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Agriculture, Food Security and Climate Change: Outlook for Knowledge, Tools and Action

CLIMATE CHANGE
AGRICULTURE AND FOOD SECURITY

Agriculture, Food Security and Climate Change:

Outlook for Knowledge, Tools and Action

Background paper prepared for The Hague Conference on Agriculture, Food Security and Climate Change on behalf of the CGIAR by the Program on Climate Change, Agriculture and Food Security of the Consultative Group on International Agricultural Research (CGIAR) and the Earth System Science Partnership (ESSP).

Scope

This paper reviews the state of current scientific knowledge on the links between climate change, agriculture and food security, in terms of anticipating impacts, managing climate variability and risks, accelerating adaptation to progressive climate change, and mitigating greenhouse gas emissions from the agricultural sector.

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Front cover photo

Following the chayote market chain in Hua Bin province, NW Vietnam.

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Summary

Agriculture and food security are key sectors for intervention under climate change. Agricultural production is highly vulnerable even to 2C (low-end) predictions for global mean temperatures in 2100, with major implications for rural poverty and for both rural and urban food security. Agriculture also presents untapped opportunities for mitigation, given the large land area under crops and rangeland, and the additional mitigation potential of aquaculture. This paper presents a summary of current scientific knowledge on the impacts of climate change on farming and food systems, and on the implications for adaptation and mitigation. Many of the trends and impacts are highly uncertain at a range of spatial and temporal scales; we need significant advances in predicting how climate variability and change will affect future food security. Despite these uncertainties, it is clear that the magnitude and rate of projected changes will require adaptation. Actions towards adaptation fall into two broad overlapping areas: (1) better management of agricultural risks associated with increasing climate variability and extreme events, for example improved climate information services and safety nets, and (2) accelerated adaptation to progressive climate change over decadal time scales, for example integrated packages of technology, agronomy and policy options for farmers and food systems. Maximization of agriculture's mitigation potential will require, among others, investments in technological innovation and agricultural intensification linked to increased efficiency of inputs, and creation of incentives and monitoring systems that are inclusive of smallholder farmers. The challenges posed by climate change to agriculture and food security require a holistic and strategic approach to linking knowledge with action. Key elements of this are greater interactions between decision-makers and researchers in all sectors, greater collaboration among climate, agriculture and food security communities, and consideration of interdependencies across whole food systems and landscapes. Food systems faced with climate change need urgent action in spite of uncertainties.

Introduction: meeting food demand in the face of climate change

Recent decades have seen global food production increasing in line with – and sometimes ahead of – demand. However, FAO projects that demand for cereals will increase by 70% by 2050, and will double in many low-income countries (FAO, 2006). Increasing demand for food is an outcome both of larger populations and higher per capita consumption among communities with growing incomes, particularly in Asia. Supply-side drivers include efficiency gains associated with vertical integration in industrial food supply chains (Reardon et al., 2004). To meet higher demand, food production is obviously of major importance. But poor households' inability to secure food through markets and non-market channels may limit food security even where food is globally abundant (Barrett, 2010). For those who rely on subsistence agriculture, food security is strongly dependent on local food availability, but for the majority who exchange cash, other commodities or labor for food, the access component is of critical importance, especially in relation to dietary diversity and nutrition. The impacts of climate change on food security therefore should consider both direct impacts on local food production and also the fuller set of interactions with the whole food system (Ericksen, 2009; Ingram, 2009; Liverman and Kapadia, 2010).

Despite considerable increase in global food production over the last few decades, the world's efforts to meet the Millennium Development Goal of reducing hunger by half by 2015 appears to be beyond reach. In fact, the number of people suffering from chronic hunger has increased from under 800 million in 1996 to over a billion according to FAO's most recent estimate in 2009 (FAO, 2009a). Most of the world's hungry are in South Asia and sub-Saharan Africa. These regions have large rural populations, widespread poverty and extensive areas of low agricultural productivity due to steadily degrading resource bases, weak markets and high climatic risks. Farmers and landless laborers dependent on rainfed agriculture are particularly vulnerable due to high seasonal variability in rainfall, and endemic poverty forcing them to avoid risks. Climate change is of particular significance for these countries, which already grapple with global and regional environmental changes (Aggarwal et al., 2004; Cook-Anderson, 2009; Toulmin, 2009) and significant interannual variability in climate (Arndt and Bacau, 2000; Haile, 2005). For example, changes in the mean and variability of climate will affect the hydrological cycle and crop production (Easterling et al., 2007) and land degradation (Sivakumar and Ndiang'ui, 2007). In recent times, food insecurity has increased in several such regions due to competing claims for land, water, labor, and capital, leading to more pressure to improve production per unit of land. Rapid urbanization and industrialization in South Asia, for example, has taken away from agriculture some very productive lands and good quality irrigation water (see e.g. Fazal, 2000).

Agriculture is highly sensitive to climate change. Even a 2C rise in global mean temperatures by 2100, in the range of the IPCC low emissions (B1) scenario, will destabilize current farming systems (Easterling et al., 2007). Climate change has the potential to transform food production, especially the patterns and productivity of crop, livestock and fishery systems, and to reconfigure food distribution, markets and access (Nelson et al., 2009). The adaptive capacity of rural and urban communities confronted by economic and social shocks and changes is enormous, but needs ongoing, robust support (Adger et al. 2007). Climate change will bring further difficulties to millions of people for whom achieving food security is already problematic, and is perhaps humanity's most pressing challenge as we seek to nourish nine billion people by 2050 (Godfray et al., 2010).

