd-6-447-2015.

Gallai, N., Salles, J.-M., Settele, J. & Vaissière, B.E. 2009. Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. *Ecol. Econ*., 68: 810–821.

Galluzzi, G., Duijvendijk, C. van., Collette, L., Azzu, N. & Hodgkin, T., eds. 2011. *Biodiversity for food and agriculture: contributing to food security and sustainability in a changing world. Outcomes of an Expert Workshop held by FAO and the Platform on Agrobiodiversity Research from 14-16 April 2010, Rome, Italy.* Rome, FAO/PAR (available at http://www.fao.org/3/a-i1980e.pdf).

Gbobaniyi, E., Sarr, A., Sylla, M.B., Diallo, I., Lennard, C., Dosio, A., Dhiédiou, A., Kamga, A., Klutse, N.A.B., Hewitson, B., Nikulin, G., Lamptey, B. 2014 Climatology, annual cycle and interannual variability of precipitation and temperature in CORDEX simulations over West Africa. *Int. J. Climatol.,* 34(7): 2241–2257. doi:10.1002/joc.3834.

Ghini, R., Hamada, E., Pedro, M.L., Marengo, J.A. & Gonçalves, R.R.V. 2008. Risk analysis of climate change on coffee nematodes and leaf miner in Brazil. *Pesquisa Agropecuária Brasileira*, 43: 187–195.

Gilbert, C.L. & Tabova, A. 2011. Coping with food price surges, *In* A. Prakash, ed. *Extreme volatility in agricultural markets: causes, consequences and policy options*. Rome, FAO.

Gitz, V. & Meybeck, A. 2012. Risks, vulnerabilities and resilience in a context of climate change. *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.

Global Food Security Programme. 2015. *Extreme weather and resilience of the global food system.* 2015. Final Project Report from the UK-US Taskforce on Extreme Weather and Global Food System Resilience. UK (available at http://www.foodsecurity.ac.uk/assets/pdfs/extreme-weather-resilience-of-global-food-system.pdf).

Gollin, D., Van Dusen, E. & Blackburn, H. 2008. Animal genetic resource trade flows: economic assessment. *Livestock Science*, 120 (3): 248–255.

Guilyardi, E., Wittenberg, A., Fedorov, A., Collins, M., Wang, C., Capotondi, A., van Oldenborgh, G.J. & Stockdale, T. 2009. Understanding El Niño in ocean-atmosphere general circulation models: progress and challenges. *Bull. Amer. Met. Soc.,* 90: 325–340.

Hanlon, J., Barrientos, A. & Hulme, D. 2010. *Just give money to the poor*. Chapter 4, pp. 53–54. Chronic Poverty Research Centre.

Hannukkala, A.O., Kaukoranta, T., Lehtinen, A. & Rahkonen, A. 2007. Late-blight epidemics on potato in Finland, 1933-2002; increased and earlier occurrence of epidemics associated with climate change and lack of rotation. *Plant Pathology*, 56: 167–176.

Hare, J.A., Morrison, W.E., Nelson, M.W., Stachura, M.M., Teeters, E.J., Griffis, R.B., Alexander, M.A., Scott, J.D., Alade, L., Bell, R.J., Chute, A.S., Curti, K.L., Curtis, T.H., Kircheis, D., Kocik, J.F., Lucey, S.M., McCandless, C,.T., Milke, L.M., Richardson, DE., Robillard, E., Walsh, H.J., McManus, M.C. & Marancik, K.E. Forthcoming. *Northeast Fisheries Climate Vulnerability Assessment (NEVA): an application of the NMFS fisheries climate vulnerability assessment methodology*. NMFS Draft document.

Havlík, P., D. Leclère, H. Valin, M. Herrero, E. Schmid, J-F. Soussana, C. Müller and M. Obersteiner. 2015. Global climate change, food supply and livestock production systems: A bioeconomic analysis. *In* A. Elbehri, ed., *Climate change and food systems: global assessments and implications for food security and trade*), Rome, FAO.

