How does climate change alter agricultural strategies to support food security?

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In this paper we focus on the issue of how climate change affects the way that agricultural systems and the people that manage and govern them need to change in the next 20 years in order to achieve food security, and how FAO and CGIAR can support that change. We build on a huge body of literature on sustainable agricultural development and intensification, as well as work on nutrition security and resource use efficiency, much of which is articulated in other papers in this conference.

As the results presented in the paper by Nelson and van der Mensbrugghe on *Public Sector Agricultural Research Priorities for Sustainable Food Security* for this conference indicate, the most significant impacts of climate change are expected to occur after 2050. In the intervening years, however, increased frequency and intensity of climate shocks such as drought, flooding and extreme temperatures are expected and already occurring (IPCC, 2012). Summarizing the effects of these major trends we find that essentially we are facing a global window of 15-20 years in which we need to increase the returns to agriculture amongst a growing population of poor and food insecure rural people in order to achieve food security and reduce poverty – which are in and of themselves key to reducing vulnerability to climate change. Between 2020 and 2025 total rural population in developing countries will peak and then start to decline (IFAD, 2011). Some 70% of the food insecure people in the world are rural, directly or indirectly dependent on agriculture for income as well as food (IFAD, 2011). Rural poverty and hunger are concentrated in two locations: South Asia, with the greatest number of poor rural people, and sub-Saharan Africa, with the highest incidence of rural poverty. These two areas are also where the bulk of expected future population growth is expected to occur, with some countries, mostly in sub-Saharan Africa, that could see population increases of 200 percent or more to the middle of this century. There is also some overlap between areas of food insecurity and climate change hotspots (Ericksen et. al. 2011) We know that GDP growth originating in agriculture has been found to be almost three times more effective in reducing poverty than growth in other sectors of the economy due not only to the direct poverty reduction effect but also from its potentially strong growth linkage effects on the rest of the economy (De Janvry and Sadoulet, 2010). Thus, the next 20 years are a critical window of time for accelerating the rate of agricultural growth in least developed countries to achieve food security and development for agriculturally-dependent populations. Reducing poverty and food insecurity over this period is in fact, an essential element of adapting to climate change, since it is the key means of reducing vulnerability and increasing the resilience of people to withstand and respond to climate change. However the agricultural growth for poverty reduction and food security needed for the next two decades requires departing from past models of development – due to the exigencies of adapting to, and mitigating climate change. Much of what is called for in strategies for sustainable agricultural development and intensification are highly relevant in the context of agricultural growth for food security under climate change. In this paper we focus on the specifics of how climate change affects this broader agenda of action for change.

1. What are the transitions in agricultural systems needed to achieve sustainable agricultural development for food security and poverty reduction under climate change?

1.1 What do know about the threats of climate change to agricultural production systems? [1]

Climate change may affect agricultural and natural systems in many ways. In general, higher average temperatures will accelerate the growth and development of plants. Most livestock species have comfort zones between 10 and 30 °C, and at temperatures above this, animals reduce their feed intake 3–5% per additional degree of temperature. Rising temperatures are not uniformly bad: they will lead to improved crop productivity in parts of the tropical highlands, for example, where cool temperatures are currently constraining crop growth. Average temperature effects are important, but there are other temperature effects too. Increased night-time temperatures have negative effects on rice yields, for example, by up to 10% for each 1°C increase in minimum temperature in the dry season. Increases in maximum temperatures can lead to severe yield reductions and

[1] Much of this section is from Thornton and Cramer (2012).

reproductive failure in many crops. In maize, for example, each degree day spent above 30 °C can reduce yield by 1.7% under drought conditions.

Climate change is already affecting rainfall amounts, distribution, and intensity in many places. This has direct effects on the timing and duration of crop growing seasons, with concomitant impacts on plant growth. Rainfall variability is expected to increase in the future, and floods and droughts will become more common. Changes in temperature and rainfall regime may have considerable impacts on agricultural productivity and on the ecosystem provisioning services provided by forests and agroforestry systems on which many people depend. There is little information currently available on the impacts of climate change on biodiversity and subsequent effects on productivity in either forestry or agroforestry systems.

Climatic shifts in the last few decades have already been linked to changes in the large-scale hydrological cycle. Globally, the negative effects of climate change on freshwater systems are expected to outweigh the benefits of overall increases in global precipitation due to a warming planet.

The atmospheric concentration of CO_2 has risen from a pre-industrial 280 ppm to approximately 392 ppm, and was rising by about 2 ppm per year during the last decade. Many studies show a beneficial effect (‘CO_2 fertilization’) on C_3 crops and limited if any effects on C_4 plants such as maize and sorghum. There is some uncertainty associated with the impact of increased CO_2 concentrations on plant growth under typical field conditions, and in some crops such as rice, the effects are not yet fully understood. While increased CO_2 has a beneficial effect on wheat growth and development, for example, it may also decrease the protein concentration in the grain. In some crops such as bean, genetic differences in plant response to CO_2 have been found, and these could be exploited through breeding. Increased CO_2 concentrations lead directly to ocean acidification, which (together with sea-level rise and warming temperatures) is already having considerable detrimental impacts on coral reefs and the communities that depend on them for their food security.

Little is known, in general, about the impacts of climate change on the pests and diseases of crops, livestock and fish, but they could be substantial. Yams and cassava are crops that are both well adapted to drought and heat stress, but it is thought that their pest and disease susceptibility in a changing climate could severely affect their productivity and range in the future. Potato is another crop for which the pest and disease complex is very important— similarly for many dryland crops—

and how these may be affected by climate change (including the problems associated with increased rainfall intensity) is not well understood. Climate change will result in multiple stresses for animals and plants in many agricultural and aquatic systems in the coming decades. In rice, there is some evidence that a combination of heat stress and salinity stress leads to additional physiological effects over and above the effects that each stress has in isolation. In general, much is unknown about how stresses may combine in agricultural and aquacultural systems in the face of climate change.

The impacts of changes in climate and climate variability on agricultural production will have substantial effects on smallholder and subsistence farmers, pastoralists and fisherfolk in many parts of the tropics and subtropics. Crop yields in sub-Saharan Africa are likely to be particularly adversely affected, and the resulting reduced food security potentially will increase the risk of hunger and undernutrition (HLPE, 2012). While many of the people who are likely to be adversely affected may have only limited capacity to adapt to climate change or to the many other stressors that may affect them, a wide range of responses is possible, outlined in the next sections.

1.2 How may agricultural producers respond?

Agricultural producers may respond to the threats posed by climate change in different ways; these may be technological, such as the use of more drought-tolerant crops; behavioral, such as changes in dietary choice; managerial, such as implementing different farm management practices; and policy-related, such as market and infrastructure development (IPCC, 2007). Adaptation options have been classified in several ways, but here we briefly outline four types: increasing the resilience of production systems, diversification, use of “no regrets” options, and risk management. Distinctions between these different types are often blurred.

1.2.1 Increasing resilience of agricultural production systems

The overall efficiency and resilience of crop and livestock production systems in the face of climate change can be enhanced through improving various components (FAO, 2010):

- Appropriate soil and nutrient management, through composting manure and crop residues, more precise matching of nutrients with plant needs, controlled release and deep placement technologies, and using legumes for natural nitrogen fixation, can increase yields and resilience of crops, while reducing the need for often costly and inaccessible synthetic fertilizers (with the co-benefit of reducing the GHG emissions associated with their use);

- In situations with decreasing rainfall and increasing rainfall variability, there are many ways of improving water harvesting and retention (through the use of pools, dams, pits, retaining ridges, increasing soil organic matter to heighten the water retention capacity of soils)) and water-use efficiency (irrigation systems).
- Climate change is already altering the distribution and intensity of weeds and animal and plant pests and diseases. While there are considerable gaps in our knowledge of systems interactions in relation to weeds, pests and diseases, increased understanding will lead to better ways to manage them in a changing climate (Gregory et al., 2009).
- Improving ecosystem management and biodiversity can provide several ecosystem services, leading to more resilient, productive and sustainable systems that may also contribute to reducing GHGs. These services include the control of pests and disease, regulation of microclimate, decomposition of wastes, regulation of nutrient cycles, and crop pollination.
- There is often considerable genetic variability in domestic crops and livestock, and characteristics such as ability to withstand temperature extremes, drought, flooding and pests and diseases are often at least partially genetically controlled. The utilization of different crops and breeds and their wild relatives is fundamental in developing resilience to climate shocks and longer-term climate change.
- Efficient harvesting and early transformation of agricultural produce can reduce post-harvest losses and preserve food quantity, quality and nutritional value of the product. Food processing allows surplus to be stored and sales staggered, and can add resilience to agricultural systems by smoothing food security and income variability.

It is worth noting that the impacts of climate change may not be negative in all parts of the tropics. In some highland regions of Latin America and Africa, for example, growing seasons may expand as temperatures increase and cold temperature constraints to crop growth are relaxed (Jones and Thornton, 2003). Even in places where crop suitability may decrease, changes in agricultural inputs and the way farmers use them may be able to more than offset projected yield declines through the use of some of the options outlined above (irrigation water, higher-temperature-tolerant crop varieties and so on) as well as through planting date modifications (Crespo et al., 2011).

Fisheries and aquaculture provide more than 2.6 billion people with at least 20 percent of their average annual per capita protein intake. There is limited observational information on climate change impacts on all aquatic (especially marine) ecosystems. Many uncertainties remain, particularly in relation to the effects of synergistic and cumulative interactions among stressors such as rising temperatures, over-fishing and pollution, the occurrences and roles of critical thresholds, and the abilities of marine and aquatic organisms to adapt and evolve to the changes (Beare, 2012). Many fishery resources are currently fully exploited or over-exploited and climate change adds an additional stress to the resources themselves and those dependent on them. In most cases, building resilience in fishery resources and their ecosystems requires allowing these systems to recover to healthier levels and states. However, over-capacity in fisheries is a problem. As for land-based systems, there are several options for increasing the climate resilience of aquaculture, notably through improving management approaches and selecting of suitable stock. Increasing feeding efficiency or switching to herbivorous or omnivorous species such as carp greatly reduces the need for fish feed inputs and achieves much higher input/output ratios than other protein sources. The integration of aquaculture within broader farming landscapes provides further opportunities: sludge produced during the treatment of aquaculture wastewater or pond sediments can be used to fertilize agricultural crops, for example. More strategic location of aquaculture infrastructure can also avoid potential climate change risks and minimize the impacts on natural systems such as wetland, mangroves and reefs (FAO, 2010). It can also provide an alternative livelihood in situations where salt water intrusion has made rice farming unproductive, as in some parts of Vietnam, for example.

Trees occur on 46 percent of all agricultural lands and support 30 percent of all rural populations (Zomer et al., 2009). Both forests and agroforestry can contribute very significantly to increasing resilience in the face of climate change. Diverse, multi-functional landscapes that include forests are often more resilient to climate shocks and provide the rural poor with a broader set of options for securing both food and income (Sunderland, 2011). Forest foods have been shown to be especially crucial in helping the rural poor cope with seasonal shortages and recurrent climate anomalies and economic downturns (Locatelli et al., 2012). Trees on farms serve a wide variety of purposes, and can help to reduce the vulnerability and increase the resilience of farming systems while providing substantial mitigation benefits as well. Trees and tree products can increase farm income and help spread risk; trees and shrubs can reduce the effects of extreme weather events such as heavy rains, droughts and wind storms. They prevent erosion, stabilize soils, raise infiltration rates and halt land degradation. They can enrich biodiversity in the landscape and increase ecosystem stability. Trees can improve soil fertility and soil moisture through increasing soil organic matter, fixing nitrogen, and providing shade (FAO, 2010). The several benefits of agroforestry options have been demonstrated on household food security in various situations, and there is growing evidence that natural resource management through agroforestry can lead to improved social protection and resilience (Chaudhury et al., 2011).

1.2.2 Diversification

Agricultural diversification occurs when more species, plant varieties or animal breeds are added to a given farm, or farming community. It includes landscape diversification – different crops and cropping systems interspersed in space and time. Livelihood diversification implies that farming households are involved in more and different (non-agricultural) activities, for instance by taking up a job in the city, setting up a shop, or by starting to process farm products. Both agricultural and non-agricultural forms of diversification may be relevant for climate risk management, although the emphasis here is on agricultural diversification. Climate-related shocks, such as heat waves, frost, excessive rain or floods, or drought spells, have different and sometimes even opposite effects on different farming system components or economic activities.

Diversification can potentially reduce the impact of weather events on income, and it can also provide farmers with a broader range of options to address future change. Given the potential benefits, diversification is often recommended as a risk management strategy. Others criticize risk-mitigating diversification strategies and emphasize the importance of risk-taking for agricultural development (World Bank, 2008). If combined with risk reducing measures, such as crop insurance, risk-taking could lead to higher incomes and poverty reduction (FAO 2012c). On the other hand, if risk-averse diversification strongly decreases average income, it can lead to a vicious cycle of decreasing household assets, eventually leading to an exposure to more risk (Dercon, 1996). Others have argued that crop diversification options for risk mitigation are limited due to the generally high and positive correlation between the yields of different crops (Barrett et al., 2001). Such critiques need to be qualified according to the geographical context and the mix of diversification and other changes that are being considered. For instance, crop diversification options are found to be most beneficial in “intermediate” conditions, where growth conditions are neither so marginal that they limit diversification options nor optimal for a single high-return crop (Kandulu et al., 2012).

Diversification is an important element of climate change adaptation. However, little systematic information exists to guide farmers and farming communities on how to best manage diversification options.