Anticipating impacts of climate change on agriculture and food security

Projections of climate change are inherently uncertain, due to the natural variability in the climate system, imperfect ability to model the atmosphere's response to any given emissions scenario, difficulties in evaluating appropriate methods to increase the temporal and spatial resolution of outputs from relatively coarse climate models, and the range of possible future emissions (see e.g. Challinor et al., 2009a).

These uncertainties are compounded by the paucity and unreliability of basic information related to agricultural production. Land-based observation and data collection systems in parts of the world have been in decline for decades. This affects the most basic data: weather data, land-use data, and crop and livestock distribution data, for example. Estimates of the cropland extent in Africa range from about 1 to more than 6 million km2, the value depending on choice of satellite-derived product (Fritz et al., 2010). The uncertainty in such basic information as which crops are grown where, and how much of them there is, adds considerable difficulty to the quantification and evaluation of impacts and adaptation options. Another key gap is existence of data, tools and models at spatial and temporal scales appropriate to decision-making. Production impacts are often aggregated over large areas such as the country or region, and this can hide considerable heterogeneity in climatic conditions and agricultural production (Jones and Thornton, 2003). Nonetheless, as outlined below, scientific knowledge is improving, with growing certainty around major trends, and emerging approaches to improve data and tools for decision-making.

Estimating trends in impacts on farming and food systems

The potential impacts of climate change on agricultural production in different parts of the world have been assessed in numerous studies and reviewed in successive assessment reports of the IPCC (2007). Ranges for major crops depend on the region under study, the methods and models used, and the emission scenarios simulated, and, as noted above, there is considerable uncertainty about such estimates (Challinor et al., 2007). Nevertheless, most studies indicate that agriculture in the tropics is likely to be severely affected in the coming decades by climate change. Some of the key impacts on farming and food systems are noted below.

Crop yields: There has been much progress in recent years in combining climate models with crop models in order to understand and project climate impacts (see review by Challinor et al., 2009b). In spite of the inherent uncertainties, robust responses of yield to climate change have been found using both empirical (e.g. Schlenker and Roberts, 2009) and process-based crop models (e.g. Challinor and Wheeler, 2008). For example, uncertainty in rainfall is not always a factor that limits the predictability of yield; temperature may be more important in a number of cases (e.g. Thornton et al., 2009; Lobell and Burke, 2008).

Livestock: Future impacts of climate change on livestock production are likely to be both direct, for example productivity losses (physiological stress) owing to temperature increases, and indirect, for example changes in the availability, quality and prices of inputs such as fodder, energy, disease management, housing and water (Thornton, 2010).

Fish: The distribution and population sizes of marine fish species are already affected by changes in sea temperature (e.g. Perry et al., 2005). Climate change will affect all dimensions of food security of fishers due to its impact on habitats, stocks and distribution of key fish species (Cochrane et al., 2009). Projected changes in the variability and seasonality of climate will also impact aquaculture through effects on growth rates and stability of domesticated fish populations.

Biodiversity: The impacts of climate change on the structure and function of plant and animal communities are widely demonstrated for terrestrial, freshwater and marine ecosystems (Walther et al., 2002; Parmesan, 2006). Changes in species distributions, phenology and ecological interactions will have impacts, for example, on pollination, invasions of agricultural systems by weeds and locations of major marine fishing grounds.

Pests and diseases: There is growing evidence that climatic variations and change are already influencing the distribution and virulence of crop pests and diseases, but the interactions between crops, pests and pathogens are complex and poorly understood in the context of climate change (Gregory et al., 2009). New equilibria in crop-pest-pesticide interactions will be established with consequences for food security. Climate change will also have significant impacts on the emergence, spread and distribution of livestock diseases through various pathways (Baylis and Githeko, 2006).

Carbon fertilization: There is ongoing debate about the impacts of carbon fertilization on plants and yields, and how changing ozone concentrations may interact with carbon dioxide effects and with other biotic and abiotic stresses (Challinor et al., 2009b). Impacts will also be felt on grassland productivity and species composition and dynamics, resulting in changes in animal diets and possibly reduced nutrient availability for animals (Thornton et al., 2009).

Irrigation: Climate change will impact the delivery and effectiveness of irrigation (Kundzewicz et al., 2007). The predicted increase in precipitation variability, coupled with higher evapotranspiration under hotter mean temperatures, implies longer drought periods and would therefore lead to an increase in irrigation requirements, even if total precipitation during the growing season remained constant.

Food storage and distribution: Climatic fluctuations are known to affect post-harvest losses and food safety during storage, for example by causing changes in populations of aflatoxin-producing fungi (Cotty and Jaime-Garcia, 2007). It is anticipated that more frequent extreme weather events under climate change will damage infrastructure, with detrimental impacts on food storage and distribution, to which the poor will be most vulnerable (Costello et al., 2009).

Food accessibility and utilization: Nelson et al. (2009) used economic modeling to predict that prices of most cereals will rise significantly due to climatic changes leading to a fall in consumption and hence decreased calorie availability and increased child malnutrition. At the same time, there are reports indicating that the nutritional value of food, especially cereals, may also be affected by climate change (Ziska et al., 1997; Hesman 2002; Nagarajan et al. 2010). Climate change will also affect the ability of individuals to use food effectively by altering the conditions for food safety and changing the disease pressure from vector, water, and food-borne diseases (Schmidhuber and Tubiello, 2007).