Hayes, B.J., Bowman, P.J., Chamberlain, A.J., Savin, K., van Tassell, C.P., Sonstegard, T.S. & Goddard, M.E. 2009. A validated genome wide association study to breed cattle adapted to an environment altered by climate change. *PLoS ONE 4*, e6676. doi:10.1371/journal.pone.0006676.

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

Hertel, T.W., Burke, M.B. & Lobell, D.B. 2010. *The poverty implications of climate-induced crop yield changes by 2030*. GTAP Working Paper No. 59 (available at http://iis-db.stanford.edu/pubs/22837/GTAP_2_2010.pdf).

Hidrobo, M., Hoddinott, J., Kumar, N. & Olivier, M. 2014. *Social protection and food security.* Paper prepared by the International Food Policy Research Institute as background to the 2015 edition of FAO's The State of Food and Agriculture report. Washington, DC, IFPRI.

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

HLPE. 2012a. *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.

HLPE. 2012b. *Social protection for food security*. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome.

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

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

HLPE. 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.

Hoddinot, J. 2006. Shocks and their Consequences Across and Within Households in Rural Zambia. *Journal of Development Studies*, 42(2): 301–321.

Hoffmann, I. 2013. Adaptation to climate change – exploring the potential of locally adapted breeds. *Animal,* 7 (Suppl. 2): 346–362.

Horčička, P. 2015. *Presentation "Challenges of wheat breeding global innovation"* (available at http://ec.europa.eu/dgs/health_food-safety/information_sources/docs/events/20150714_climate-change_expo_milan_pres_10.pdf).

Hurley, T. 2010. *Review of agricultural production risk in the developing world*. HarvestChoice Working Paper 11. Washington, DC, International Food Policy Research Institute (IFPRI), 56 p.

IBRD/WB (International Bank for Reconstruction and Development/ World Bank). 2010. *Development and climate change* (available at: http://siteresources.worldbank.org/INTWDRS/Resources/477365-1327504426766/8389626-1327510418796/Front-matter.pdf).

ICEM (International Centre for Environmental Management). 2013. *USAID Mekong ARCC climate change impact and adaptation on livestock*. Prepared for the United States Agency for International Development by ICEM.

IFAD. 2011. *Rural poverty report 2011. New realities, new challenges: new opportunities for tomorrow's génération* (available at http://www.ifad.org/rpr2011/report/e/rpr2011.pdf).

IPCC. 2000. *Emissions scenarios.* A Special Report of IPCC Working Group III. N. Nakićenović, J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Griibler, T. Yong Jung, T. Kram, E. Lebre La Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K. Riahi, A. Roehrl, H.-H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. van Rooijen, N. Victor & Z. Dadi, eds. Cambridge University Press , Cambridge. UK.

IPCC. 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 & A. Reisinger, eds. Geneva, Switzerland, IPCC. 104 p.

IPCC. 2012. *Managing the risks of extreme events and disasters to advance climate change adaptation.* C.B. Field, C. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor & P.M. Midgley, eds. Available from Cambridge University Press, Cambridge, UK, 582 p.

IPCC. 2013. *Climate change 2013: the physical science basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. 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. Cambridge, UK, and New York, USA, Cambridge University Press. 1535 p.

IPCC. 2014a. *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. Core Writing Team, R.K. Pachauri & L.A. Meyer, eds. Geneva, Switzerland, IPCC. 151 p.

IPCC. 2014b. *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. 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. Cambridge, UK, and New York, USA, Cambridge University Press. 1132 p.

IUCN. 2010. *Building climate change resilience for African livestock in sub-Saharan Africa*. World Initiative for Sustainable Pastoralism (WISP): a program of IUCN Eastern and Southern Africa Regional Office, Nairobi, March 2010. viii + 48 p.

Jarvis, A., Upadhyaya, H., Gowda, C.L.L., Aggarwal, P.K., Fujisaka, S. & Anderson, B. 2010. *Climate change and its effect on conservation and use of plant genetic resources for food and agriculture and associated biodiversity for food security.* ICRISAT/FAO. Thematic Background Study for the Second Report on The State of the World's Plant Genetic Resources for Food and Agriculture. Rome (available at http://www.fao.org/docrep/013/i1500e/i1500e16.pdf).