1.2.3 Expanding use of "no regrets" technologies

Adaptations to climate change can be thought of as incremental changes to existing systems (Section 1.2.1) or more systemic changes (Section 1.2.2) which bring new components to (or remove old components from) systems, often with the goal of increasing diversification and hedging against new, unknown risk. These are part of a spectrum of levels of adaptation to climate changes. They are not unreasonable as first adaptation steps as they build from existing infrastructure, practice, technologies and knowledge, largely fit within existing institutional arrangements, often conform to cultural and social norms, are reasonably quick and easy for farmers to evaluate and involve limited risk, investment and complexity to manage (Rickards and Howden, 2012). However, various analyses suggest that such adaptations will become less effective above temperature increases of 2 °C (Easterling et al., 2007; Howden et al., 2007; Challinor et al,. 2013) requiring further, transformative adaptation (Howden et al., 2010; Kates et al., 2012). Furthermore, in countries with strongly climate-affected agriculture such as Australia, there are already examples of agricultural industries and enterprises making more transformative adaptations in response to existing climate changes or perceptions of future changes (Park et al., 2012). In these cases, transformational adaptation has been as much about seeking opportunity as in avoiding threats. Hence these adaptations are intended to be 'low regrets' strategies. They are characterized by either changes in goal (resulting in a major change in land use and/or employment, for example) and/or changes in location (of an agricultural activity and/or farmers).

Transformational change in agriculture is not new: the planting of biofuel crops instead of food crops, the replacement of subsistence-based agriculture with modern science-based agriculture, or migration in the face of extreme drought being a few examples amongst many (Rickards and Howden, 2012). What does seem to be new is that transformational adaptations to climate change are being taken pro-actively with at least a partial recognition of the intersection of climate drivers with broader change processes, in the landscape and socioeconomically, technically and politically.

Large-scale changes often incur additional risk and cost and given uncertainties in trajectories of future climate change, transformational adaptation may be maladaptive or may be seen as 'over-adapting'. This may be particularly so given the long-lead times and uncertainty associated with climate change. There is at least one case in Australia where the transformative adaptation has been reversed (Jakku et al., 2013). Consequently, transformational adaptation has been framed as not a single step but rather a continuing process which may reverse, or may be normed and then undergo incremental change before being further transformed (Park et al., 2012). Key costs that need to be considered for transformational adaptation include transaction costs which is the toll on resources (mental, emotional, physical, financial, social) that the process of change exacts, opportunity costs including those associated with path dependency and costs of unintended consequences (Rickards and Howden, 2012).

Transformative adaptation is likely to occur more successfully with farmers, industry and regions which have significantly greater adaptive capacity, particularly managerial capacity (Park et al., 2012). Building these capacities may be one area where policy can enhance prospects for transformation, providing an environment where the vision of adaptation to climate change is not limited by the agricultural system as it is now, but rather how it could be.

1.2.4 Risk management and the crucial role of information

Managing risk and uncertainty has always been a priority for farmers who are exposed to multiple forms of risk ranging from weather variability to pests and disease and to price volatility. Climate change can be a risk multiplier affecting the probability and severity of these types of events in ways that are difficult for individual farmers to incorporate into their decision-making. This is particularly challenging for the 40% of the rural population in developing countries that is food insecure, who also have typically the least assets and limited access to information.

Climate change is expected to alter the productivity of the natural resource base, disproportionately affecting consumption, production, and asset accumulation of the rural poor (Hertel and Rosch, 2010). Farm household decisions will typically be influenced by perceptions of risk and climate variability, their assets and natural resource base, and the policy environment. In this respect, climate change may be regarded both as destroying information (Quiggin and Horowitz, 2003) and running down assets if extreme events become more frequent. Information is particularly relevant because as climate signals become noisier, farmers' capacity to forecast climate for planting decisions will be affected, as will their ability to evaluate the risk of extreme events. At the same time, the level of household assets, being affected by climate change, has an impact on the decision by farm households in terms of how to minimize climate risks (Lybbert et al., 2004; Ziervogel et al., 2006).

Several aspects need to be taken into consideration when trying to address the potential information gap created by climate change. These are the extent to which:

- it is possible to know how climate change affects the probability distribution of events at a spatial scale that is relevant to farmers;
- all actors (farmers, policymakers, extension agents) are adequately informed, and correctly perceive, how climate change affects the probability distribution of events;
- information is available on the technology and policy options to address the impacts;
- barriers to adoption (financial, institutional, technical) may hinder effective risk management under climate change.

A traditional risk management approach typically assumes that probabilities are known by all actors. However, climate change may disrupt traditional risk management because historical experience may no longer apply and knowledge of probabilities may be challenging to update, requiring a better understanding of the local impacts of climate change and how to communicate such knowledge and possible responses. Given limited resources to finance adaptation actions, a top priority is that such support be appropriately targeted to those whose livelihoods are more vulnerable. However, adaptation responses may differ even within such a targeted group, depending on assets, access to information, perceived risk, and social relations in the community (Pelling and High, 2005; Patt and Schröter, 2008; Grothmann and Patt, 2005).

1.3 How may mitigation be considered?

Globally, agriculture contributes 30 to 40 % of anthropogenic greenhouse gas (GHG) emissions. Emission reductions by rich countries alone will not be enough to limit warming to tolerable levels. While cumulative per capita emissions have been small not only in low-income but also in middle-income countries, total annual energy-related CO_2 emissions in middle-income countries have now caught up with those of rich countries, and the largest share of current emissions from land-use change comes from tropical countries. Significant emissions growth is projected for developing countries.

Three-quarters of agricultural GHG emissions occur in developing countries, and this share may rise above 80% by 2050 as nearly all emissions growth under business as usual will occur in developing countries (Smith et al., 2007). As conventionally counted, although there is a case for counting forestry as an additional source of emissions, reported emissions from land-use change all result from conversion of tropical forest and tropical peat lands to other uses. In nearly all cases, these uses will be agricultural, although data challenges sometimes make this difficult to show. The developing world is therefore the focus of agricultural greenhouse gas emissions. Estimates of emissions from production by region (excluding land-use change and energy used in agriculture) are shown in Figure 1 (Popp et al., 2010). Total emissions from livestock over the period 1995-2005 were between 5.6 and 7.5 $GtCO_2eq$ per year (Herrero et al., 2013). The most important sources of emissions were enteric methane (1.6-2.7 $GtCO_2eq$), N_2O emissions associated with feed production (1.7 $GtCO_2eq$) and land use for animal feed and pastures, including change in land use (1.6 $GtCO_2eq$). The developing world contributes to 70% of emissions from ruminants and 53% of emissions from monogastrics, and this share is expected to grow as livestock production increases in the developing world to meet demand increases. Mixed crop-livestock systems dominate livestock emissions (58% of total emissions), while grazing-based systems contribute 19%. Industrial and other systems comprise the rest.

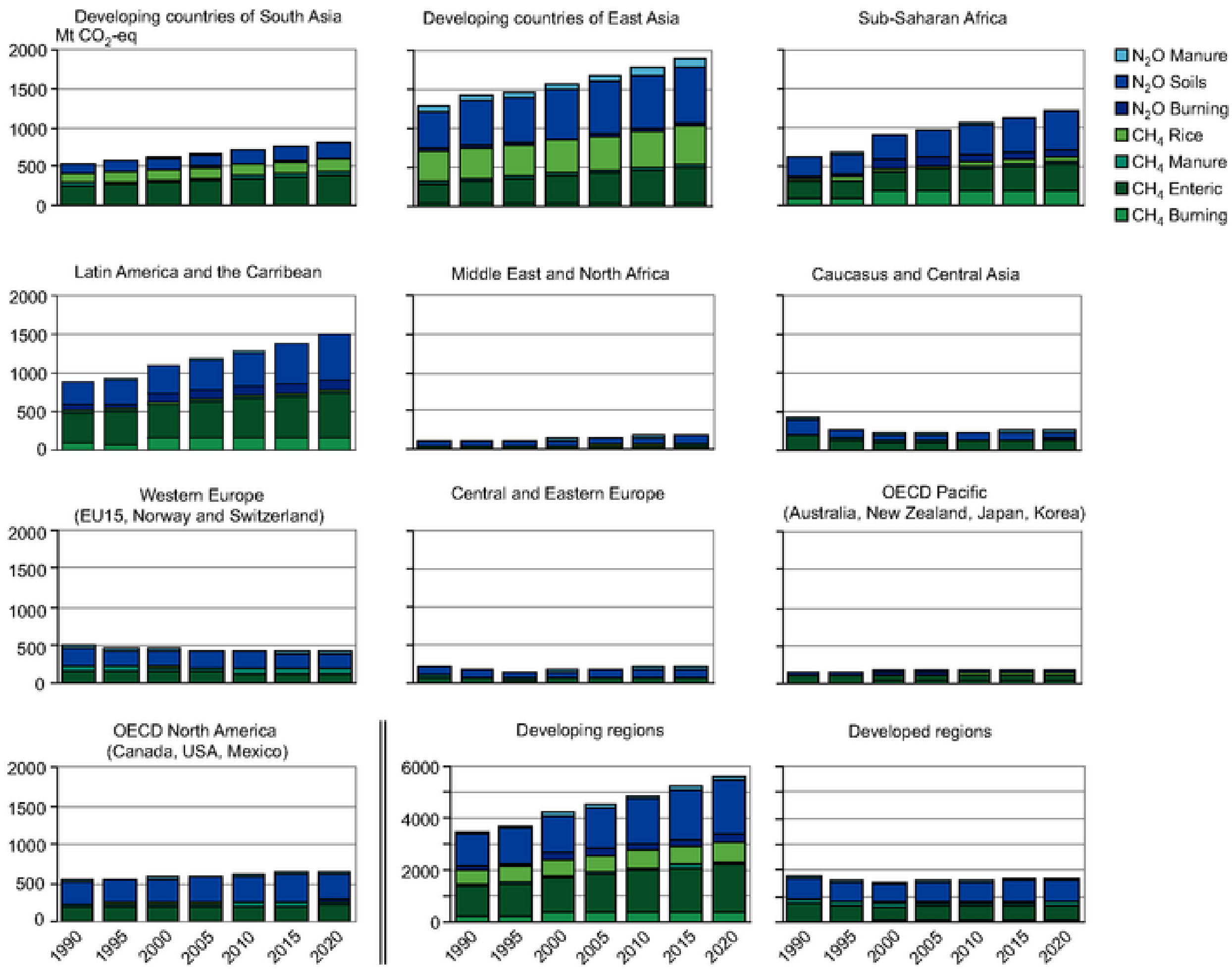

Figure 1. Estimated evolution to 2020 of GHG emissions from agricultural production by region, excluding land use change and energy used in agriculture (Popp et al., 2010).

Delayed action to significantly lower emission trajectories will result in higher global costs for any chosen mitigation target and for adaptation to impacts of increasing intensity and magnitude. Delaying mitigation actions in developing countries until 2050 could more than double the total cost of meeting a particular target; and an international agreement that covers only the five countries with the highest total emissions (covering two-thirds of emissions) would triple the cost of achieving a given target, compared with full participation (World Bank, 2010). Shrinking the pool of mitigation opportunities available for reaching a set target requires pursuing not only the negative-and low-cost measures but also the high-cost measures.

GHG emissions are largely related to inefficiencies in production systems, and so increasing efficiency is both a key development and mitigation strategy. In ruminant livestock herds, for example, a large share of the enteric methane emissions may come from the “breeding and maintenance overhead”: the part of animals that are not in production (milked or fattened) but dedicated to maintain and replace the herd.   Methane losses from manure also represent a loss of energy from the system, although these can be recovered when wastes are fed to a biogas digester. Emissions of nitrous oxide (direct and indirect) from manure storage and processing amount to some 678 Mt CO_2eq, while manure N_2O emissions (direct and indirect) from manure application on crops and application on pasture amount to 1,499 Mt CO_2eq (FAO, 2013). For carbon dioxide, energy consumption along the supply chain contributes a significant share of emissions, especially in monogastric production systems, where they can represent up to 40 % of emissions in chicken production (FAO, 2013). Energy use efficiency can be improved in many systems.

The efficacy of grassland carbon management is something of an enigma. On the one hand, there is strong evidence that many grazing lands have lost carbon, and that changes in management practices can increase soil carbon. On the other, scientific results are highly variable and inconsistent, largely because of the diversity of ecological conditions (Lipper et al. 2010). (The multiple roles of agroforestry practices have been referred to in section 1.2.1 above.) Fourth, there is “green sourcing”: energy consumption accounts for about 30 percent of emissions in monogastric systems, and much of the energy could come from renewable resources. There are also “end of the pipe” measures, such as biogas digesters, which could contribute to green sourcing as well as increasing systems’ efficiency**.**

2. How to make these transitions happen?

2.1 Introduction

Section 1 highlighted the most important ways that climate change may impact agricultural livelihoods in the near future and analysed the specific features that agricultural development strategies would need to include to respond to these challenges. In this section, we examine which steps might support or enable transitions that are inclusive of these features, including in particular the roles of CGIAR and FAO in this regard. Two general considerations can help frame more specific action: (i) the importance of explicitly embedding adaptation and mitigation capacity into agricultural growth strategies to support food security; and (ii) given the variation in the rate and nature of projected impacts, as well as differences in socio-economic and agro-ecological conditions and political choices, site-specific responses will be essential.

Before embarking on an analysis of key actions FAO and CGIAR can take to support needed change, it is useful to put them in the context of policy work at the international level, including the UNFCCC and recent attention given to food security and climate change by the Committee on World Food Security (CFS).