Improving the knowledge system: databases and models

Technology is being brought to bear to improve the quality and accessibility of data on agriculture under climate change. Advances include better remote sensing of weather information (including prospects to backfill missing daily weather data from historical records), validation of different land-use products using Wikis and Google Earth ("crowsourcing": see www.geo-wiki.org, for instance), and dissemination of information using mobile phone technology, to name just a few. But many of these things need to complement land-based observations, not substitute for them. A similar situation exists with respect to germplasm data; specific information on the response of crops to weather and climate is often not collected, but it could be with relatively modest additional effort.

New approaches are emerging to tailor agricultural climate-impact predictions to the needs of decision-makers at household, district and national levels. One example is the Agricultural Model Intercomparison and Improvement Project (AgMIP), based at Columbia University, a highly distributed climate-scenario simulation activity for historical model comparison and for future climate change conditions. AgMIP is being designed on the basis of the participation of multiple crop, livestock and world agricultural trade modeling groups around the world, with the goals of improving the characterization of food security due to climate change and to enhance adaptive capacity in both low-income and high-income countries. A second example is EQUIP (End-to-end Quantification of Uncertainty for Impacts Prediction, www.equip.leeds.ac.uk), a consortium project bringing the UK climate modeling, statistical modeling, and impacts communities together to work on developing risk-based prediction for decision making in the face of climate variability and change.

There are parallels between the situation for agricultural impacts modeling and the data needed to run them. Data are needed not only as input for modeling and scenario analysis, but also for characterization of food production systems in target sites, monitoring, and impact assessment, for example. There have been considerable improvements in recent years with regard to data availability. There are now large holdings of publicly available spatial and other data concerning natural resources, such as the Consortium for Spatial Information initiative of the Consultative Group for International Agricultural Research (www.cgiar-csi.org) and HarvestChoice (www.harvestchoice.org), for example. The International Household Survey Network (www.ihsn.org) is doing the same for household-level sample survey data, and is improving the availability, accessibility and quality of survey data in low-income countries, and encouraging their analysis and use. Sachs et al. (2010) recently called for a global monitoring system of agricultural practices and technologies, a database that would undoubtedly aid countries in strategically deploying the most promising technological adaptation options.

A major challenge for the research community and policymakers is to understand not only the impacts, but also the interactions among components of the farming system (see e.g. Tubiello et al., 2007) and the food system (Ericksen, 2009). While an impact-based perspective suggests that increasing interactions results in increasing uncertainty (Challinor, 2009), we also know that adaptive strategies will, even in the absence of intervention, reduce the range of plausible futures (Morton, 2007). Farmers will do all they can to prevent negative impacts. This fact alone may help to improve prediction in the face of uncertainty as it reduces the range of possible futures. However, the extent to which adaptation will reduce uncertainty will vary according to the particular situation, so that the nature of adaptation remains one of the key uncertainties in anticipating impacts of climate change on agriculture and food security.

Modeling approaches are beginning to provide policy guidance based on linking climate models, crop models and economic implications (Lobell et al., 2008; Nelson et al., 2009). Broader frameworks could consider the interactions of different technical and policy sectors, thus addressing the issues outlined above. For example, agricultural intensification for the sole purpose of increased food production, or exclusively for climate change mitigation, will not create sustainable agricultural landscapes. Research must also support institutional learning, recognizing the potential threats that change presents to people's livelihoods, particularly those in already precarious situations. Increased institutional capacity would allow for the development of adaptation and mitigation options that go beyond sector-specific management and lead to more systemic changes in resource management and allocation.

Managing climate variability and risk

Due to the natural variability of the climate system, anthropogenic climate change will be experienced largely as shifts in the frequency and magnitude of extreme events (Karl et al., 2008). Since many of the projected impacts of climate change are amplifications of the substantial challenges that climate variability already imposes on agriculture, particularly for smallholder rainfed farming systems in the tropical and sub-tropical drylands, better managing the risks associated with climate variability provides an immediate opportunity to build resilience to future climate change. Climate shocks such as drought, flooding or heat waves lead not only to loss of life, but also long-term loss of livelihood through loss of productive assets, impaired health and destroyed infrastructure (McPeak and Barrett, 2001; Dercon, 2004; Carter et al., 2007). The uncertainty imposed by climate variability is a disincentive to investment in improved agricultural technology and market opportunities, prompting the risk-averse farmer to favor precautionary strategies that buffer against climatic extremes over activities that are more profitable on average (surveyed in Barrett et al., 2007; Hansen et al., 2010). Apart from effective intervention, projected increases in climate variability can be expected to intensify the cycle of poverty, vulnerability and dependence on external assistance. A comprehensive strategy for adapting agriculture and food systems to a changing climate must therefore exploit the range of promising strategies for managing current climate-related risk.

Seasonal forecasts for adaptive management

Interaction between the atmosphere and the oceans provides the basis for forecasting climate conditions several months in advance. Seasonal climate forecasts, in principle, provide opportunity for farmers to adopt improved technology, intensify production, replenish soil nutrients and invest in more profitable enterprises when climatic conditions are favorable; and to more effectively protect their families and farms against the long-term consequences of adverse extremes. Research with smallholder farmers in low-income countries reveals a high level of interest and a range of promising management responses, but also highlights widespread communication failure (Hansen et al., 2010). Furthermore there is a mismatch between farmers' needs and the scale, content, format, or accuracy of available information products and services. These factors have limited the widespread use of seasonal forecasts among smallholder farmers. Adoption rates and reported benefits have been moderately high in pilot projects that have sought to overcome some of the communication barriers (Huda et al., 2004; Patt et al., 2005; Meinke et al., 2006; Roncoli et al., 2009).