Jiménez Cisneros, B.E., Oki, T., Arnell, N.W., Benito, G., Cogley, J.G., Döll, P., Jiang, T. & Mwakalila, S.S. 2014. Freshwater resources. In: *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*. 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. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 229–269.

Jones, P.G. & Thornton, P.K. 2009. Croppers to livestock keepers: livelihood transitions to 2050 in Africa due to climate change. *Environmental Science & Policy,* 12(4): 427–437.

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.

Kazianga, H. & Udry, C. 2006. Consumption smoothing? Livestock, insurance and drought in rural Burkina Faso. *Journal of Development Economics*. 79: 413–466.

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. 2013. 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 I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, UK, and New York, USA, Cambridge University Press.

Klein, A., Steffan Dewenter, I. & Tscharntke, T. 2003. Fruit set of highland coffee increases with the diversity of pollinating bees. *Proceedings of the Royal Society*, 270: 955–961.

Kurosaki, T. & Fafchamps, M. 2002. Insurance market efficiency and crop choices in Pakistan. *Journal of Development Economics*, 67(2): 419–453,.

Kurukulasuriya, P. & Rosenthal, S. 2013. *Climate change and agriculture: a review of impacts and adaptations*. Environment Department Papers No. 91. Climate Change Series. Washington, DC, World Bank (available at http://documents.worldbank.org/curated/en/2013/06/17911216/climate-change-agriculture-review-impacts-adaptations).

VWY Lam, WWL Cheung, W Swartz and UR Sumaila. 2012. Climate change impacts on fisheries in West Africa: implications for economic, food and nutritional security. *African Journal of Marine Science 2012, 34(1)*

Lambrou, Y. & Nelson, S. 2010. *Farmers in a changing climate – Does gender matter? Food security in Andra Bradesh.* Rome, FAO.

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 andAfrica. *In* P. Rowlinson, M. Steele & A. Nefzaoui, eds. *Livestock and global climate change,* pp. 87–89. Proceedings of the British Society of Animal Science (BSAS) International Conference on Livestock and Global Climate Change, Hammamet, Tunisia, 17–20 May 2008. Cambridge, UK, Cambridge University Press.

Leblois, A. & Quirion, P. 2011. Agricultural insurances based on meteorological indices: realizations, methods and research challenges. *Meteorological Applications*, 20(1): 1–9.

Lioubimtseva, L., Dronin, N. & Kirilenko, A. 2015. Grain production trends in the Russian Federation, Ukraine and Kazakhstan in the context of climate change and international trade. *In* A. Elbehri, ed. *Climate change and food systems: global assessments and implications for food security and trade*. Rome, FAO.

Liu, J., Hertel, T.W., Taheripour, F., Zhu, T. & Ringler, C. 2014. International trade buffers the impact of future irrigation shortfalls, *Global Environmental Change*, 25: 22–31.

Lloyd, S., Kovats, R.S. & Chalabi, Z. 2011. Climate change, crop yields, and malnutrition: development of a model to quantify the impact of climate scenarios on child malnutrition. *Environ. Health Persp.,* 119: 1817–1823.

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

Lobell, D., Baldos U. C. and Hertel, T.W. 2013. Climate adaptation as mitigation: the case of agricultural investments. *Environmental Research Letters,* 8: 1–12.

Loo, J., Fady, B., Dawson, I., Vinceti, B. & Baldinelli, G. 2011. *Climate change and forest genetic resources: state of knowledge, risks and opportunities.* Commission on Genetic Resources for Food and Agriculture. Background Study Paper No. 56. Rome, FAO (available at http://www.fao.org/docrep/meeting/023/mb696e.pdf).

Luck, J., Spackman, M., Freeman, A., Tre̦bicki, P., Griffiths, W., Finlay, K. & Chakraborty, S. 2011, Climate change and diseases of food crops. *Plant Pathology*, 60: 113–121. doi: 10.1111/j.1365-3059.2010.02414.x.