Explicit consideration of agriculture within the UNFCCC negotiations, shaped by the Bali Action Plan, only began in 2009. It has remained somewhat of a marginal issue in the negotiations as a whole and, in the context of climate change and land use, has been overshadowed by REDD+. Some developed and developing countries have called for a programme of work on agriculture under SBSTA but others, so far, have not agreed to this proposal. Lack of agreement has resulted in little progress in making agriculture a stand-alone issue, wherein adequate attention is given to its specificities within the negotiations. There are fears that this may lead to policies that ignore the important linkages among food security, agriculture and climate change, with perverse effects for one or all. There are also fears that this may directly affect potential access to climate financing by some of the most climate and socio-economically vulnerable countries with agriculture-based economies. The climate change negotiations have undoubtedly been a catalyst for action on agriculture and climate change at country level. At this level, there is currently keen interest and a broad range of initiatives. Some believe a lack of explicit international enabling policy may adversely affect the momentum and sustainability of these efforts.

The CFS commissioned its High Level Panel of Experts (HLPE) to prepare a report on food security and climate change for its consideration in 2012. The report was presented and discussed at a Policy Roundtable at the 39th CFS session held at FAO in October 2012. In its Final Report [2]on the session CFS referred to this Policy Roundtable and outlined relevant action, which it invited key stakeholders to undertake in order to address the effects of climate change on food security. Both CCAFS and FAO were involved in the preparations for this Policy Roundtable and are interested in supporting country action to achieve food security under climate change.

[2] (available at http://www.fao.org/fileadmin/user_upload/bodies/CFS_sessions/39th_Session/39emerg/MF027_CFS_39_FINAL_REPORT_compiled_E.pdf)

In recent years, both FAO and the CGIAR have instituted programs that respond to each of these challenges. The CGIAR has established the Climate Change and Food Security (CCAFS) program, which is a 10-year research initiative that seeks to overcome the threats to agriculture and food security in a changing climate, exploring new ways of helping vulnerable rural communities adjust to global changes in climate. FAO has established a program of work on climate smart agriculture, which provides support for developing and implementing policy, technology and financing approaches to enable countries to achieve sustainable agricultural development under climate change. In 2012, FAO initiated a climate smart agriculture project with funding from the EC. The project involves three partner countries: Malawi, Zambia and Vietnam, who will be supported by FAO for period of 3 years to establish an evidence base on synergies and trade-offs between mitigation, adaptation and food security, barriers to adoption of climate smart agricultural practices, support to achieving more coordinated and informed policy-making and risk management strategies and the development of country agricultural investment plans that incorporate adaptation and mitigation and links to climate financing. CCAFS is a partner in this project as well.

In the following sections we highlight four major categories for priority actions that FAO and CGIAR can take to support stakeholders from farm to national and international level to identify and implement responses that will generate agricultural transformation to support food security under climate change: 1) promoting agricultural technologies and innovations; 2) strengthening local institutions; 3) achieving coordinated and informed policies; and 4) increasing access to financing.

2.2 Promoting agricultural technologies and innovations

A key defining principle for agricultural technologies and innovations to support food security and poverty reduction in much of the recent literature is the need for sustainable agricultural intensification (Garnett and Godfrey 2012; FAO, 2012b; FAO 2012c; FAO, 2011; Foley et. al. 2011; Foresight, 2011) Building on this literature with the analysis from section 1, we posit the following as major principles for sustainable agricultural intensification under climate change:

- While the causes of hunger and malnutrition are various and not a simple challenge of increasing supply, some increases in food output will be needed in coming years as populations grow and diets change.
- Increased production will need to be achieved mostly without bringing new land into agriculture. In many cases there is no land available for agricultural expansion; furthermore,

in the context of climate change, land use conversion to agriculture is a major source of emissions (as well as loss of biodiversity).

- Increasing the stability of agricultural production systems requires much greater attention to building ecosystem services that increase resilience (FAO 2012c; FAO 2012d).
- Improving the efficiency of agricultural production systems, increasing sequestration and reducing waste are not only important forms of mitigation, they may also generate higher and more stable returns.
- If yields are to increase sustainably, then there is a need to harness and develop the knowledge and insights gained from all current systems of agricultural production, including those based on organic principles, local indigenous knowledge, and innovative plant breeding technologies (Box 2).

Box 2. Climate change brings challenges for crop breeding in CGIAR

Plant breeders have been responding to climate-related stresses for a long time, but climate change is adding urgency to new breeding activities and the use of new technologies directly linked to factors such as increased drought, more extreme temperatures, more widespread flooding, higher levels of salinity and shifting patterns of pest and disease occurrence, all of which are associated with climate change. The ways in which breeding is carried out is changing. Many CGIAR centres have adopted new collaborative forms of germplasm development and diffusion involving various kinds of partners. An example is CIMMYT's MasAgro project, a partnership of more than 50 national and international organisations dedicated to improving sustainable agriculture. Projects like MasAgro have been influenced by the shift in international development culture towards achieving impact and thus the need to provide farmers with tangible, measurable ways to improve their production systems. Others are using participatory approaches to crop improvement, such as ICARDA, through participatory variety selection in collaboration with NAROs and NGOs. Some of this work focuses on adaptation to climate change. Centres are also working on parental lines to be used by private companies for the development of hybrid varieties. Recent partnerships with the private sector are leading to uptake and diffusion of improved technologies that were not otherwise possible. Still other centres, in collaboration with NAROs, are collaborating directly with farmers' organizations and NGOs to select the most useful varieties and then bulk up quality seed and distribute it to farmers. ICRISAT, for example, is making small seed packets available commercially to farmers.

Centres have also been looking closely at their breeding objectives. With climate change, average temperature effects are important, but there are other temperature effects too. Increased night-time temperatures have negative effects on rice yields, for example, and increases in maximum temperatures can lead to severe yield reductions and reproductive failure in many crops. There may be genetic differences in plant response to such changes, and these could be exploited in future breeding programs. The increases in atmospheric concentration of CO_2 that are driving climate change provide challenges as well. Increased CO_2 can have a beneficial effect on many crops, although it may decrease the protein concentration in wheat grain, for instance. In beans, genetic differences in plant response to CO_2 have been found, and these could be exploited through breeding. The impacts of climate change on the pests and diseases of tropical crops and livestock are not well understood, but in future there could be substantial gains from breeding programs that exploit the natural resistance found in some plants and animals.

Sources: Ronnie Vernoy, "Plant breeders respond to climate-related stresses in multiple ways", at ccafs.cgiar.org/node/1695, and Thornton & Cramer (2012).

In contrast to earlier approaches for agricultural intensification where yield growth was the only metric of success, sustainable intensification encompasses environmental, social and economic objectives. Thus a broader range of metrics for measuring its success are also needed. It is essential to consider agricultural production in the context of broader goals for a sustainable food system, where sustainability is defined not just in environmental terms but in relation to broader social, ethical and developmental objectives. A critical social objective for the food system is to produce not only enough food, but sufficiently nutritious food. In the context of agricultural development to support food security, a key role of agriculture is that it should support and sustain livelihoods and economic development. As noted in section 1, improving the resilience and stability of production are key emerging objectives for agricultural intensification under climate change as well (FAO 2012c; FAO 2012d).

At the same time, effective mitigation of the GHGs emitted by agriculture will be needed. There are several priority mitigation actions that need to happen in the next ten years. First, ruminant productivity can be substantially increased, via improved livestock management, grazing management and energy use efficiency. Second, crop yields can be boosted to save forests. In general, if a hectare of forest can be saved by yield gains or a hectare of land can be reforested because of yield gains, there would be large carbon gains. Increasing yields through increases in fertilizer would reduce emissions substantially compared to the alternative of clearing more land to provide the same food. Yield gains by themselves can provide a form of climate mitigation, and the gains need occur not only in crops. Brazil, for instance, could readily produce all the additional food needed by 2030 by achieving reasonable rates of pasture intensification on already cleared agricultural land (Strassbourg et al., 2013). Third, there are opportunities to increase carbon sequestration. In cropland, those carbon sequestration opportunities focusing on improving agricultural production have generally held out the most hope for soil carbon build-up through changed agricultural management practices. One challenge is growing uncertainty about the potential, and a growing sense of the practical challenges (Powlson et al., 2011).

There is thus a complex set of objectives for agricultural intensification, and this has important implications for how we should go about developing new technologies or assessing existing ones. First, it implies that the "best" technology options will vary considerably depending on local socio-economic and agro-ecological realities. But they will also vary based on political realities which determine the priority objectives of agricultural sector management. For example, the degree to which food self-sufficiency is a policy priority, or maintaining a large smallholder production sector to minimize urban migration, are both key political decisions that are fundamental to determining which intensification strategies are most suited for a given context.

A second important implication of explicitly incorporating multiple objectives into agricultural strategies is the need for assessing technologies across multiple objectives. In the FAO climate smart agriculture approach, adaptation and food security are considered the primary objectives for agricultural intensification, with mitigation as a co-benefit. Both CGIAR and FAO have done considerable work on assessing where trade-offs arise between these objectives for a given location and strategy, as well as where synergies can be achieved. Indicators and analysis are needed for such assessments. For example, to identify adaptation benefits from any specific agricultural development activity, we need to have an idea about how climate change is projected to affect that location and agricultural system, as well as about the effectiveness of strategies for reducing vulnerability and increasing adaptation to such changes. For mitigation we need to understand the increase in emissions that could be expected under a conventional agricultural growth strategy, as well as the degree to which these “business as usual” baseline emissions could be reduced under alternative agricultural growth strategies.

Of course, it is not just identifying the right technologies or practices that will result in successful change at the field level: the engine that will drive sustained adaptation and transformation of agricultural systems is innovation of all forms - social, institutional and technological. Innovation is the process by which social actors create value from knowledge. It emerges as the cumulative result of millions of interactive, experiential learning cycles involving the social actors – laborers, farmers, entrepreneurs, policy makers, etc. From this point of view the key question becomes “how can agricultural research for development (Ag R4D) better foster rural innovation so as to build adaptive capacity for food security and wellbeing under climate change?”

Complexity science points to three levers for fostering innovation - increasing the pool of new ideas and technology that feed into these learning cycles, changing how people interact while innovating and making sense of the results, and changing the ways they measure and select what works and what does not (Axelrod and Cohen, 2000). Behind this is the notion that innovation is an evolutionary-like process driven by ‘learning selection’ analogous to ‘natural selection’ (Douthwaite, 2002).

Agricultural research for development has largely focused on the first lever, probably because arguably its greatest success came through the contribution high yielding crop varieties made to the Green Revolution. This has reinforced a still-dominant ‘pipeline’ view of the role of Ag R4D in which researchers' role is primarily to deliver technological fixes, rather than to support local capacity to innovate.

If Ag R4D is to better support adaptive capacity then it needs to put greater emphasis on the second and third levers through developing approaches that change ways people interact while innovating, and by developing methods that help people make better and faster decisions about how technology and institutions are working. This implies a greater emphasis on networking - both its practice and the theory behind it.

By emphasizing learning and networks in the innovation process we aim to foster, we will simultaneously support building 'latent social capacities' (Pelling and High, 2005) which are useful for long term adaptive capacity. Through this lens different types of social network structures and functions that support adaptive capacity become visible so that both formal and informal networks are of particular importance in climate change adaptation (Pelling et al., 2008).

There are a range of practices and interventions that we use already in R4D to alter network structure and the quality of the links within, including setting up different types of formal network or innovation platform and various types of collaborative and participatory research in which different social agents engage in joint inquiry to solve problems that builds relationships and capacity in the process. One example is given in Box 3.

Box 3. Building youth networks to support innovation

An example of an innovative model for building new networks to support technology transfers comes from a FAO supported project aimed at increasing youth employment implemented in 2011 in Malawi, Tanzania and the Zanzibar archipelago. The project involves public and private sectors in the countries in training youths in agricultural sector related activities – including climate smart agriculture practices. Assessments of the program indicate that when back in the home districts, youths that had participated in the program were actively involved in mobilizing and sensitizing their peers to innovations learned through the program. The spill-over effect initiated by the youth themselves when returning to their villages is as important as the initial effects of the training. The private sector gains new young and skilled members while the public sector decreases the number of rural youth unemployed. The model offers facilitated access to markets for young people' products through the producers' organizations networks while the youth gain a fair negotiated price for their produce and a voice in local associations.

Source: FAO CSA sourcebook

2.3 Strengthening local institutions

Local institutions, both formal and informal, play a key role in facilitating and encouraging agricultural producers to make changes in production systems, and manage natural resources and their overall livelihoods needed to achieve food security under climate change. Local institutions are a conduit for transferring information – on climate change effects on weather patterns relevant for agricultural production decisions, new technologies and practices and new market opportunities. Implicitly or explicitly, local institutions can support the capacity of local populations to identify and manage risks. Such institutions are also key in implementing (and in many cases devising) rules by which productive assets, such as land, water, trees can be accessed and collective action can be undertaken.

There is a vast literature on the role of local institutions in supporting sustainable agricultural intensification and development (see McCarthy et. al. 2011 for a recent review), but in this paper we focus on three key functions under climate change: information generation and dissemination to agricultural producers, risk management and collective action. Building and strengthening networks to support adaptive capacity – as described in the preceding section is an important way of improving the performance of local institutions. Some examples of how innovative approaches to mobilizing both formal and informal institutions and networks to strengthen local institutional capacity for information dissemination, risk management and collective action are given below.