Index-based insurance

Index insurance is an innovation that triggers payouts based on a meteorological index (e.g. rainfall or modeled water stress) that is correlated with agricultural losses, rather than observed losses. Basing payouts on an objectively measured index overcomes problems with moral hazard, adverse selection and the high cost of verifying losses (Skees and Enkh-Amgalan, 2002; Hess and Syroka, 2005; Barrett et al., 2007). Basis risk – the gap between an insured index and the risk it is meant to target – is regarded as the price paid for removing moral hazard, adverse selection and their resulting transaction costs as barriers to insuring vulnerable farmers against climate-related risk. Because it avoids the key problems that make traditional crop insurance unviable in most low-income countries, recent innovations have prompted a resurgence of interest in managing risk for smallholder agriculture through insurance. Recent reviews of index insurance initiatives targeting agriculture in low-income countries (Barrett et al., 2007; Hellmuth et al., 2009; Hazell et al., 2010) emphasize the need to develop a framework for targeting particular index insurance products to particular agricultural systems, build capacity to manage index insurance in the private sector, bundle insurance within broader suites of services, and develop indices that reduce basis risk particular where meteorological data are sparse.

Managing climate-related risk through the food system

The actions that governments and aid organizations take in response to climate shocks can have major impacts on farmers and local agricultural markets. Climate-driven price fluctuations can lead to acute food insecurity for the relatively poor who spend most of their incomes on food. Using climate-based forecasts of food production to better manage trade and stabilize prices, offers considerable potential benefits to both agricultural producers and consumers (Arndt and Bacou, 2000; Arndt et al., 2003; Hallstrom, 2004; Hill et al., 2004). Assistance, particularly food aid, in response to a major food crisis can have complex impacts on farmers and on agricultural markets (Barrett, 2002; Abdulai et al., 2004).

Assistance can protect productive assets, foster investment and intensification through its insurance effect, and stimulate agricultural value chain development; but can contribute to price fluctuations, disincentives to agricultural production and market development, and a cycle of dependency of poorly targeted and managed. Although waiting for verifiable consumption or health impacts before initiating action may improve targeting, the resulting delay can greatly increase the cost of delivering assistance, and the long-term livelihood impacts of the crisis (Broad and Agrawala, 2000; Haile, 2005; Barrett et al., 2007). Improving the lead-time and accuracy of early warning information provides an opportunity to support more timely interventions.

Climate information services

Several of the promising opportunities to manage agricultural risk depend on climate information, and have not been fully exploited, in part because of gaps in existing climate information services. The gaps appear to be widespread globally. A multi-stakeholder assessment of the use of climate information in Africa describes inadequate use of climate information, across sectors and from local to policy levels (with a few noteworthy exceptions), relative to the scale of the development challenge (IRI, 2006). It attributed the substantial gap in the provision and use of climate information to "market atrophy" associated with long-term ineffective demand by development practitioners and inadequate supply of relevant climate information services. Positive responses to this gap include the Regional Climate Outlook Forums (RCOFS), which bring national meteorological services and a set of users from a region together to produce authoritative consensus seasonal climate forecasts, and discuss their potential application (Dilley, 2001).

Accelerated adaptation to progressive climate change

Progressive climate change, which refers to long-term changes in the baseline climate (i.e. changes in absolute temperatures and shifts in rainfall regimes) over periods of decades, presents the overarching major challenge to agricultural and food systems in terms of both policy and science. The key question for both food security and the agricultural economy is whether the food system can keep pace with growing demand in the face of climate and other drivers (Hazell and Wood, 2008). In many cases, this is unlikely; even without climate change, FAO predicts a need for increased cereal production in 2050 in the range of 70% to meet growing population sizes and dietary shifts (FAO, 2006).

The major challenge is therefore to enable accelerated adaptation without threatening sensitive livelihood systems as they strive to cope with stress. Accomplishing this task requires a multi-pronged strategy: analysis of farming and food systems, learning from community-based approaches, generation and use of new technologies, changes in agricultural and food supply practices including diversification of production systems, improved institutional settings, enabling policies, and infrastructural improvements, and above all a greater understanding of what is entailed in increasing adaptive capacity (Agrawal and Perrin, 2008; Tubiello et al., 2008). Some of these have a good track record. For example, germplasm improvement, improved management of crops, livestock, aquaculture and natural resources, and enhanced agrobiodiversity have all been shown to decrease susceptibility to individual stresses, and therefore constitute important tools for adapting to progressive climate change (Jackson et al., 2007). Nonetheless, significant knowledge gaps exist as to what adaptations options are available, what their likely benefits or costs are, where and when they should be deployed, and what the learning processes are that can support widespread change under uncertainty.

Adaptation can occur at multiple levels, from changed agricultural practices (e.g., staggering the crop calendar), to varietal change, to substitution or diversification, to moving out of crop farming, livestock rearing or aquaculture altogether. Many options that are technologically, economically and socially feasible are now emerging, some of which are outlined below (and covered in more detail in the background paper for this conference prepared by FAO). Options for technology, farming systems and policies will need to be packaged effectively to provide meaningful adaptation options for policy makers, food producers and consumers.