Luedeling, E., Steinmann, K.P., Zhang, M., Brown, P.H., Grant, J. & Girvetz, E.H. 2011. Climate change effects on walnut pests in California. *Global Change Biology*, 17: 228–238.

Madalena, F.E. 2008. How sustainable are the breeding programs of the global main stream dairy breeds? - The Latin-American situation. *Livest. Res. Rural Dev.,* 20: 1–10.

McCarthy, M., Best, M. & Betts, R.2010. Climate change in cities due to global warming and urban effects. *Geophysical Research Letters*, 37(9).

McPeak, J. 2004. *Contrasting income shocks with asset shocks: livestock sales in northern Kenya*. Oxford Economic Papers 56, no. 2: 263–284.

Meehl, G.A., Goddard, L., Boer, G., Burgman, R., Branstator, G., Cassou, C., Corti, S., Danabasoglu, G., Doblas-Reyes, F., Hawkins, E., Karspeck, A., Kimoto, M., Kumar, A., Matei, D., Mignot, J., Msadek, R., Pohlmann, H., Rienecker, M., Rosati, T., Schneider, E., Smith, D., Sutton, R., Teng, H., Van Oldenborgh, G. J., Vecchi, G. & Yeager, S. 2014. Decadal climate prediction: an update from the trenches. *Bulletin of the American Meteorological Society*, 95 (2): 243-267. ISSN 1520-0477 doi: 10.1175/BAMS-D-12-00241.1 (available at http://centaur.reading.ac.uk/32097/).

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.

Miraglia, M., Marvinb, H.J.P., Kleterb, G.A., Battilanic, P., Breraa, C., Conia, E., Cubaddaa, F., Crocia, L., De Santisa, B., Dekkersd, S., Filippic, L., Hutjese, R.W.A., Noordamb, M.Y., Pisantef, M., Pivac, G., Prandinic, A., Totia, L., van den Borng, G.J. & Vespermannh, A. 2009. Climate change and food safety: an emerging issue with special focus on Europe. *Food and Chemical Toxicology,* 47(5): 1009–1021.

Morrison, W. Forthcoming. *Methodology for assessing the vulnerability of fish species in a changing climate.* NMFS draft document.

Mottet, A., Msangi, S., Conchedda, G., Ham, F., Lesnoff, M., Fillol, E., Ickovicz , A., Cervigni, R., de Haan, C. & Gerber, P. 2015. Modeling livestock production under climate constraints in the African dry lands to identify interventions for adaptation. *In:* 3rd Global Science Conference on Climate-Smart Agriculture CSA2015 Montpellier-France, March 16–18, 2015

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.

Myers, S.S., Zanobetti, A., Kloog, I., Huybers, P., Leakey, A.D.B., Bloom, A.J., Carlisle, E., Dietterich, L.H., 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(7503): 139–142.

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*. IFPRI (available at http://cdm15738.contentdm.oclc.org/utils/getfile/collection/p15738coll2/id/16557/filename/16558.pdf).

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, International Food Policy Research Institute (IFPRI).

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. 2014a. Climate change effects on agriculture: economic responses to biophysical shocks. *PNAS*, 111(9): 3274–3279.

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. 2014b. Agriculture and climate change in global scenarios: why don't the models agree? *Agricultural Economics*. 45(1): 85–101.

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*. pp. 1199–1265. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA. Cambridge University Press.

Nikulin, G., Jones, C., Giorgi, F., Asrar, G., Büchner, M., Cerezo-Mota, R., Bøssing Christensen, O., Déqué, M., Fernandez, J., Hänsler, A., van Meijgaard, E., Samuelsson, P., Bamba Sylla, M. & Sushama, L. 2012. Precipitation climatology in an ensemble of CORDEX-Africa regional climate simulations. *J. Climate*, 25: 6057–6078.

NOAA. 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).

Oerke, E.C. 2006. Crop losses to pests. *The Journal of Agricultural Science*, 144: 31–43.