2.3.1 Information generation and dissemination

Much effort has been invested in helping farmers to make more effective climate-sensitive decisions (e.g. planting times, livestock shelter) via improved access to timely, meaningful and trustworthy climate information and knowledge. This work links a technical component – development of agro-climate tools (Hansen and Coffey, 2011) – with institution building to improve channels both for uptake of information and for demand for that information, allied with new information technology (Box 4). Evaluations in Africa show that investing in institutions for sharing of seasonal forecasts (one key area of climate information) can increase the capacity of farmers to reduce their exposure to risks (Hansen et al., 2011). Likewise, for disaster relief agencies, overcoming institutional barriers to use of seasonal forecasts has proven critical to saving lives during climate crises (Tall et al., 2012). For farmers and higher-level agencies alike, relevant institutions include channels for two-way communication across barriers of language and scientific understanding, systematic capacity building of both users and providers of information, and trust-building among partners. Information transfers may occur between a number of sources/recipients, including government extension programmes and non-governmental organization (NGO)/donor programmes. An example of an innovative way to link farmers to extension information is given in Box 5.

Box 4. New ways of getting information to (and from) farmers

The continuing rapid pace of change of technology is opening up new opportunities. For example, a new global cropland data layer has recently been developed by IIASA (the International Institute for Applied Systems Analysis in Austria) with many partners, including FAO and CGIAR, and it has been calibrated using crowd-sourcing. More calibration data are being collected using the geo-wiki land cover validation tool (geo-wiki.org), and it is being developed into a multi-mass player game with support from CGIAR partners. Other examples are using mobile phone technology to collect household survey and farming systems data using crowd sourcing, and using mobile phone transmission towers to collect rainfall data and as a basis for providing flash flood warnings. Recent advances in high-resolution satellite imagery and making it more readily accessible are opening up other opportunities in monitoring land-use change and weather forecasting, for example.

Box 5. Audio Conferencing for Extension Service Delivery in Ghana.

Many Ghanaian young farmers are losing confidence in the quality of extension services because extensionists do not come with demand driven extension messages via innovative methodologies. Farmers are usually not involved in the development of the extension content and therefore find the extension services not adequately tailored to address their farming challenges in order to enable them to take up agriculture as a business and a sustainable livelihood. The Savannah Young Farmers Network (SYFN), a youth-led NGO in Ghana, is running the Audio Conferencing for Extension (ACE) project in the north of Ghana, offering innovative extension services. SYFN organizes these audio conferences for extension service twice a week with farmer groups consisting of minimum ten and maximum fifteen farmers. During these audio conferences, farmers are put in touch with agricultural officers from SYFN and other agricultural extension experts, agronomists, ICT professionals and Agricultural researchers. A cell phone with an audio conferencing system is used and attached to a portable loudspeaker to enable all farmers present at the conference to interact with the advisors. Community Agricultural Information (CAI) Officers are present with the farmers to ensure that the capacity building sessions are well planned, moderated and that the desired impact is achieved.

Providing appropriate information, such as improved forecasts, better ways to communicate them, and designing appropriate safety nets that enable farmers to make informed decisions, is particularly important under climate change. Several areas warrant particular attention:

- How information on climate change and possible responses can be improved and made more relevant to farmers and communities. This is linked to a rich body of literature that indicates that risk perceptions and behavioral biases, often due to limited information or poor communication, affect the response to increased climate variability, indicating the need for participatory approaches to appropriate policy formulation (Patt and Schröter, 2008; Marx et al.; 2007). Areas where improved information and communications would be beneficial include local forecasts and communication in a way that is relevant to farmers, availability of technological options that are appropriate under evolving climatic conditions, and how to overcome barriers to adoption.

- Even with the best available information, climate change introduces additional uncertainty, both in terms of probabilities and extent of exposure to impacts and farmers' behavioral response, which requires new approaches to identify appropriate courses of action (Clarke, 2008; Hallegatte et al, 2012; Heltberg et al., 2009; Dalton and Muhammad, 2011; Brunette et al., 2012, Antón et al., 2012).

Information also interacts with the role of assets (physical, human, and social) in choosing appropriate courses of action and the ability to act upon the information received. This point is also linked to the interaction of the damage incurred by farm households (especially subsistence producers) and potential opportunities for farm households through markets (Hertel and Rosch, 2010; Ziervogel et al., 2006). A better understanding of the role of different types of assets in building resilience and diversifying sources of income in the face of climate change and other shocks is critical for vulnerable households and should be part of a broader strategy for managing risk. In such a broader context, information also matters for how policy design, such as safety nets, affects farmers' management decisions, incentives to adapt, and resilience, addressed in the context of assets,perceptions, and communication.

2.3.2 Design elements in managing risk

The risk mitigation effects of different agricultural alternatives can occur at multiple scales. At the plot level, intercropping varieties with different phenological traits, such as with variation in time to maturity, spreads the risk of drought spells (Cavatassi et. al. 2010). Ethiopian farmers growing traditional barley varieties have been found to decrease overall yield variance as well as the odds of crop failure (Di Falco et al., 2006). At the farm level, many households favor mixed livestock-crop systems when weather risks increase, such as in sub-Saharan Africa (Seo, 2012; Rufino et al., forthcoming), as livestock can be used as an asset to smooth income fluctuations (Fafchamps et al., 1998; Miura et al. 2012). Furthermore, diversified farms can play an important role in maintaining and increasing ecosystem service provision (Ricketts, 2001). Maintaining a high response diversity can facilitate post-disturbance recovery (LaLiberte et al., 2010) and thus compensate for the negative effects of climate change and increase overall resilience (Kremen and Miles, 2012). Better ways are needed to assess the complicated linkages between (and respective costs associated with) diversification at different scales and other measures that contribute to vulnerability reduction, including agricultural insurance, weather information provision, and social protection measures are needed to guide policy.

In this context, institutional interventions can either support farmers' own strategies at the local level, or improve the wider governance of food systems to dampen the negative effects of climatic shocks on food security. Halstead and O'Shea (1989) distinguish five mechanisms for risk transfer: (a) mobility: distribution of risk across space; (b) storage: distribution of risk across time; (c) diversification[3]: distribution of risk across asset classes; (d) communal pooling: distribution of risk across households; and (e) market exchange: purchase and sale of risk via contracts (which can substitute for any of the above). For each of these, there are multiple corresponding adaptation strategies and associated institutions (Table 1).

While some of the recommended avenues for institution-building are specific to climate risks, many are generic to sustainable development, and need to build on existing development institutions such as those created in the context of community based adaptation and distaster risk reduction (Box 6).

[3] Note that in section 1, we take a broader view of diversification (in that it can have other benefits that are not primarily related to the transfer of risk).

Table 1. Examples of adaptation strategies and institutions for risk transfer under climate change. Adapted and expanded from Agrawal and Perrin (2008).

Risk transfer category	Adaptation strategies	Institution-building opportunities at the local level	Institution-building opportunities at higher levels
Mobility	• Agropastoral, wage labour or involuntary migration • Distribution & trade of ag produce & inputs	• Conflict mgmt e.g. croppers vs. pastoralists • Functioning of local informal markets • Support to local exit strategies	• Residence & border controls • Safe & fair transfers of remittances • International trade controls & tariffs
Storage	• Water storage • Food storage • Natural capital including livestock & trees • Pest control	• Participatory action research • Local tenure & entitlements • Access to information	• Incentives for affordable private sector innovation • Knowledge systems for pests & diseases • Food safety interventions
Diversification	• Diversification of agricultural assets, including crop & livestock varieties, production technologies • Occupational diversification & skills training • Dietary & other consumption choices	• Farmer field schools & other locally-led innovation systems • Microfinance • Local business development • Household food management • Local future climate scenarios exercises	• Public and private extension services • Accessible banking & loan schemes • Skills retraining linked to job creation • Consumer food knowledge & preferences
Communal pooling	• Infrastructure development • Community forestry • Disaster preparation • Labour pooling • Knowledge management • Redistribution among kin or across society	• Producer groups & collective action • Benefit-sharing arrangements • Capacity building in climate knowledge • Local accountability & anti-corruption measures • Gender relations	• Land & resource tenure policy • Cooperative & producer association law • Tax-funded social welfare schemes & safety nets • Investment in research & social learning
Market exchange	• Improved market access • Wage labour, food-for-work • Insurance schemes	• Market information networks • Equity of access to government schemes	• Private sector procurement policy • Labour standards • Subsidised index-based insurance

Box 6. Enhancing community based adaptation through institutionalization of good practices in Bicol Region, Philippines

The Bicol region in the Philippines is exposed to high annual and seasonal rainfall variability and is highly vulnerable to natural disasters such as typhoons, flash floods, strong winds, thunderstorms and drought that cause variations in production as well as seasonal price fluctuations. These fluctuations have a significant impact on agricultural incomes. It is expected that climate change will further exacerbate the regions' exposure to climate-induced risks. This prompted the Philippine Government to initiate a project with the Department of Agriculture (DA) Regional Field Unit in Bicol, and Local Government Units (LGUs), aimed at reducing the vulnerability of poor producers to climate variability. The project was initiated with a participatory action research process led by the DA, in collaboration with two Bicol Universities, the Meteorological Agency (PAGASA), selected municipalities, barangays, farmers groups and farmers. It included technical and institutional capacity-building to expand the current disaster risk reduction system to include medium and long term adaptation needs. A set of good practices in cropping, livestock and fisheries management were identified and selected and field tested with farmers' groups through an action research approach facilitated by the agricultural universities and agricultural extension. Enhanced climate information products produced jointly by PAGASA and DA were designed for the specific needs of farmers and informed the season-specific selection of crop varieties for field demonstrations.

Source: Baas and Ricoy 2013

2.3.3. Collective action

In many farming systems, there are a number of activities that are more effective when undertaken by groups rather than by individuals alone, e.g. addressing market failures, providing local public goods, and managing communal resources. For instance, many of the biophysical improvements to increase resilience in smallholder agricultural production systems require action and coordination amongst many stakeholders in the rural landscape. Restoration of degraded areas to improve soil quality, improved management of communal water and pasture resources, and informal seed systems to facilitate the exchange of plant genetic resources are all examples of collective resource management activities that are likely to become more important under climate change. In many cases, local institutions exist to govern collective action and access to collective natural resources, but they are often coming under increased pressure due to population growth, conflicts, changes in market patterns and state intervention (Meinzen-Dick et al., 2002; McCarthy and Swallow, 2000; Niamir-Fuller, 1999;).

Effective property rights and tenure systems to regulate use and access are essential to achieve improved management of natural resources including land, water and genetic resources, but in many cases they are unclear, overlapping and not formalized. Increasing security of rights to resource use does not necessarily mean formalization of these rights, but rather a system for identifying, coordinating and recognizing informal rights. In fact, research on informal, customary systems has indicated that formalization through titles/certificates to property for smallholders has rarely led to increased access to formal credit sources, thus constraining hoped-for impacts on increased investment (Otsuka and Place, 2001). Additionally, ambiguous, complex and overlapping rights to resources often serve as an insurance mechanism, which is especially important where other safety nets are not available – and is likely to become even more important with increased weather variability (Goodhue and McCarthy, 2008; Chimhowu and Woodhouse, 2006). Increasing tenure security, then, requires a sound understanding of current claimants' circumstances. A process of moving through different stages towards formalization – from legally unacknowledged, customary tenure through to state-backed freehold title – is often the best way to maintain the benefits of customary tenure and incorporating the benefits to individualized tenure as these become relatively more important. Again, climate change is likely to increase the benefits to flexible access to resources, making the design of tenure security programs even more important, especially for the poor and most vulnerable.

2.4 Achieving coordinated and informed policies

2.4.1 Policy coordination

Given the cross-cutting nature of the response needed to achieve rapid transformation of developing country agriculture, institutional and policy innovations that favor greater integration and coordination will be essential. Key requirements include (i) the holistic approach advocated by FAO CSA, CCAFS and the CFS in addressing food security, agriculture and climate change; (ii) the involvement of multiple stakeholders, sectors, policy areas, time horizons, and levels of governance; (iii) the need for integrated responses in dealing with complexities, uncertainties and volatilities, and (iv) the current fragmentation of the existing institutional architecture at national and international levels.

The consequences of unaligned policies can be serious. Increasing demand for food, fuel and carbon storage in biomass and soils cuts across multiple policies - bioenergy, climate change, food security, agriculture and forest – and can result in fragmented approaches to land use. For example, bioenergy production from crops may compete with food crops for land and water or may divert food to fuel, resulting in negative impacts on food availability. Also using residues for biogas may limit their use as soil amendments or feed for livestock.

Integrated land-use planning and landscape approaches may allow multiple goals or targets to be addressed within spatial planning and there is a growing interest in both. Expansion of agriculture is a major driver of deforestation and drainage of wetlands in many developing countries. In the case of forest and agriculture boundaries, there is a need to look across environmental and agricultural policies and take into account the dynamic opportunity costs that farmers and forest communities may face in foregoing agricultural production on forested and wetland areas (Angelson and Kaimowitz, 2001).

Coordination mechanisms to overcome institutional fragmentation are needed but at national level generally need to be embedded in the existing institutional architecture and be nationally owned in order to be sustainable. Ministries in both developed and developing countries, as well as multilateral organizations that mirror the ministerial structure, are often referred to as silos in view of their lack of integration and tendency to see their own issues in isolation from, rather together with, those of other parts of government. Greater interaction, consultation and dialogue among Ministries of Agriculture, Environment and Finance, as well as other key stakeholders is needed in order to better enable more coherent policies, planning and investment.