Technology development

Overcoming abiotic stresses in crops through crop breeding has proven to be an effective means of increasing food production (Evenson and Gollin, 2003), and arguably mitigating climate change effects (Burney et al. 2010). There is also substantial biological potential for increasing crop yields through conventional crop breeding (Ortiz et al., 2008) and the development of transgenic crops supported by biotechnology (Godfray et al., 2010). Investment in crop improvement to address specific characteristics of a progressively changing climate (e.g. heat, drought, waterlogging, pest resistance) is therefore an important component of any global effort to adapt farming systems. Targeting this investment effectively requires understanding the circumstances under which different abiotic stresses dominate (e.g. Thornton et al., 2009; Challinor and Wheeler, 2008) and matching crops to future climates in a way that accounts for uncertainties (e.g. Challinor et al., 2009c).

Better agricultural practices

Today's farming systems are adapted, to the extent possible given resource endowments, to the current climate conditions they experience, yet we know little about how well they will stand up to progressive climate change particularly as they come under increasing pressure from other global drivers. Many broad-scale analyses identify regions and crops that will be sensitive to progressive climate change (Jones and

Thornton, 2003; Parry et al., 2007; Jarvis et al., 2008; Lobell et al., 2008), but there is sparse scientific knowledge as to how current farming systems can adapt, and which current farming systems and agricultural practices will enable adaptation. As climates effectively migrate, the transfer of best practices and technology from one site to the next will be crucial. Many of these are grounded in local knowledge. Candidate adaptation practices include agronomic innovations, planting strategies, improved livestock and fish management systems, pest and disease management, diversification of agriculture and livelihoods, and enhancement of agrobiodiversity (Easterling et al., 2007). The diversity of traits and characteristics among existing varieties of agricultural biodiversity (both inter- and intra-specific) provide enormous potential for adaptation to progressive climate change (Lane and Jarvis, 2007).

Enabling policies in food systems

Significant opportunities exist for national and sub-national policies that help enable adaptation at the community and household level. For example, policies that improve access and rights to water through investments in storage facilities or community-managed irrigation systems could aid rural communities in overcoming short- or long-term periods of drought (IWMI, 2009). The development of communal plans and strategies, such as pooling of financial resources or food storage facilities, may also prove invaluable. At the national level, concrete policy options include subsidies and incentives for crop substitution or expensive farming inputs (e.g. agrochemicals, bovine vaccines), as well as investment plans for improved infrastructure for food systems (e.g. transport). Public and private sectors and civil society organizations must work together to ensure that adaptation plans and strategies are coordinated through value chain and food systems. For example, since climate change will likely lead to extreme seasonal or annual production shocks, and countries have historically responded by restricting trade or pursuing large purchases in international markets (e.g. Chinese rice in 2008, Russian wheat in 2010), global strategies may be necessary to address agricultural price volatility (Battisti and Naylor, 2009) and to manage impacts such as large-scale land acquisition for food production for foreign markets (Cotula and Vermeulen, 2009). Under uncertain and highly dynamic changes in food systems, there is a considerable risk of conflicting policies and investments contributing to maladaptation.

Mitigating greenhouse gas emissions in agriculture

In 2005 agriculture contributed an estimated 10-12% of total anthropogenic emissions of greenhouse gases (GHGs). Reducing N_2O and CH_4 emissions, increasing C sequestration, or avoiding emissions through use of biomass for fuels or reduced land clearing are technical options to reduce emissions (Smith et al., 2007a). Global climate mitigation by agriculture for the period 2015–2020 could achieve approximately 1000 Mt CO_2-eq. below the "business-as-usual" scenario through 10% reductions in greenhouse gas emissions in concert with similar levels of improvement in the substitution of fossil fuels by biomass energy. If deforestation through agricultural expansion were reduced by 10% for the period 2015–2020 through agricultural development pathways that involve intensification, about a further 500 Mt CO_2-eq. could be stored (Smith et al., 2008).

Clearly, changes in farming practices can help reduce climate change, but whether society can also meet projected food needs under mitigation regimes remains unclear. Four issues underpin the joint achievement of food security and climate change mitigation: (a) the opportunities for sustainably intensifying agricultural production and avoiding conversion of high carbon landscapes, (b) the technical compatibility of food production and measures that reduce or sequester GHGs, (c) the need for inexpensive, on-farm measurement and monitoring to test real GHG budgets, and (d) the economic feasibility of and incentives for changing farming practices without compromising investments in food security. Innovation and capacity building will be required in all four areas. We review these challenges briefly to inform agricultural investments and policy.

Agricultural intensification

Producing more crops from less land is the single most significant means of jointly achieving mitigation and food production in agriculture, assuming that the resulting "spared land" sequesters more carbon or emits fewer GHGs than farm land (Robertson et al., 2000). The crop area in low-income countries is expected to expand 2-49% (Balmford et al., 2005), and avoided land conversions in the humid tropics and tropical wetlands are the most critical for mitigation (Paustian et al., 1998). Agricultural intensification (or the increase of yields per unit land area) is widely assumed necessary to meet projected food needs, given current economic and dietary trends (Gregory et al., 2005), and yield gaps still exist for rice and maize (Tilman et al., 2002). Burney et al. (2010) demonstrated that increases in crop productivity from 1961 to 2005 helped to avoid up to 161 Gt of carbon emissions and were a relatively cost effective intervention for mitigation, despite use of inputs that increased emissions. Similarly, Vlek et al. (2004) found that an increase of 20% of fertilizer on rice, wheat, and maize could take almost 23 million hectares out of cultivation without changing production.