Olson, T. A., Lucena, C.J., Chase, C.C. & Hammond, A.C. 2003. Evidence of a major gene influencing hair length and heat tolerance in *Bos taurus* cattle. *Journal of Animal Science,* 81: 80–90.

Paes-Sousa, R., Santos, L.M.P. & Miazaki, E.S. 2011. Effects of a conditional cash transfer programme on child nutrition in Brazil. *Bulletin of the World Health Organization*, 89: 496–503.

Parry, M., Rosenzweig, C. & Livermore, M. 2005. Climate change, global food supply and risk of hunger. *Phil. Trans. Roy. Soc. B,* 360: 2125–2138. doi:10.1098/rstb.2005.1751.

Pautasso, M., Döring, T.F., Garbelotto, M., Pellis, L. & Jeger, M.J. 2012. Impacts of climate change on plant diseases –opinions and trends. *Eur. J. Plant Pathol*., 133(1): 295–313.

Perry, A.L., Low, P.J., Ellis, J.R. & Reynolds, J.D. 2005. Climate change and distribution shifts in marine fishes. *Science*, 308(5730): 1912–1915.

Pilling, D. & Hoffmann, I. 2011. *Climate change and animal genetic resources for food and agriculture: state of knowledge, risks and opportunities.* Commission on Genetic Resources for Food and Agriculture. Background Study Paper No. 53. Rome, FAO (available at http://www.fao.org/docrep/meeting/022/mb386e.pdf).

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 (available at http://www.pim.cgiar.org/files/2013/01/FoodSecurityandSustainableResourceUse2.pdf).

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*, pp. 485–533. 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.

Pörtner, H.-O. 2008. Ecosystem effects of ocean acidification in times of ocean warming: a physiologist's view. *Marine Ecology Progress Series*, 373: 203–217.

Pörtner, H.-O., Karl, D.M., Boyd, P.W., Cheung, W.W.L., Lluch-Cota, S.E., Nojiri, Y., Schmidt, D.N. & Zavialov, P.O. 2014: Ocean 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*, pp. 411–484. 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.

Prakash, A. 2011. Why volatility matters. *In* A. Prakash, ed. *Safeguarding food security in volatile global markets*, pp. 3–26. Rome, FAO.

Pullin, R. & White, P. 2011. *Climate change and aquatic genetic resources for food and agriculture: state of knowledge, risks and opportunities.* Commission on Genetic Resources for Food and Agriculture Background Study Paper No. 55. Rome, FAO (available at http://www.fao.org/docrep/meeting/022/mb507e.pdf).

Raemaekers, S. & Sowman, M. Forthcoming. *Community-level socio-ecological vulnerability assessments in the Benguela Current Large Marine Ecosystem*. FAO Fisheries and Aquaculture Circular. Rome, FAO.

Ravagnolo, O. & Misztal, I. 2002. Effect of heat stress on nonreturn rate in Holsteins: fixed-model analyses. *Journal of Dairy Science*, 85: 3101–3106.

Robledo, C. & Forner, C. 2005. *Adaptation of forest ecosystems and the forest sector to climate change.* FAO Forests and Climate Change Working Paper 2. Rome, FAO.

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*, pp. 255–276. A World Bank Research Publication. Baltimore, USA, Johns Hopkins University Press.

Rosenthal, J. 2009. Climate change and the geographic distribution of infectious diseases. *Ecohealth*, 6: 489–495.

Rosenzweig, M.R. & Binswanger, H.P. 1993. Wealth, weather risk and the composition and profitability of agricultural investments. *Economic Journal*, 103: 56–78**.**

Rosenzweig, C., & Parry, M.L. 1994. Potential impact of climate change on world food supply. *Nature*, 367: 133–138. doi:10.1038/367133a0.

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. *Proc. Natl. Acad. Sci.,* 111(9): 3268–3273. doi:10.1073/pnas.1222463110.

Sadoulet, E. & de Janvry, A. 1995. Behavior and welfare under risk. In *Quantitative development policy analysis.* Chapter 5. Baltimore, USA, Johns Hopkins University Press.