Recognizing this need for greater coordination, quite a few coordination mechanisms have recently been developed at national level. In Malawi, a National Climate Change Programme has been established to coordinate all climate change activities in country. In Zambia, a National Climate Change Response Strategy has been prepared and a mechanism to coordinate climate change action is being developed. There are many other country examples of such coordination mechanisms, although they do not guarantee better integration or mainstreaming of climate change into the work of sectoral ministries. In particular, the integration of climate change issues into the technical, policy and financing decisions of ministries of agriculture is essential for achieving needed transformations. Modalities for more focused coordination and integration among the most concerned ministries and stakeholders, based on the principle of subsidiarity, may also be needed for implementation, in addition to an all-of-government approach.

2.4.2 Linking policy and research

As outlined in earlier sections of this report, policy-makers in developing countries concerned with agricultural growth and development for food security under climate change are operating under increasing uncertainty and yet need to be cognizant of tradeoffs and synergies between multiple objectives of strategies and implications for risk management – considering short run exigencies as well as long run implications. Clearly this is a huge challenge, requiring accessible and reliable information, analysis and evidence. This is where improving links between researchers and policy-makers becomes essential.

Planning in a policy context is often 1) incremental and relatively short-term, 2) oriented toward a single, normative vision, 3) based on notions of acting on a "high likelihood", forecasted future or a combination of these elements. In the context of future uncertainty generated by interacting biophysical and socio-economic changes across multiple system levels concerning issues of food security and climate adaptation, this type of policy making is limited and potentially dangerous. In such issues related to complex systems change, there is a need for policy to engage future uncertainty together with research to avoid planning blindly (Wilkinson and Eidinow, 2008). This is without even considering political realities and the changing strategic positions of actors. Scenarios that explore multiple plausible futures together with key stakeholders across multiple sectors have the potential of informing such a science-policy interface and allowing diverse actors to share and combine perspectives (Kok et al., 2006). Scenarios are effectively alternative narratives of the future, developed in words, numbers, images and/or other formats, that are based in a complex systems perspective and therefore do not seek prediction but rather a scoping of plausible future contexts and the consequences these might have for decision-makers (van Notten et al., 2003).

CCAFS, for example, is engaging governments, the private sector, researchers, civil society and the media in multi-stakeholder scenarios processes at the sub-continental level in East and West Africa and South Asia. Together, these stakeholders explore key socio-economic uncertainties for future food security, environments and livelihoods. Multiple socio-economic scenarios are developed by stakeholders and then quantified using agricultural economic models: IMPACT (Rosegrant et al., 1995) and GLOBIOM (Havlík et al., 2011). Socio-economic scenarios are combined directly with climate scenarios to explore how these human and biophysical future stressors interact to impact future food security, environments and livelihoods.

Through the scenarios processes in multiple sub-continental regions, CCAFS seeks to expressly engage in decision-making processes by asking decision-makers to "back-cast", or plan backwards, from desired policy objectives, in the different contexts offered by multiple scenarios, each of which offers its unique challenges and opportunities for policy options and strategies (Kok et al., 2011). Through a continual engagement process (Reid et al., 2009), the implementation of the outcomes of such processes is then facilitated by CCAFS partners experienced in inter-sectoral work. A FAO supported climate smart agriculture project is now engaging with CCAFS to develop similar processes for Malawi and Zambia in the context of climate adaptation. Furthermore, FAO-ESA and CCAFS aim to work together on a regional process for South East Asia to develop and use scenarios with actors across multiple sectors.

The direct combination of stakeholder perspectives with quantitative modeling through socio-economic and climate scenarios provides a linked science-policy interface, especially when there is ample time for feedback and iteration between the two sources of knowledge. The use of the qualitative-quantitative scenarios as context for policy development further integrates the two domains. However, researchers involved in such science-policy interfaces have to be careful not to be naïve about the realities of policy and avoid assuming that policy actors are not strategic, are open about their motivations, have no self-centered interests and do not consider the behavior of others in the policy arena (Dryzek, 2009). These realities of policy engagement offer challenges for researchers. A preliminary insight emerging from CCAFS work is that if socio-economic scenarios feature the wicked problems of policy reality such as a lack of policy implementation, corrupt practices, etc., they can form the basis for more grounded strategizing with policy actors, leading to strategy development that participants considered highly engaging, challenging and plausible.

2.5 Increasing Access to Financing

2.5.1 Financing gaps

We do not have good estimates of what it will cost to achieve food security under climate change, although there are some useful indications. Recent projections for the incremental investments needed in agriculture in 93 developing countries to meet projected food demands by 2050 – relative to a baseline scenario – estimate an average annual additional investment of US$ 209 billion per year would be required. An additional expenditure on investments and safety nets of US$ 50.2 billion per year were estimated to be needed to reach a world free from hunger by 2025. These estimates do not include the additional investment requirements that climate change adaptation and mitigation impose, which are likely to be substantial. The World Bank estimated the annual costs of adaptation in the agriculture sector in developing countries at US$2.5-2.6 billion a year between 2010 and 2050 (World Bank, 2010). The UNFCCC (2008) estimated that additional investment and financial flows needed in developing countries for mitigation from the agriculture sector would be about US$12.25-14 billion a year in 2030. Costs for measurement and monitoring, capacity and infrastructure building and carbon-credit-monetization are estimated to be 3.8 billion euros for the agriculture sector in 2030 and total expenditures for abatement levers over 2010-2030 is estimated to be € 13 billion. Transaction costs, without aggregation mechanisms, could be high for the multitude of smallholders involved and incentive programmes to ensure adoption of abatement technologies may also be required.

Two recent reports on agricultural and climate finance give some indication of a financing gap to support agricultural transitions for food security under climate change. The FAO State of Food and Agriculture report for 2012 on investment in agriculture found that two important measures of agricultural investment, expenditure per worker, and share of agricultural expenditure related to importance of the sector in GDP, were low and declining in the two regions of the world where agricultural transition for food security is most important - South Asia and sub-Saharan Africa. The report also indicates that redistributing investments in agriculture to generate the highest returns to poverty reduction and food security is needed. For example, increasing shares of expenditure on agricultural research and development, roads and education, and less on subsidies for private goods such as fertilizer inputs is needed. The Landscape of Climate Finance report 2012 estimated a total of US$ 345-385 billion in climate financing flows for 2010-2011, which is overwhelmingly directed to mitigation activities primarily in the energy and transport sectors. Some 33% of that finance was directed to emerging economies: Brazil, China and India. The report found that the agriculture and forestry sectors were the main recipients of climate-resilient finance in the period 2010/2011, receiving 27% (US$ 4.4 billion) of the total. Multilateral development finance organizations allocated 12.7% of total adaptation finance to capacity building and technical assistance, including awareness raising programs, training to address vulnerabilities, early warning systems, and strengthening of institutions, policies, and regulations. Dedicated climate funds, such as the pilot countries for climate resilience (PPCR) program, accounted for only 2.5% of total adaptation finance to the agriculture and forestry sectors.

2.5.2 CGIAR and FAO actions to support increased access to finance

This discussion of the demand and supply of financing to support agricultural transitions for food security under climate change gives rise to three important challenges. First, overall financing flows are inadequate to meet investment demands, implying a need for increasing flows, and perhaps even more importantly, improving the capacity of existing financial flows to stimulate increases from sources currently underinvesting. The most important example here is better targeting of public sector finance to leverage and incentivize private sector investments, particularly those from agricultural producers themselves. Secondly, the overwhelming share of mitigation finance in climate finance indicates the need to develop policies and financing mechanisms to increase financing for adaptation, as well as a need to identify where mitigation finance and the activities it supports are synergistic with agricultural transitions that promote food security under climate change. Thirdly, better targeting of agricultural and climate financing to agricultural transitions that generate the highest returns to food security is needed. FAO and CGIAR have important roles to play in meeting each of these challenges, through advocacy, policy and investment support and the development of financing mechanisms appropriate to supporting agricultural transitions.

Advocacy and information provision on the specificities of the agricultural sector and its importance to food security are needed to support international policy dialogues and negotiations to reach an agreement that allocates responsibilities, commitments and financing to achieve a global response to mitigating and adapting to climate change. FAO and CGIAR have been active in the UNFCCC discussions in providing information about the magnitude and nature of policy, technical and financing needs to support adaptation in the agricultural sectors of developing countries, as well as on the potential to design mitigation financing mechanisms to capture synergies with food security and adaptation objectives. FAO and CGIAR are also engaged in building an evidence base for identifying where synergies can be obtained between mitigation and food security/adaptation in agricultural transitions. Analysis of tradeoffs and synergies between objectives are being carried out by both CCAFS and the FAO CSA project. The FAO MICCA programme and CCAFS have a coordinated program on agricultural mitigation for food security. Two pilot projects , a small holder livestock system in western Kenya and conservation agriculture with trees as an alternative for slash and burn in Tanzania act as laboratories for developing menus of climate smart practices, building capacities to adopt them and measuring their impact on emissions and livelihoods of the farmers. The knowledge generated is used for capacity development at national level and also fed to the UNFCCC process as technical advice. A community of practice links people all over the world sharing experiences of good practices, solving problems and learning through virtual learning events. Both FAO and CGIAR are actively involved in providing technical support to national agricultural investment planning. The degree to which climate change adaptation and mitigation is integrated into such investment planning varies considerably, and this is an area where improvements are needed. FAO and the World Bank developed a method for screening agricultural investment plans to identify climate smart agricultural investments, and one of the main outputs of the FAO CSA project is the development of country agricultural investment plans that integrate adaptation and mitigation and explicitly link to sources of climate finance. One of the main barriers to linking climate finance to agriculture is the need for measurable, reliable and verifiable indicators of adaptation and mitigation benefits from agricultural transitions, and this is another area that CGIAR and FAO can clearly provide support. In the following section of this paper we look in more detail at the issue of developing indicators to measure progress on agricultural transitions to achieve food security under climate change.

3. How to monitor and evaluate?

3.1 The importance of monitoring progress towards development outcomes in FAO and CGIAR

Both FAO and CGIAR are undergoing reform processes to improve the effectiveness of their respective work programs. A fundamental aspect of this reform is moving to the use of results-based frameworks which require the development of indicators for tracking progress towards stated objectives. In this section we provide a brief overview of recent developments in FAO and CGIAR related to the development of indicators and then move on to discussing suggested indicators for tracking progress in making agricultural transitions to support food security under climate change.

In 2012 FAO initiated a process to develop a new framework organized around five strategic objectives:

1. Contribute to the eradication of hunger, food insecurity and malnutrition;
2. Increase and improve provision of goods and services from agriculture, forestry and fisheries in a sustainable manner;
3. Reduce rural poverty;

4. Enable more inclusive and efficient agricultural and food systems at local, national and international levels;
5. Increase the resilience of livelihoods to threats and crises.

Climate change is raised as a challenge in all of these strategic objectives and actions to assist countries in coping with the effects of climate change in strategies to meet these five objectives are currently being defined. Organizational outputs are aimed at achieving changes at four broad levels: agricultural producers (defined to include crops, livestock, fishery and forestry), national policy makers and regulators, international policy / governance processes, and a broad set of stakeholders involved in efforts to change the governance, policy, institutional and technical processes in countries related to obtaining each of the strategic objectives. The type of action FAO envisions taking to support transitions at these four levels encompass technical support, policy assistance and guidance, capacity building, information gathering, and dissemination and analysis.

For CGIAR, a Strategy and Results Framework (SRF) provides the basis for setting priorities, identifying metrics to measure success in its implementation, and connects the performance of the 16 CGIAR Research Programs (CRPs) to a set of System Level Outcomes (SLOs). These SLOs are:

- Reducing rural poverty: agricultural growth through improved productivity, markets and incomes has shown to be a particularly effective contributor to reducing poverty especially in the initial stages of development;
- Improving food security: access to affordable food is a problem for millions of poor people in urban and rural communities and it requires increasing global and regional supply of key staples and containing potential price increases and price volatility;
- Improving nutrition and health: poor populations suffer particularly from diets that are insufficient in micronutrients affecting health and development, particularly in women and children;
- Sustainable management of natural resources: agriculture demands better management of natural resources to ensure both sustainable food production and provision of ecosystem services to the poor, particularly in light of climate change.

The SLOs represent a distinctive set of interactive targets for the contributions of agricultural research to development (CGIAR, 2011). These SLOs are being linked to sets of quantitative Intermediate Development Outcomes (IDOs) developed both top-down and bottom-up for each of the CRPs and linked to CRP activities. A key part of this process is the installation of data gathering and synthesis capacity, along with agreement on consistency regarding data and metrics by which progress towards the IDOs can be regularly evaluated. The setting up of this cascade of CRP activities, objectives, outcomes, IDOs and SLOs is not yet complete, but it should be in place by the end of 2013. Having been negotiated with a wide range of stakeholders and investors, it will provide sets of quantifiable indicators by which the CRPs will be evaluated in the coming years. At the same time, a balance is likely to be needed between quantitative and qualitative indicators: it is not always possible to measure important outcomes, and research is inherently a risky business. Such considerations, coupled with the need to allow for failure and for rapid response to things of the moment that suddenly arise, all point to the need for learning cycles as we go about pursuing these IDOs.