But this "land sparing" effect of intensification is uneven in practice and requires policies and price incentives to strengthen its impacts (Angelsen and Kaimowitz, 2001). Investing in agricultural technologies to increase yields may have perverse effects, especially where demand for increased production is increasing, due for instance to population or income growth. Analyzing 961 agricultural sectors in 161 countries from 1970 to 2005 for 10 major crops, Rudel et al. (2009) found no paired relationship between crop yields and area cultivated. The authors observed that farmers tended to expand land areas with intensification, i.e. economic efficiency led to expansion not curtailment of the activity. Exceptions occurred in mostly temperate countries with conservation set-aside programs or where price supports were eliminated and imported grains substituted for local production. Similarly, Ewers et al. (2009), studying 23 crops from 1979 to 1999 in 124 countries, found that even where the per capita area of staple crops had declined slightly, the cultivation of non-staple crops often simultaneously increased, resulted in an expanded area of cultivated land. Declines were more likely where in low-income countries with existing large food supplies.

Intensification in the future will require more attention to the efficiency of inputs and their environmental costs (Matson et al., 1997; Gregory et al., 2002). Increased use of fertilizers, pesticides and fossil fuel energy as currently practiced may not be possible or desirable over the long term.. More efficient use of these inputs, more sustainable alternatives and breeding for efficiency will be required to reduce the carbon intensity (emissions per unit yield) of products, as well as reduce land areas and inputs that damage environmental health. (Tilman et al., 2002). For example, mid-term drainage and intermittent irrigation of wet rice systems appears to reduce methane emissions by more than 40%, with minimal impact on yields (Wassman et al., 2009). Precision fertilizer can result in higher yields per emissions. Agricultural intensification will require appropriate institutional and policy support to create environmental benefits as well as increases in crop yields for smallholders (Pretty et al., 2003).

Technical compatibility

The other major option is to farm in ways that reduce GHG emissions or sequester more carbon without reducing food production. The potential trade-offs and synergies between mitigation practices and food production have been well reviewed (Lipper et al., 2009). Enhancement of soil carbon through for example conservation tillage or management of crop residues (Lal 2004), and to a lesser extent agroforestry (Verchot et al., 2007) or high productive grassland restoration (Smith et al., 2008; Olsson and Ardo, 2002; Batjes, 2004) are expected to have significant impacts on climate without compromising food production. These technologies do have a saturation or maximum point though that will occur in 50-100 years beyond which further sequestration is not possible (Paustian et al. 1998). Enhancing soil carbon also has important environmental benefits in terms of water storage, soil biodiversity, and soil aggregate stability. Sustainable agricultural land management (SALM) is an umbrella term for practices expected to enhance productivity and mitigation. SALM should also enhance agroecosystem resilience and adaptation to climate change (Smith and Oleson, 2010). Soil carbon sequestration is estimated to have the highest economic mitigation potential (Smith et al., 2007a), although incentives for its adoption, as well as permanence, variability and monitoring need to be addressed. FAO has shown that areas with large food insecure populations also tend to have soils lacking carbon (FAO, 2009b), suggesting that these locations would be suitable for SALM approaches to mitigation.

Measurement and monitoring

Since mitigation measures can potentially affect the cost, yields and sustainability of food, getting more precise estimates of mitigation and its related effects on food systems (Ericksen, 2009) is essential to assessing actual trade-offs. Mitigation potentials remain uncertain as most have been estimated through highly aggregated data (Paustian et al., 2004). Greenhouse gas budgets at the local and national levels for specific farm practices, foods and landscapes are often unavailable, especially in low-income countries. Full accounting of GHGs across all land uses will be necessary to account for leakage and monitor the impacts of intensification. Measurement technologies are well known, but monitoring of indicators and life cycle analysis can be expensive and interactions among farm practices difficult to assess. Current efforts of the Global Research Alliance are focused on research to measure and enhance mitigation in industrialized agriculture. Similar efforts are needed for smallholder farming in low-income countries, which are major contributors to emissions. FAO's Mitigation of Climate Change in Agriculture (MICCA) project, the Cool Farm Tool assessments of the Sustainable Food Lab, GEF's Carbon Benefits Project, the UK-China Sustainable Agriculture Innovation Network (SAIN), IFPRI's Climate Change Mitigation and High Value Food Crops project, and CCAFS are programs that will contribute toward this aim. Comparable measurements are needed both for carbon intensity (CO_2-eq. per unit food or per tons yield) and land–based emissions (CO_2-eq. ha^{-1}) to compare efficiencies and aggregate among like units.

Economic feasibility and incentives

Knowledge of the economic feasibility of agricultural mitigation and its links to investments in food security need improvement (Cannell, 2003). Smith et al. (2007b) estimate that less than 35% of the total biophysical potential for agricultural mitigation is likely to be achieved by 2030 due to economic constraints. Measurement costs and the transactions costs associated with start-up costs and aggregating among numerous smallholders are presently major barriers that require innovation. The uncertainty of carbon prices and the policies supporting them also presently limit the technical potential for implementing mitigation.