Salinger, M.J. & Stigter, C.J. & Das, H.P. 2000. Agrometeorological adaptation strategies to increasing climate variability and climate change. *Agricultural and Forest Meteorology*, 103(1-2): 167-184.

Schmidhuber, J. 2007. *Biofuels: an emerging threat to Europe's food security?* Notre Europe (available at http://www.delorsinstitute.eu/011-1317-Biofuels-An-Emerging-Threat-to-Europe-s-Food-Security.html).

Scoones, I. 1996. *Hazards and opportunities: farming livelihoods in dryland Africa. Lessons from Zimbabwe.* London, Zed Books.

Selvaraju, R., Gommes, R. & Bernardi, M. 2011. Climate science in support of sustainable agriculture and food security. *Climate Research*, 47: 95–110.

Seppälä, R, Buck, A. & Katila, P. eds. 2009. *Adaptation of forests and people to climate change. A global assessment report*. IUFRO World Series Volume 22. Helsinki, International Union of Forest Research Organizations.

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*, pp. 271–359. 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.

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, International Food Policy Research Institute (IFPRI). 40 p.

Skoufias, E. & Quisumbing, A.R. 2005. Consumption insurance and vulnerability to poverty: a synthesis of the evidence from Bangladesh, Ethiopia, Mali, Mexico and Russia. *European Journal of Development Research*, 17: 24–58.

Stramma, L., Schmidtko, S., Levin, L.A. & Johnson, G.C. 2010. Ocean oxygen minima expansions and their biological impacts. Deep-Sea Research Part I. *Oceanographic Research Papers*, 57(4): 587–595.

Stramma, L., Prince, E.D., Schmidtko, S., Luo, J., Hoolihan, J.P., Visbeck, M., Wallace, D.W.R., Brandt, P. & Körtzinger, A. 2012. Expansion of oxygen minimum zones may reduce available habitat for tropical pelagic fishes. *Nature Climate Change*, 2(1): 33–37.

Streftaris, N., Zenetos, A. & Papathanassiou, E. 2005. Globalisation in marine ecosystems: the story of non-indigenous marine species across European seas. *Oceanography and Marine Biology – an Annual Review*, 43: 419–453.

Svobodová, E., Trnka, M., Dubrovský, M., Semerádová, D., Eitzinger, J., Stěpánek, P. & Zalud, Z. 2014. Determination of areas with the most significant shift in persistence of pests in Europe under climate change. *Pest Manag. Sci.*, 70(5): 708–15. doi: 10.1002/ps.3622.

Talon, M. & Gmitter, F.G. Jr. 2008. Citrus genomics. *International Journal of Plant Genomics*, Article ID 528361, 17 p. doi:10.1155/2008/528361 (available at http://www.hindawi.com/journals/ijpg/2008/528361/cta/).

Talon, M. n.d. *Presentation "Plant breeding to tackle the challenges of climate change"* (available at http://ec.europa.eu/dgs/health_food-safety/information_sources/docs/events/20150714_climate-change_expo_milan_pres_08.pdf).

Tangerman, S. 2011. *Policy solutions to agricultural market volatility: a synthesis*. Issue Paper No. 33. Geneva, Switzerland, International Center for Trade and Sustainable Development (ICTSD).

Tester, P.A., Feldman, R.L., Nau, A.W., Kibler, S.R. & Litaker, R.W. 2010. Ciguatera fish poisoning and sea surface temperatures in the Caribbean Sea and the West Indies. *Toxicon*, 56(5): 698–710.

The Times of India. 2015. *Intense heatwave in many parts of India*. 27 May (available at http://timesofindia.indiatimes.com/india/Intense-heatwave-in-many-parts-of-India-toll-1242/articleshow/47445116.cms).

Thomas, T. & Rosegrant, M. 2015. Climate change impact on key crops in Africa: using crop models and general equilibrium models to bound the predictions. *In* A. Elbehri, ed. *Climate change and food systems: global assessments and implications for food security and trade*. Rome, FAO.