3.2 Developing metrics to monitor and evaluate the necessary transitions

A robust framework with specific indicators and metrics of whose behavior has changed and how, across food systems, is a tall order, for several reasons. First, there are almost no universally agreed indicators to measure adaptation "success" (Hedger et al., 2008) in any sector, and a recent review indicates that food system and food security-specific adaptation measures largely do not exist (Chesterman and Ericksen, 2013). Second, ensuring adaptation to climate change across food systems will entail transitions and behavior change at multiple temporal, spatial and institutional levels. Adaptation requires both short and long term decisions, catering for immediate needs as well as systemic changes (Antle and Capalbo, 2010). Third, behavior change requires collective learning and action as adaptation is ongoing, which means that monitoring frameworks have to allow for learning to modify intended strategies. Fourth, the "success" of an adaptation intervention can be evaluated from more than one perspective; often economic tools are used, but goals such as food security and environmental security also have normative and socially defined dimensions, as well as physical. Tradeoffs between these different perspectives are often unavoidable. Finally, uncertainty is an inherent feature of the future, especially for climate change. Multiple drivers, including food prices and income growth, affect adaptive capacity in food systems, and their interactions are uncertain, as are the specific impacts of climate change on precipitation, temperature, seasonal and annual variability, and extreme events. Thus we are monitoring impact under uncertainty and have low predictive capacity.

Here we set out several premises that make the monitoring and evaluation (M&E) challenge a little more tractable. First, the desired outcomes from food systems are clearly identified as food security, enhanced livelihoods, and enhanced ecosystem services. Five priorities pertaining to these outcomes have been identified: increased returns to smallholder agriculture, reduced vulnerability to income shocks, increased efficiency in the use of scarce resources, increased nutritional value, and reduced emissions growth rates associated with agriculture. Thus even though there is uncertainty inherent in the future and dynamism along the transition pathways that make monitoring of behavior change challenging, the desired outcomes will not change. And for any given context, it is possible to identify desired targets for the outcomes, such as percent more food secure, percent increased income from food systems, and target levels of soil carbon and other ecosystem services. Third, elsewhere in this paper several areas of intervention have been identified and the desired behavior change for each has been elaborated. As many of these interventions have been tried before in multiple contexts, an evidence base can be compiled.

We advocate the use of a food systems framework such as that outlined by Ericksen (2008) and Ericksen et al. (2010) to develop metrics and indicators for M&E of the adaptation interventions described for food systems. This allows for the impact of an intervention across food systems, the interactions between interventions, and the tradeoffs among outcomes to all be assessed (Warner et al., 2012). This also allows for the approach to doing M&E under uncertainty advocated by Antle and Capalbo (2010), in which the desirable objectives of food systems are evaluated under a range of conditions for agricultural growth and food security, allowing for different strategies adapted to the changing and uncertain conditions. A more resilient food system, they argue, is the one able to ensure the desired objectives under more than one future scenario. There are various examples of scenario-based approaches; CCAFS, for instance, is using participatory scenarios as a tool to stimulate regional and national action on adaptation and mitigation in the face of perceived climate change, under varying economic, political and social conditions (Vervoort et al., 2013).

Ex-ante assessment of adaptation investments and interventions is one first step, followed by continued monitoring as the adaptation process unfolds. This will require the sharing of data and model results from both site specific and more general regional assessments. We are limited by the fact that few analyses to date combine the economic, physical and social impacts (Antle and Capalbo, 2010). Continued efforts by groups such as the CGIAR centres, FAO, IIASA, and the UNFCCC Nairobi Programme of Work to share their models and data and improve the capacity of these models to answer the critical questions about the impact of adaptation are an important research and knowledge management priority.

A second step is for the climate change adaptation community to learn from ongoing M&E efforts in traditional development arenas (Hedger et al., 2008). There are a host of indicators in use to evaluate whether populations are food secure from all four perspectives of access, availability, utilization and stability. Similarly, the quantity and variability of income from agriculture can also be tracked and measured, as can the efficiency of resource use in agricultural production. Development practitioners are also accustomed to using M&E as a tool to demonstrate accountability to donors. However, as less is known about the "success" of these interventions in relation to the uncertain impacts of climate change in the future, participatory tools such as outcome mapping with multiple stakeholders are necessary to collectively track progress and agree when a change of strategy is needed. This is particularly important given that current adaptation to economic risk or to enhance food security, may not also guarantee adaptation to future climate change (Eriksen and O'Brien, 2007; Eakin and Luers, 2006).

A third and more difficult challenge is to build the learning networks across food systems and across levels of action and governance. Although many adaptation decisions about agricultural production and food security are taken at the household level, these decisions are heavily influenced by higher-level institutions and policies. The use of a comprehensive food systems framework can assist multiple players to understand the impact of any given intervention in the context of a whole system and other interventions. As already mentioned, key institutions need to support learning networks and the establishment of shared data bases.

Within the M&E literature, reference is made to the difference between monitoring processes, outcomes and impacts. We argue that all three are needed to track adaptation in food systems (Table 2). The causal pathways outlined for the necessary food system transitions suggest the processes that we think will achieve adaptation. We need to monitor how well these are implemented. Second, each of the interventions is hypothesized ex-ante to achieve a certain outcome, which needs to be monitored. At the highest level, there are impacts on food security, incomes and the environment, which also need to be monitored.

Table 2. Example of food system adaptation metrics.

Key food system objective	Strategies to achieve this	Process indicator	Outcome indicator	Impact indicator
Enhance nutritional value	More nutritious food grown	Farmers' crop choices change	Foods with greater nutritional value harvested	Diets contain more nutritious foods
	Price of nutritious food reduced	Pricing policies implemented.	Households purchase more nutritious food	Diets contain more nutritious foods

More efficient use of scare resources	Revise input prices	Pricing policies implemented	Fertilizers use modified	Less fertilizer waste
	Implement land tenure	Tenure policies designed and implemented	Land tenure more secure	Land used more efficiently

3.3 Outcome indicators: how does climate change affect what we would like to see?

As has often been pointed out, climate change adds considerably to the challenges of sustainable development and global food security. As the sections above have attempted to show, addressing these challenges in the face of climate change will require substantial behavioural changes at several different levels. At the same time, short- and long-term climate change imposes additional challenges on measuring changes in behavior and outcomes. In this subsection, we consider outcome indicators in relation to several features of climate change and the agricultural sector: risk-adjusted returns to agricultural systems; changes in transitory food insecurity in the wake of climate shocks; greenhouse gas (GHG) emissions; and the problem of maladaptation.

3.3.1 Risk-adjusted returns to agricultural systems

Increasing frequencies of heat stress, drought and flooding events are projected for the rest of this century, and these are expected to have many adverse effects over and above the impacts due to changes in mean variables alone (IPCC, 2012). Adaptation to climate change is sometimes most appropriately framed within the context of risk management: helping decision-makers understand and deal with current levels of climate variability can provide a critical entry point to a consideration of longer-term changes not only in climate variability but also in climate means. On the face of it, there are several ways in which agricultural systems can be evaluated in terms of their variability so that risk-adjusted returns can be quantified. In practice, however, there may be real challenges in doing this. First, major difficulties exist relating to the uncertainty of climate projections and projected impacts over short to decadal time scales, and how this uncertainty is best treated in the search for "social relevance". The climate models are still quite a way from being able to produce robust estimates of changes in climate variability into the future that can used with any confidence. Second, appropriate cross-sectional and panel household / systems data may be difficult to come by in many situations, particularly information on inputs and farming practices, for example. Third, while various analytical frameworks exist for evaluating risk and decision-making under risk, there is considerable debate as to the adequacy of some of these frameworks (expected utility, for instance) in typical developing-country subsistence-orientated settings. Moving from an agenda based on mean yields and income towards a more relevant one based on the variance of yields and income and threshold probabilities has clear implications for measurement, monitoring and analysis: there is a major research agenda here, touching particularly on data collection methods, climate modeling and downscaling, and decision analytics and modeling.

3.3.2 Changes in transitory food insecurity in the wake of climate shocks

Food security has many dimensions and there is no one indicator that can capture all these, so a suite of indicators has to be developed and monitored. A considerable literature exists concerning how food insecurity can be measured and how its various determinants can be assessed in relation to agricultural production of smallholders in developing countries. These include things such as the probability of falling below a food security threshold, a proxy of which is the probability of falling below a specific income, food consumption or food expenditure threshold (Lovendahl and Knowles, 2005); and empirical approaches using household survey and climate data to establish the links between climate change, agricultural productivity and household food consumption expenditure, to estimate the likelihood of households falling below the food poverty line (Karfakis et al., 2011). FAO (2012) provide a conceptual framework for looking at household food security changes after a climatic shock as the sum of benefits from safety nets and assets and from household-level adaptation (i.e. productivity increases and reduced variability via adoption of particular practices, diversifying on-farm livelihood strategies, and diversifying income through off-farm activities). The issues surrounding the assessment of transitory food insecurity in the wake of shocks of different types (including climate) are dealt with in WFP (2009), for example, and much is made of rapid data collection methods and use of proxies. As Barrett (2010) notes, measurement drives diagnosis and response; and considerable improvements are needed so that we can better identify food-insecure people and their targetable characteristics. This is particularly true if the nature of climate shocks will change with increased variability or long-term temperature increases. This is an area where the use of qualitative surveys of household behavior and perceptions can add a lot, and enrich our knowledge and monitoring capacity beyond what can be understood with standardized quantitative indicators (Webb et al., 2006).

3.3.3 GHG emission intensity per unit agricultural output

Indicators for GHG mitigation are relatively easy to conceptualise but difficult to measure. As outlined in section 1.3 above, agriculture is a net emitter of different GHGs, in particular carbon dioxide, methane and nitrous oxide, and these gases have different atmospheric lifetimes and radiative properties. The different Global Warming Potential of these gases makes it possible to express emissions as tons of carbon dioxide equivalent. Indicators for climate change mitigation revolve around measurement of the gases emitted or of the carbon sequestered. These measurements are not without several sources of uncertainty, including uncertainty over whether or not an agricultural carbon sequestration activity is actually implemented and an accurate accounting of the land area involved, uncertainty arising from emission factors attributed to mitigation actions, particularly in heterogeneous agricultural landscapes, and uncertainty due to lack of scientific documentation of the impacts of management practices on non-CO_2 emissions associated with carbon sequestering processes (FAO, 2012). Standardised methodologies and life-cycle assessment methods are key, otherwise results can be dependent on (e.g.) where the system boundary is drawn. Nevertheless, mitigation has substantial potential to diversify income sources for agricultural households in developing countries. There are many examples of household adaptation strategies that have mitigation co-benefits that could provide an extra source of income (one would be the use of agroforestry trees on-farm that provide high-quality dry-season fodder, thus increasing livestock productivity and production, while at the same time sequestering carbon and providing a further potential source of income). Some mitigation activities, while providing additional income, may involve a trade-off in income from other agricultural activities (an example would be the case of funding for reducing emissions from deforestation, which could entail a decrease in agricultural land and farm income) (FAO, 2010). This highlights the importance of analyses using robust tools that are capable of evaluating the synergies and trade-offs that may result, not only at the household level but at different scales too (at the landscape-watershed level, in relation to down-stream impacts, for example; and at the national and regional levels, in relation to production shifts as an adaptation strategy, for instance). In all cases, it needs to be established that the public and private costs and benefits are distributed appropriately and in accord with government policy objectives.

3.3.4 Indicators that can identify potential maladaptation well in advance

As noted in section 1.2.3 above, there is recent documentation of a case in Australia where transformative adaptation was undertaken and then reversed (Jakku et al., 2013). Moving from a linear approach of 'cascading uncertainty' (Challinor, 2009) such that climate uncertainties are seen to dominate the inputs to decision-making, towards a decision-centred approach in which climate change risk is recognised as only one driver (Willows and Connell, 2003), may help to avoid large-scale and unnecessary change. But it seems likely that examples of maladaptation will become increasingly frequent, if there are limits to the number of "low regrets" options that are either genuinely effective across a wide range of different, plausible futures, or that are relatively insensitive to the uncertainties associated with the future climate. If adaptation is framed as a continuing process, this has considerable implications for monitoring, in attempts to identify divergences from desired outcomes as soon as possible. For large-scale, costly or heavily time-lagged alternatives, it may be far better to pre-screen them before embarking on such adaptations. Barnett and O'Neill (2010) identified five distinct types or pathways through which maladaptation may arise. These include increasing the emission of greenhouse gases (for example, through the use of energy-intensive adaptation options), through disproportionately burdening the most vulnerable, through implementing adaptation alternatives that have high opportunity costs, that reduce people's incentives to adapt, and that set paths that limit the choices available to future generation (i.e., path dependency through technology lock-in or massive sunk costs, for example). For these reasons, adaptation planning frameworks need to be built on robust approaches that are as insensitive to uncertainties as possible, and planning responses need to be robust to social and political factors, which will need flexible approaches that protect the interests of different stakeholders (Macintosh, 2012).

4. Conclusions: Suggested priority actions for FAO and CGIAR

In this final section, we focus on what more FAO and CGIAR can, and should, do to enhance the effectiveness of our work supporting agricultural transitions to achieve food security under climate change. The previous sections have already highlighted several areas where the two organizations are working on this issue, as well as four priority areas for immediate action: promoting agricultural technologies and innovations, strengthening local institutions, achieving coordinated and informed policies and improving access to financing. While both organizations already conduct significant amount of work in each of these priority areas, we argue that given the urgency of responding to the challenge, a more coordinated, effective and rapid support response from our two organizations is needed. To some extent this involves greater coordination between FAO and CGIAR, as well as enhancing the capacity for effective responses of each.