Farmers and others driving the expansion of cultivated areas will require incentives to undertake mitigation practices. Lessons should be gleaned from existing national schemes for payments for environmental services programs to farmers, such as those that exist in the European Union, Australia, Canada, Japan, Norway, Switzerland and US (Tilman et al., 2002). International agreements that enable agricultural GHG reductions to count towards countries' emissions reductions commitments could create an important policy incentive (Paustian et al., 2004). Understanding the potential for mitigation through alternative agricultural development pathways and the incentives driving them will be important for transforming agriculture towards more sustainable practices. Compliance with mitigation standards before receiving farm assistance, taxes on fertilizers or pesticides (or removal of subsidies), voluntary markets and consumer-related incentives related to labeling are all additional options for creating incentives (Tilman et al., 2002). The revenues generated by even moderate levels of agricultural mitigation (USD20 per t CO2) equivalent should yield USD30 billion in annual revenues that could also be used to encourage additional investments in mitigation or food (FAO 2009c).

Implications for policy support to GHG mitigation in the smallholder agricultural sector

Investments in technological innovation and agricultural intensification strategies should be linked to increased efficiency of inputs, and to comprehensive land use policies and payments for environmental services that discourage forest conversion and negative environmental impacts. Impacts on smallholders should be monitored. Investments should also be made in technical and institutional innovations that reduce the costs of mitigation and increase incentives for the implementation of mitigation. These investments would enhance the technical biophysical potential for reducing GHGs from agriculture. Incentives for sustainable agricultural land management (SALM) are also needed, either through government programs or voluntary market payments, targeting areas with high potential mitigation first for highest impact. Technical compatibilities need to be field-tested on farms.

Finally, developing a better understanding of the GHG budgets for specific mitigation practices on smallholder farms and landscapes and for food products, and developing simple, inexpensive monitoring techniques for use in low-income countries is a priority.

Linking science with policy and other actions

Knowledge must be linked with action – changes in policies, institutions, technologies and management strategies – if it is to help enhance food security and resilience to climate change. For example, national adaptation programs of action (NAPAs) are being developed in many countries by national ministries of environment with the support of the United Nation's Development Program (UNDP), but most are not based upon scientific evidence as to the range of relevant adaptation options and impacts in different environments, or of the critical role institutions play in future adaptation of rural livelihoods (Agrawal and Perrin, 2008). Reasons for the disconnect between science and policy may be that the knowledge most needed by policymakers and other action-oriented stakeholders is not given priority in research and development efforts, nor is communicating it in ways that best support decision making, management and policy (Cash and Buizer, 2005). Further issues with perceptions of untrustworthiness and political bias in scientific work (Clark and Holliday, 2006) are illustrated by the recent incident in which climate scientists' email conversations were hacked and sections selectively made available on the internet, leading to perceptions by some that the climate change evidence was rigged (Hickman and Randerson, 2009).

Credibility (perceived technical quality and authority of information), salience (perceived relevance to users' decisions) and legitimacy (perception that the information service seeks the user's best interest) have been proposed as prerequisites for successful use of climate information for agriculture (Cash and Buizer, 2005; Meinke et al., 2006; Crane et al., 2010). Credibility – in the sense of providing authoritative forecasts through national meteorological services in the face of multiple (and sometimes conflicting) information sources – was part of the rationale for the RCOFs (Dilley, 2001; Orlove and Tosteson, 1999). The climate community has invested in credibility through processes such as the Regional Climate Outlook Forums (Dilley, 2001). However, institutional arrangements that gave farmers and other agricultural stakeholders little influence over the design of products (at a cost to salience) and little ownership of the process (at a cost to legitimacy) may contribute to the gap between needed versus available climate information (Cash et al., 2006; Hansen et al., 2007). Giving farmers and other agricultural stakeholders a more effective voice in the design of climate information products and services can bridge this gap. Greater investment is also needed in the capacity of rural communities to access, interpret and act on climate-related information.

In short, climate change demands rethinking of how research is done – with primary emphasis on active integration with policy and implementation. New initiatives such as the program on Climate Change, Agriculture and Food Security (CCAFS) and ClimDev-Africa may re-invigorate how climate knowledge informs agricultural practice. What distinguishes many of these initiatives is their commitment to collaboration among partners from different sectors and backgrounds. Research into mechanisms to create influential knowledge suggests that it generally requires active collaborations between researchers and particular decision-makers, with trusted intermediaries or "boundary spanners" often playing a crucial integrative role (Agrawala et al., 2001, Cash et al., 2003).

The role of the private sector, and building public-private partnerships (and the challenges in doing so) is also increasingly recognized as important in supporting the kind of generation of knowledge in the agricultural sector that is needed to deal with food security and climate change challenges (Spielman et al., 2007). For example, 25 of the world's largest agrifood companies have created an integrated platform for sharing best practices (the Sustainable Agriculture Initiative; www.saiplatform.org), which is developing the Cool Farm Tool, described in an earlier section of this paper, among other activities. While private sector actions are not a substitute for public obligations, there are bountiful opportunities for private sector innovation to support adaptation and mitigation in the agricultural and food sectors (Forstater et al., 2009; UNEP, 2009).

Tools for linking knowledge with action are increasingly tested and applied by interdisciplinary, multi-organizational research-for-development teams (Kristjanson et al., 2009). Examples include participative mapping of impact pathways (Douthwaite et al., 2007; Reid et al., 2010), negotiation tools informed by research (van Noordwijk et al., 2001), social network analysis, innovation histories, cross-country analyses and game-theory modeling (Spielman et al., 2009). But there is much yet to discover about means to improve the links between knowledge and action, and, critically for climate change approaches, about the interactive links between science and policy. For example, political science analyses of policy making are not yet well utilized by climate change and food security communities. Efforts aimed at increasing the knowledge and capacities of farmers' organizations to innovate, along with strengthening of networks and alliances to support, document and share lessons on farmer-led innovation are also needed (Clark et al., 2010). Other needs include innovative engagement and communication strategies to ensure that scientific results inform international policy processes (e.g. UNFCCC), regional (e.g. adaptation funds) and national processes (e.g. NAPAs and NAMAs) – these different audiences will likely require different strategies to elicit effective responses.