Thompson, I., Mackey, B., NcNulty, S. & Mosseler, A. 2009. *Forest resilience, biodiversity, and climate change. A synthesis of the biodiversity/resilience/stability relationship in forest ecosystems*. Technical Series No. 43. Montreal, Canada, Secretariat of the Convention on Biological Diversity.

Thornton, P.K. & Herrero, M. 2014. Climate change adaptation in mixed crop–livestock systems in developing countries. *Global Food Security,* 3(2): 99–107.

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

Thornton, P., Ericksen, P.J., Herrero, M., Challinor, A.J. 2014. Climate variability and vulnerability to climate change: a review. *Global Change Biology*, 20(11): 3313–3328.

Thornton, P.K., Boone, R.B. & Ramirez-Villegas, J. 2015. *Climate change impacts on livestock*. CCAFS Working Paper No. 120. Copenhagen, CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) (available at: www.ccafs.cgiar.org).

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.

Tirvayi, N., Knowles, M. & Davis, B. 2013. *The interaction between social protection and agriculture. A review of evidence*. Rome, FAO.

Uleberg, E., Hanssen-Bauer, I., van Oort, B. & Dalmannsdottir, S. 2014. Impact of climate change on agriculture in Northern Norway and potential strategies for adaptation. *Climatic Change,* 122: 27–39.

UN. 2015. *The Millennium Development Goals Report 2015* (available at http://www.undp.org/content/dam/undp/library/MDG/english/UNDP_MDG_Report_2015.pdf)

UNFCCC. 2010. *Handbook on vulnerability and adaptation assessment*. Consultative group of experts on national communications from parties not included in Annex I to the Convention.

UNFCCC. 2015. *Synthesis report on the aggregate effect of the intended nationally determined contributions*. Note by the Secretariat, 30 October 2015. FCCC/CP/2015/7.

UNISDR/OECD. 2013. *Disaster risk reduction – donor effort*. A survey of development co-operation providers (available at http://www.preventionweb.net/files/34577_34577donoreffortondisasterriskreduc.pdf).

USC Canada. 2008. *Growing resilience: seeds, knowledge and diversity in Honduras*. Canadian Food Security (avaliable at http://www.ccic.ca/_files/en/working_groups/003_food_2009-03_case_study_honduras.pdf).

Uyttendaele, M. & Hofstra, N., eds. 2015. Impacts of climate change on food safety. *Food Research International*. 68: 1–108 (available at http://www.sciencedirect.com/science/journal/09639969/68).

Valenzuela, E. & Anderson, K. 2011. *Climate change & food security to 2050: a global economy-wide perspective*, contributed paper for the 55th Annual Conference of the Australian Agricultural and Resource Economics Society.

Vargas Hill, R. 2009. Using stated preferences and beliefs to identify the impact of risk on poor households. *The Journal of Development Studies*, 45.2: 151–171.

Von Lampe, M., Willenbockel, D., Ahammad, H., Blanc, E., Cai, Y., Calvin, K., Fujimori, S., Hasegawa, T., Havlík, P., Heyhoe, E., Kyle, P., Lotze-Campen, H., d'Croz, D., Nelson, G., Sands, R., Schmitz, C., Tabeau, A., Valin, H., van der Mensbrugghe, D. & van Meijl, H. 2014. Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison. *Agricultural Economics,* 45(1): 3–20.

Wajih, S.A. 2008. Adaptive agriculture in flood affected areas. *LEISA Magazine*, 24(4): 24–25.

WCRP. 2014. *CMIP Phase 6 (CMIP6)* (avaliable at http://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip6).

Wheeler, T. & von Braun, J. 2013. Climate change impacts on global food security. *Science*, 341(6145): 508–513.

WHO. 2014. *Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s.* S. Hales, S. Kovats, S. Lloyd & D. Campbell-Lendrum, eds. Geneva, Switzerland.

Wilkes, A. 2011 *An economic analysis of the Qinghai Grasslands Restoration and Herd Improvement Pilot Project*. Consultant report to FAO.

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.

Wilson, J., Deinum, B. & Engels, F. 1991. Temperature effects on anatomy and digestibility of leaf and stem of tropical and temperate forage species. *Netherlands Journal of Agricultural Science*, 39: 31–48.