FAO provides technical support (including economic aspects) to countries in the design and implementation of agricultural development, food security and natural resource management policies, strategies and investments. Under the climate smart agriculture approach FAO has developed, climate change adaptation and mitigation are directly integrated into agricultural strategies, policies and investments. However much of the work of the organization on agriculture and food security is still conducted without explicit recognition of climate change's impacts and this is an area where much improvement can be made. FAO is also a forum for technical discussion on international policy issues relating food security, climate change and agriculture that ensures policy coherence across food security (CFS) and climate change (UNFCCC), with the understanding that UNFCCC is the preferred intergovernmental arena for climate change negotiations. The HLPE report on climate change and food security in 2012 was a first step in the direction of improving coordination between agriculture, food security and climate change policies, but much more is needed here as well. The CGIAR undertakes research to reduce rural poverty, increase food security, improve human health and nutrition, and ensure more sustainable management of natural resources. CGIAR Research Programs, in close collaboration with hundreds of partner organizations, including national and regional research institutes, civil society organizations, academia, and the private sector, generate and disseminate knowledge, technologies, and policies for agricultural development. Together, FAO and CGIAR can combine their comparative advantages to support the adoption of CSA practices and the enabling policies, strategies and investment required for farmers to do this. Below, we make some suggestions for priority actions that FAO and CGIAR could undertake in three broad areas: better understanding of climate change impacts, improving tools to evaluate alternative actions, and facilitating innovation and strengthening the links between knowledge and action.

4.1 Enhancing our understanding of how climate change impacts agriculture

With a few exceptions, the likely impacts of climate change on key staples and natural resources in developing countries are not understood in any great depth (FAO 2012d). There are many uncertainties as to how changes in temperature, rainfall and atmospheric carbon dioxide concentrations will interact in relation to agricultural productivity; the resultant changes in the incidence, intensity and spatial distribution of important weeds, pests and diseases are largely unknown. The impacts of climate change and increases in climate variability on agricultural systems and natural-resource-dependent households, as well as on food security and the future vulnerability of already hungry people in the tropics and subtropics, are similarly unknown. At the same time, Ramirez et al. (2013), evaluating the latest Global Climate Models (GCMs), estimate that at current rates of improvement, several decades' more work are required to improve regional temperature and precipitation simulations to the point where they could be used as direct inputs into agricultural impacts models. The prognosis for robust evidence of quantifying changes in weather and climate variability over the short-to-medium term is thus gloomy, and the agricultural research for development community will need to strengthen considerably links with the global change community if these GCM-based uncertainties are to be addressed adequately in impact studies. The inputs of CGIAR and FAO, along with many other partners, will be crucial if light is to be thrown on these issues (Thornton and Cramer, 2012).

4.2 Evaluating options

The sections above have highlighted the importance of risk management as one of the keys to improving resilience in agricultural households. The provision of guidelines for risk management under climate change, and practical advice on how these can be implemented, is a critical area of ongoing research. There are several ways in which FAO and CGIAR might develop this work in the future. These include increased understanding the role of assets (physical, human and social capital) and collective action in managing climate risks, how risk aversion affects farmers' decision-making in response to climate change, and increased engagement of civil society to bring about more participatory approaches to risk management and communication. FAO and CGIAR are already collaborating in the mitigation arena in several ways, and this work should be further developed. There are opportunities to facilitate multi-stakeholder action in implementing mitigation actions; more work is needed to quantify packages of mitigation practices in different situations, and to evaluate the regional and global implications of such practices on resource use and commodity supply. There are substantial opportunities for developing measurement, reporting and verification (MRV) methodologies for mitigation projects as well as producing harmonized and robust guidelines for carbon footprinting, as well as providing support for pilot activities in countries that are keen to move forward in this area.

Another area that has been highlighted above is the need to assess technologies and policies in relation to multiple objectives and multiple temporal and spatial scales. There are several elements to this: one is being able to evaluate the trade-offs and synergies between the development outcomes of increased food security, enhanced rural livelihoods, and sustaining the environment. A second relates to the importance of evaluating costs and benefits at different spatial scales and in relation to public and private bearers/recipients. A third relates to the issue of timing, and avoiding short-term gains that may be maladaptive in the longer term. Understanding the limits to adaptation of different types, and the existence of thresholds, beyond which transformation of livelihood systems may be required, are all areas in which CGIAR and FAO can contribute.

4.3 Promoting innovation and linking knowledge with action

As noted above, the engine that will drive sustained adaptation and transformation of agricultural systems is innovation: social, institutional and technological. CGIAR and FAO are themselves in the process of transformation that offers increased potential for partnerships, inter-centre collaboration, and trans-disciplinary research. The explicit inclusion of development objectives at the system and program level creates considerable space for new approaches to be tested and implemented within FAO and CGIAR. For example, social learning approaches are critically relevant to achieving development goals, and they may be crucial in climate change adaptation research, mainly because of the need for researchers to connect with the local context (Gonsalves, 2013). A rich array of social learning approaches exists (Harvey et al., 2012), some of which are already being used within FAO and CGIAR, and such efforts can be built on at the same time as methods for assessing their results are made more rigorous, in the effort to build a better evidence base for such approaches (Gonsalves, 2013).

Scenario approaches have considerable power to engage governments, the private sector, researchers, civil society and the media. Multi-stakeholder processes can explore key socio-economic uncertainties, and can be combined directly with climate scenarios to explore how these human and biophysical future stressors interact to affect future food security, environments and livelihoods. The combination of stakeholder perspectives with quantitative modeling can provide a linked science-policy interface. CGIAR has recently been working with scenario approaches, and planning for FAO-CGIAR collaboration in new regions is underway, in the context of adaptation to climate change. One challenge for the future is how to sustain continual engagement in such processes, so that the potential benefits of linking science with policy can be fully realised.

References

Agrawal A, Perrin N, 2008. Climate adaptation, local institutions and rural livelihoods. IFPRI Working Paper # W08I-6. Washington DC.

Ali M, 2008. Horticultural revolution for the poor: nature, challenges and opportunities. AVRDC, Tainan, Taiwan.

Angelson A, Kaimowitz D, 2001. Agricultural technologies and tropical deforestation. Centre for International Forestry Research, Bogor.

Antle JM, Capalbo SM, 2010. Adaptation of agricultural and food systems to climate change: an economic policy perspective. Applied Economic Perspectives and Policy, 32:386-416.

Antón, J., S. Kimura, J. Lankoski, and A. Cattaneo, 2012. "A Comparative Study of Risk Management in Agriculture under Climate Change," OECD Food, Agriculture and Fisheries Papers 58, OECD Publishing.

Axelrod R, Cohen MD, 2000. Harnessing Complexity: Organizational Implications of a Scientific Frontier. Free Press, New York.

Barnett J, O'Neill S, 2010. Maladaptation. Global Environmental Change 20, 211–213.

Barrett CB, T. Reardon and C. Webb 2001 Nonfarm Income Diversification and Household Livelihood Strategies in Rural Africa: Concepts, Dynamics, and Policy Implications. Cornell University Working Paper available at: http://inequality.cornell.edu/publications/working_papers/Barrett-Reardon-Webb_IntroFinal.pdf

Barrett CB, 2010. Measuring food insecurity. Science 327, 825-828.

Beare D, 2012. Fisheries and Aquaculture. Pp 56-67 in: P Thornton, L Cramer (eds), Impacts of climate change on the agricultural and aquatic systems and natural resources within the CGIAR's mandate. CCAFS Working Paper 23. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Copenhagen, Denmark.

Brunette, M., L. Cabantous, S. Couture, A. Stenger. "The impact of governmental assistance on insurance demand under ambiguity: a theoretical model and an experimental test" *Theory and Decision* (2012).

Cavatassi, R., L. Lipper and U. Narloch 2010 Modern variety adoption and risk management in drought prone areas: insights from the sorghum farmers of eastern Ethiopia Agricultural Economics Volume 42, Issue 3, pages 279–292

CGIAR, 2011. A strategy and results framework for the CGIAR. 20 February 2011, online at library.cgiar.org/bitstream/handle/10947/2608/Strategy_and_Results_Framework.pdf

Challinor AJ, 2009. Towards the development of adaptation options using climate and crop yield forecasting at seasonal to multi-decadal timescales. Environmental Science & Policy 12, 453-465.

Challinor AJ, Watson J, Lobell D, Howden M, Smith D, Chhetri N, 2013. A meta-analysis of crop yield under climate change and adaptation. Nature Climate Change (submitted).

Chaudhury M, Ajayi OC, Hellin J, Neufeldt H, 2011. Climate change adaptation and social protection in agroforestry systems: enhancing adaptive capacity and minimizing risk of drought in Zambia and Honduras. ICRAF Working Paper 137. Nairobi, Kenya: World Agroforestry Centre (ICRAF).

Clarke, H. (2008) , Classical Decision Rules and Adaptation to Climate Change. *Australian Journal of Agricultural and Resource Economics*, Vol. 52, No. 4, pp. 487-504,

Chesterman S, Ericksen P, 2013. Adaptation indicators used to monitor food systems. CCAFS Working Paper, CGIAR Research Program on Climate Change, Agriculture and Food Security, Copenhagen, Denmark.

Chimhowu, Admos and Phil Woodhouse. 2004. Customary vs Private Property Rights? Dynamics and Trajectories of Vernacular Land Markets in Sub-Saharan Africa." Journal of Agrarian Change 6, 3: 346-371.Christoplos I, 2010. The multiplicity of climate and rural risk, DIIS Working Paper 2010:8. Copenhagen, Denmark.

Crespo O, Hachigonta S, Tadross M, 2011. Sensitivity of southern African maize yields to the definition of sowing dekad in a changing climate. Climatic Change 106, 267-283.

Dalton, T.J., M. Yesuf and L, Muhammad (2011) "Demand for Drought Tolerance in Africa: Selection of Drought Tolerant Maize Seed using Framed Field Experiments," paper presented at AAEA Annual Meeting, July 24-26, 2011, Pittsburgh, Pennsylvania.

De Janvry A, Sadoulet E, 2010. Agricultural growth and poverty reduction: additional evidence. World Bank Res Obs 25 (1), 1-20.

Dercon S, 1996. Risk, crop choice, and savings. Economic Development and Cultural Change 44, 485-513.

Di Falco S, Chavas J-P, 2006. Crop genetic diversity, farm productivity and the management of environmental risk in rainfed agriculture. Eur Rev Agric Econ 33 (3), 289-314.

Douthwaite B, 2002. Enabling Innovation: a practical approach to understanding and fostering technological change. Zed Books, London.

Dryzek JS, 2009. Democratization as deliberative capacity building. Comparative Political Studies 42, 1379-1402.

Eakin H, Luers AL, 2006. Assessing the vulnerability of social-environmental systems. Annual Review of Environment and Resources 31, 365-394.

Easterling WE, Aggarwal PK, Batima P, Brander KM, Erda L, Howden SM, Kirilenko A, Morton J, Soussana J-F, Schmidhuber J, Tubiello FN, 2007. Food, fibre and forest products. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, ML Parry, OF Canziani, JP Palutikof, PJ van der Linden, CE Hanson, Eds., Cambridge University Press, Cambridge, UK, 273-313.

Ericksen PJ, 2008. Conceptualizing food systems for global environmental change research. Global Environmental Change 18, 234-245.

Ericksen PJ, Stewart B, Dixon J, Barling D, Loring P, Anderson M, Ingram J, 2010. The value of a food systems approach. Pp 25-45 in J Ingram, P Ericksen, D Liverman (eds), Food Security and Global Environmental Change. Earthscan, London.

Ericksen S, O'Brien K, 2007.Vulnerability, poverty and the need for sustainable adaptation measures. Climate Policy 7, 337-352.

Ericksen, P., Thornton, P., Notenbaert, A., Cramer, L., Jones, P. and Herrero, M. 2011. Mapping hotspots of climate change and food insecurity in the global tropics. CCAFS Report 5. Copenhagen, Denmark: CCAFS.

Fafchamps M, Udry C, Czukas K, 1998. Drought and saving in West Africa: are livestock a buffer stock? Journal of Development Economics

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C.,Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J.,Sheehan, J., Siebert, S., Tilman, D. & Zaks, D.P.M. 2011. Solutions for a Cultivated Planet Nature, 478: 337–342.

Food and Agriculture Organization of the United Nations (FAO), 2010. Climate-Smart Agriculture: Policies, Practices and Financing for Food Security, Adaptation and Mitigation. Rome Italy.

Food and Agriculture Organization of the United Nations (FAO), 2011. Save and Grow: a policymaker's guide to the sustainable intensification of smallholder crop production. Rome Italy.

Food and Agriculture Organization of the United Nations (FAO), 2012a. Developing a climate-smart agriculture strategy at the country level: lessons from recent experience. Background Paper for the Second Global Conference on Agriculture, Food Security and Climate Change, Hanoi, Vietnam, 3-7 September 2012. Rome, Italy.

Food and Agriculture Organization of the United Nations (FAO), 2012b. Towards the future we want: end hunger and make the transition to sustainable agriculture and food systems. Policy paper for the Rio+20 Conference 13-22 June 2012 http://www.fao.org/docrep/015/an894e/an894e00.pdf

Food and Agriculture Organization of the United Nations (FAO), 2012c. Stability of food security in a green economy environment. FAO Greening the Economy Working Paper Number 3. Available at: http://www.fao.org/fileadmin/user_upload/suistainability/papers/Executive_Summaries_engl.pdf

Food and Agriculture Organization of the United Nations (FAO), 2012d. Building resilience for adaptation to climate change: proceedings of a joint FAO/OECD Workshop 23-24 April 2012 Rome.

Food and Agriculture Organization of the United (FAO), 2013. Greenhouse gas emission form livestock – Global patterns and mitigation options. FAO, Rome, Italy, in press.

Foresight, 2011 The Future of Food and Farming. Final Project Report. The Government Office for Science, London.