Conclusions: Appropriate research and action in the face of uncertainty and interdependence

Significant uncertainty exists regarding the direction and magnitude of climate change, which in turn leads to uncertainty in the realm of food production and its impact on food systems and food security across complex geographies and societies.

It remains to be seen whether uncertainty propagates, remains the same or reduces along the causal pathways and associated analysis from climate science through agriculture to human systems.

Research in agriculture, food security and climate change must continue to improve understanding of uncertainty, to allow more confident decision-making and allocation of limited resources towards new climatic futures.

Food systems faced with climate change need urgent action in spite of uncertainties. The urgency of climate change provides a new impetus for paradigms of integrated research, policy and action.

There is a pressing need to invest in databases and tools to inform policy and practice in the spheres of agricultural risk-management, adaptation and mitigation; these need to be co-developed with users.

Likewise, initiatives to develop capacity to tackle climate change impacts on farming and food must address not only scientific capacity but also the capacity of users to demand, interpret and apply scientific outputs effectively.

Decision-makers need not just a holistic view of the system but rather a strategic approach that focuses on key dependencies and processes. Some of the work outlined above demonstrates that this approach can work for well-defined subcomponents of the farming system, for example crop yield.

A key challenge in assuring future food security is to apply such approaches across the whole food system and across multi-purpose landscapes.

This calls for collaboration among researchers and practitioners from a range of backgrounds, sectors and disciplines.

Action will need to move ahead of knowledge, with decisions made and reviewed on the basis of emerging research and consensus.

This paper has provided a brief review of the state of knowledge in the key areas of managing climate variability and risks, accelerating adaptation to progressive climate change, mitigating greenhouse gas emissions from the agricultural sector, and generating relevant knowledge for policy. Major research questions for each of these areas are outlined below.

Managing climate variability and risks

- How effectively do rural communities manage climate-related risk, and which local strategies hold promise for transferring and upscaling?
- What combination of livelihood diversification, intensification, innovation and risk transfer has the best prospect for building resilience and reducing the long-term climate vulnerability of rural communities?
- What combination of new products, services, delivery mechanisms and institutional arrangements offers the best opportunity to deliver useful, equitable, transferable and scalable climate risk-management in rural areas?
- What is the feasibility and best strategy to use advanced information to target and initiate safety net interventions and responses to climate-related market fluctuations and emerging food crises?

Accelerated adaptation to progressive climate change

- How can information from global climate models and regional climate models be incorporated into support for adaptation processes that in agriculture and food systems are both location-specific yet robust enough to apply across the range of plausible climate futures?

- How can climate-driven shifts in the geographical domains of varieties, cultivars, wild relatives, pests and diseases, and beneficial soil biota be anticipated and best managed to protect food security, rural livelihoods and ecosystem services?

- Given rapid change in non-climatic drivers, what is the best approach for integrating individual technological, biodiversity management, livelihood, market adaptation and policy options into comprehensive local-level adaptation packages?

- How do social, cultural, economic and institutional factors mediate adaptation processes at the local level and how can these be mobilized to improve resilience?

Mitigating greenhouse gas emissions from the agricultural sector

- What are alternative trajectories for low carbon agricultural development and how can they be managed to secure food production while providing for livelihoods and food security?

- What technologies and management systems can deliver reduction of emissions and sequestration of greenhouse gases (GHGs) cost-effectively with maximum benefits to poverty alleviation, food security and environmental health at the landscape level?

- What is the GHG abatement potential, technical feasibility and economic feasibility of different agricultural mitigation practices among smallholders in low-income countries?

- What institutional arrangements and incentives can enable the poor, especially women, participate in the design of and gain better access to the benefits available through the trade of carbon and other GHGs?

Generating relevant knowledge for policy

- What are plausible futures for agriculture and food systems, encompassing interactions among changes in climate and other key drivers of agricultural systems and food security?

- What are the main factors causing vulnerability to climate change and climate variability among agricultural and food systems and the people who depend on them, and how may this vulnerability change in the future?

- What are the consequences of international, national and local policy and program options for improving environmental benefits, enhancing livelihoods and boosting food security in the face of a changing climate?

Actions taken over the next decade will be critical. Responses need to come quickly, faster than the pace of change in climate. Actions towards adaptation firstly entail better management of agricultural risks associated with increasing climate variability and extreme events, for example improved climate information services and better safety nets. Additionally, we need accelerated adaptation to deal with progressive climate change in the coming decades. Feeding nine billion people in 2050 requires transformation of agriculture – growing more food without exacerbating environmental and social problems under climate change. Maximization of agriculture's mitigation potential will require, among other interventions, investments in technological innovation and agricultural intensification linked to increased efficiency of inputs, and creation of incentives and monitoring systems that are inclusive of smallholder farmers. We need to integrate and apply the best and most promising approaches, tools and technologies. The involvement of farmers, policy-makers, the private sector and civil society in the research process is vital. Successful mitigation and adaptation will entail changes in individual behavior, technology, institutions, agricultural systems and socio-economic systems. These changes cannot be achieved without improving interactions between scientists and decision-makers at all levels of society.

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