Winarto, Y.T., Anantasari, E., Hidayah, S.N. & Stigler, K. 2008. *Climate Field Schools in Indonesia: Improving "response farming" to climate change. Agricultures*, Leisa magazine, 24.4, December 2008.

Winsemius, H.C., Dutra, E., Engelbrecht, F.A., Archer Van Garderen, E., Wetterhall, F., Pappenberger, F. & Werner, M.G.F. 2014. The potential value of seasonal forecasts in a changing climate in southern Africa, Hydrol. *Earth Syst. Sci.,* 18: 1525-1538.

World Bank. 2002. *Sustaining forests. A World Bank strategy* (available at http://siteresources.worldbank.org/INTFORESTS/214573-1113990657527/20632625/Forest_Strategy_Booklet.pdf).

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

World Bank. 2009. *Guidance notes mainstreaming adaptation to climate change in agriculture and natural resources management projects*. Note 7: evaluate adaptation via economic analysis (available at http://climatechange.worldbank.org/content/note-7-evaluate-adaptation-economic-analysis).

World Bank. 2013. *Risk and opportunity, managing risk for development.* World Development Report (available at http://siteresources.worldbank.org/EXTNWDR2013/Resources/8258024-1352909193861/8936935-1356011448215/8986901-1380046989056/WDR-2014_Complete_Report.pdf).

World Bank/FAO/IFAD. 2012. *Gender, agriculture and climate change*. Module 17 of the Gender in Agriculture Sourcebook. Washington, DC, World Bank.

World Bank/FAO/IFAD. 2015. *Gender in climate-smart agriculture*. Module 18 of the Gender in Agriculture Sourcebook. Washington, DC, World Bank.

World Bank/FAO/WorldFish Center. 2010. *The hidden harvests: the global contribution of capture fisheries*. Agriculture and Rural Development Department Sustainable Development Network. Washington, DC, World Bank.

World Food Summit. 1996. *Rome Declaration on World Food Security*. Rome, FAO.

Yohe, G.W., Lasco, R.D., Ahmad, Q.K., Arnell, N.W., Cohen, S.J., Hope, C., Janetos, A.C., Perez, R.T., Brenkert, A., Burkett, V., Ebi, K.L., Malone, E.L., Menne, B., Nyong, A., Toth, F.L. & Palmer, G.M. 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*, pp. 811–841, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York, Cambridge University Press.

Ziska, L.H., Bunce, J.A., Shimono, H., Gealy, D.R., Baker, J.T., Newton, P.C.D., Reynolds, M.P., Jagadish, K.S.V., Zhu, C., Howden, M. & Wilson, L.T. 2012. Food security and climate change: on the potential to adapt global crop production by active selection to rising atmospheric carbon dioxide. *Proceedings of the Royal Society B*, 279: 4097–4105.

Zumbach, B., Misztal, I., Tsuruta, S., Sanchez, J.P., Azain, M., Herring, W., Holl, J., Long, T. & Culbertson, M. 2008. Genetic components of heat stress in finishing pigs: development of a heat load function. *Journal of Animal Science*, 86(9): 2082–2088.

By adopting the sustainable development goals, the world has committed to ending hunger, achieving food security and improving nutrition by 2030. But climate change is already undermining the livelihoods and food security of the most vulnerable populations. Ensuring food security and good nutrition in the face of climate change is among the most daunting challenges facing humankind.

The report *Climate change and food security: risks and responses* brings together evidence from the Intergovernmental Panel on Climate Change (IPCC), updated by the latest evidence and scientific findings as well as by results from experience on the ground, on the impacts of climate change on food security and nutrition. It shows how a cascade of impacts from ecosystems to livelihoods interacts with a series of vulnerabilities, undermining food security and nutrition, especially of the most vulnerable populations. The report presents ways to adapt, to reduce vulnerabilities and to build resilience to climate change. It shows the importance of acting now to address climate change, to ensure food security and good nutrition for all, now and in the future.

I5188E/1/11.15