Garnett T and Godfray C (2012). Sustainable intensification in agriculture. Navigating a course through competing food system priorities, Food Climate Research Network and the Oxford Martin Programme on the Future of Food, University of Oxford, UK

Gonsalves JF, 2013. A new relevance and better prospects for wider uptake of social learning within the CGIAR. CCAFS Working Paper No. 37. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Copenhagen, Denmark. Available online at www.ccafs.cgiar.org

Goodhue, R. and N. McCarthy. 2009. Traditional Property Rights, Common Property, and Mobility in semi-Arid African Pastoralist Systems. Environment and Development Economics. 14: 29-50.

Gregory PJ, Johnson SN, Newton AC, Ingram JSI, 2009. Integrating pests and pathogens into the climate change/food security debate. Journal of Experimental Botany 60, 2827–2838.

Grothmann T, Patt A, 2005. Adaptive capacity and human cognition: the process of individual adaptation to climate change. Global Environmental Change 15, 199–213.

Hallegatte, S., Shah, A., Lempert, R., Brown, C., and S. Gill (2012) "Investment Decision Making under Deep Uncertainty: Application to Climate Change. World Bank Policy Research Working Paper #6193.

Halstead P, O'Shea J (eds), 1989. Bad Year Economics: cultural responses to risk and uncertainty. New York City, USA: University of Cambridge Press.

Hansen J, Mason SJ, Sun L, Tall A, 2011. Review of seasonal climate forecasting for agriculture in sub-Saharan Africa. Experimental Agriculture 47, 205-204.

Hansen J, Coffey K, 2011. Agro-climate tools for a new climate-smart agriculture. CCAFS, Copenhagen, Denmark.

Harvey B, Ensor J, Carlile L, Garside B, Patterson Z, Naess LO, 2012. Climate change communication and social learning–Review and strategy development for CCAFS. CCAFS Working Paper No. 22.

CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Copenhagen, Denmark. Available online at www.ccafs.cgiar.org

Havlík P, Schneider UA, Schmid E, Böttcher H, Fritz S, Skalský R, Aoki K, Cara SD, Kindermann G, Kraxner F, Leduc S, McCallum I, Mosnier A, Sauer T, Obersteiner M, 2011. Global land-use implications of first and second generation biofuel targets. Energy Policy 39(10), 5690-5702.

Hedger MM, Mitchell T, Leavy J, Greeley M, Downie A, Horricks L, 2008. Desk review: Evaluation of adaptation to climate change from a development perspective. Institute of Development Studies, Brighton, UK.

Heltberg, R., P. B. Siegel, and S. L. Jorgensen. 2009. "Addressing human vulnerability to climate change: Toward a 'no-regrets' approach." *Global Environmental Change* 19(1): 89-99.

Herrero M, Conant R T, Havlik P, Hristov A N, Smith P, Gerber P, Gill M, Butterbach-Bahl K, Henderson B, Thornton P K, 2013. Greenhouse gas mitigation potentials in the livestock sector. Nature Climate Change (submitted).

Hertel TW, Rosch SD, 2010. Climate change, agriculture, and poverty. Applied Economic Perspectives and Policy 32(3), 355-385.

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

Howden SM, Crimp SJ, Nelson RN, 2010. Australian agriculture in a climate of change. In Jubb I, Holper P and Cai W (Eds) Managing Climate Change. CSIRO Publishing, Melbourne. pp 101-111.

Howden SM, Soussana JF, Tubiello FN, Chhetri N, Dunlop M, Meinke HM, 2007. Adapting agriculture to climate change. Proceedings of the National Academy of Sciences 104, 19691-19696.

IFAD, 2011. Rural Poverty Report 2011. New realities, new challenges: new opportunities for tomorrow's generation. International Fund for Agricultural Development (IFAD), Rome.

IPCC (Intergovernmental Panel on Climate Change), 2007. Climate Change 2007: Impacts, Adaptation and Vulnerability. Summary for policy makers. Online at www.ipcc.cg/SPM13apr07.pdf

IPCC (Intergovernmental Panel on Climate Change), 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [CB Field, V Barros, TF Stocker, D Qin, DJ Dokken, KL Ebi, MD Mastrandrea, KJ Mach, G-K Plattner, SK Allen, M Tignor, PM Midgley (eds)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.

Jakku E, Thorburn PJ, Mendham E, Marshall NA, Moon K, Howden SM, 2013. Learning the hard way: A case study of an agricultural company undertaking transformational adaptation to climate change. Climatic Change (submitted).

Jones PG, Thornton PK, 2003. The potential impacts of climate change in tropical agriculture: the case of maize in Africa and Latin America in 2055. Global Environmental Change 13, 51-59.

Karfakis P, Knowles M, Smulders M, Capaldo J, 2011. Effects of global warming on vulnerability to food insecurity in rural Nicaragua, ESA Working Paper No. 11-18, FAO, Rome.

Kandulu JM, Bryan BA, King D, Connor JD, 2012. Mitigating economic risk from climate variability in rain-fed agriculture through enterprise mix diversification. Ecological Economics 79, 105-112.

Kates RW, Travis WR, Wilbanks TJ, 2012. Transformational adaptation when incremental adaptations to climate change are insufficient. Proceedings National Academy of Sciences 109, 7156–7161.

Kok K, Rothman DS, Patel N, 2006. Multi-scale narratives from an IA perspective: Part I. European and Mediterranean scenario development. Futures 38(3), 261-284.

Kok K, van Vliet M, Bärlund I, Dubel A, Sendzimir J, 2011. Combining participative backcasting and exploratory scenario development: Experiences from the SCENES project. Technological Forecasting and Social Change 78(5), 835-851.

Kremen C, Miles A, 2012. Ecosystem services in biologically diversified versus conventional farming systems: benefits, externalities, and trade-offs. Ecology and Society 17(4): 40.

Laliberté E, Wells JA, DeClerck F, Metcalfe DJ, Catterall CP, Queiroz C, Aubin I, Bonser SP, Ding Y, Fraterrigo JM, McNamara S, Morgan JW, Merlos DS, Vesk PA, Mayfield MM, 2010. Land-use intensification reduces functional redundancy and response diversity in plant communities. Ecology Letters, 13: 76–86.

Lipper, L., Dutilly-Diane D., McCarthy N., 2010. Supplying Carbon Sequestration from West African Rangelands: Opportunities and Barriers. Rangeland Ecology and Management 63 (1) : 155-166.

Locatelli B, Sunderland T, Padoch C, Murdiyarso D, Verchot L, 2012. Forests. Pp 182-188 in: P Thornton, L Cramer L (eds), Impacts of climate change on the agricultural and aquatic systems and natural resources within the CGIAR's mandate. CCAFS Working Paper 23. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Copenhagen, Denmark.

Løvendal CR, Knowles M, 2005. Tomorrow's hunger: a framework for analysing vulnerability to food insecurity, ESA Working Paper No. 05-07, FAO, Rome.

Lybbert TJ, Barrett CB, Desta S, Coppock DL, 2004.Stochastic wealth dynamics and risk management among a poor population. The Economic Journal 114, 750–777.

Macintosh A, 2012. Coastal climate hazards and urban planning: how planning responses can lead to maladaptation. Mitigation and Adaptation Strategies for Global Change, DOI 10.1007/s11027-012-9406-2

Marx SM et al., 2007. Communication and mental processes: experiential and analytic processing of uncertain climate information. Global Environmental Change 17 (1), 47.

McCarthy, N., L. Lipper and G. Branca. 2011. Climate-Smart Agriculture: Smallholder Adoption and Implications for Climate Change Adaptation and Mitigation. MICCA Working paper, Nr. 4, Food and Agriculture Organization of the United Nations, Rome.

Meinzen-Dick, R., A. Knox, F. Place and B. Swallow (eds). 2002. Innovation in Natural Resource Management: The Role of Property Rights and Collective Action in Developing Countries. Baltimore, MD: Johns Hopkins University Press.

Miura K, Kanno H, Sakurai T, 2012. Rainfall shock and livestock transactions in rural Zambia: an empirical examination using high frequency panel data. Asian Historical Economics Conference, Kunitachi, Tokyo, 13-15 Sep, 2012.

Park SE, Marshall NA, Jakku E, Dowd AM, Howden SM, Mendham E, Fleming A, 2012. Informing adaptation responses to climate change through theories of transformation. Global Environmental Change 22, 115-126.

Patt AG, Schröter G, 2008. Perceptions of climate risk in Mozambique: Implications for the success of adaptation strategies. Global Environmental Change 18, 458-467.

Pelling M, High C, 2005. Understanding adaptation: What can social capital offer assessments of adaptive capacity? Global Environmental Change 15, 308–319.

Pelling M, High C, Dearing J, Smith D, 2008. Shadow spaces for social learning: a relational understanding of adaptive capacity to climate change within organisations. Environment and Planning A, 40, 867-884.

Popp A, Lotze-Campen H, Bodirsky B, 2010. Food consumption, diet shifts and associated non-CO_2 greenhouse gases from agricultural production. Global Environmental Change 20, 451–462.

Powlson DS, Whitmore AP, Goulding KWT, 2011. Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false. European Journal of Soil Science 62, 42-55.

Quiggin J, Horowitz J, 2003. Costs of adjustment to climate change. Australian Journal of Agricultural and Resource Economics 47, 429–446.

Ramirez-Villegas J, Challinor AC, Thornton PK, Jarvis A, 2013. Implications of regional improvement in global climate models for agricultural impacts research. Environmental Research Letters (submitted).

Reid R, Nkedianye D, Said M, Kaelo D, Neselle M, Makui O, Onetu L, Kiruswa S, Kamuaro NO, Kristjanson P, 2009. Evolution of models to support community and policy action with science: Balancing pastoral livelihoods and wildlife conservation in savannas of East Africa. Proceedings of the National Academy of Sciences.

Rickards L, Howden SM, 2012. Transformational adaptation: agriculture and climate change. Crop and Pasture Science 63, 240-250.

Ricketts TH, 2001. Conservation Biology and Biodiversity. eLS.

Rosegrant MW, Agcaoili-Sombilla M, Perez ND, 1995. Food Projections to 2020: Implications for Investment. International Food Policy Research Institute, Washington, DC.

Rufino MC, Thornton PK, Ng'ang'a SK, Mutie I, Jones PG, van Wijk MT, Herrero M, 2013. Transitions in agro-pastoralist systems of East Africa: impacts on food security and poverty. Global Change Biology (submitted).

Seo SN, 2012. Decision making under climate risks: an analysis of sub-Saharan farmers' adaptation behaviors. Wea. Climate Soc. 4, 285–299.

Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, McCarl B, Ogle S, O'Mara F, Rice C, Scholes B, Sirotenko O, Howden M, McAllister T, Pan G, Romanenkov V, Schneider U, Towprayoon S, Wattenbach M, Smith J, 2008. Greenhouse gas mitigation in agriculture. Phil. Trans. R. Soc. B 363, 789–813.

Sunderland TCH, 2011. Food security: Why is biodiversity important? International Forestry Review 13(3), 265–274.

Tall A, Mason SJ, van Aalst M, Suarez P, Ait-Chellouche Y, Diallo AA, Braman L, 2012. Using seasonal climate forecasts to guide disaster management: the Red Cross experience during the 2008 West Africa floods. International Journal of Geophysics doi:10.1155/2012/986016.

Thornton P, Cramer L (eds), 2012. Impacts of climate change on the agricultural and aquatic systems and natural resources within the CGIAR's mandate. CCAFS Working Paper 23. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Copenhagen, Denmark. Available online at: www.ccafs.cgiar.org

UNFCCC 2008 Challenges and opportunities for mitigation in the agricultural sector. Technical paper FCCC/TP/2008/8.2008 UNFCCC Bonn Germany

van Notten PWF, Rotmans J, van Asselt MBA, Rothman DS, 2003. An updated scenario typology. Futures 35(5), 423-443.

Vervoort J, Thornton PK, Kristjanson P, Förch W, Ericksen P, Kok K, Ingram JSI, Herrero M, Palazzo A, Helfgott A, Wilkinson A, Havlik P (2013). Food systems futures: towards adaptation pathways across multiple dimensions and levels. Global Environmental Change (submitted).

Warner K, Afifi T, Henry K, Rawe T, Smith C, Sherbinin AD, 2012. Where the rain falls: climate change, food and livelihood security and migration. An eight-country study to understand rainfall, food security and human mobility. United Nations University, Institute for Environment and Human Security.

Webb P, Coates J, Frongillo FA, Rogers BL, Swindale A, Bilinsky P, 2006. Measuring household food insecurity: why it is so important and yet so difficult to get right. Journal of Nutrition 136, 1404-1408.

Wilkinson A, Eidinow E, 2008. Evolving practices in environmental scenarios: a new scenario typology. Environmental Research Letters 3(4), 045017.

Willows R, Connell R (eds), 2003. Climate Adaptation: Risk, Uncertainty and Decision-Making. UKCIP, Oxford.

World Bank, 2010. World Development Report 2010: Development and Climate Change. World Bank, Washington, DC.

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

World Food Programme, 2009. Emergency Food Security Assessment Handbook - second edition. United Nations World Food Programme, Rome.

Ziervogel G, Bharwani S, Downing TE, 2006. Adapting to climate variability: Pumpkins, people, and policy. Natural Resources Forum 30, 294-305.

Zomer RJ, Trabucco A, Coe R, Place F, 2009. Trees on farm: analysis of global extent and geographical patterns of agroforestry. ICRAF Working Paper no. 89. Nairobi, Kenya: World Agroforestry Centre.