Short Title: ***Integrated adaptation and mitigation framework***

Full Title: An integrated adaptation and mitigation framework for developing agricultural research: synergies and trade-offs

Authors: Andy Jarvis[1,2], Charlotte Lau[1,2], Simon Cook[2], Eva Wollenberg[2,3] , James Hansen[2,4], Osana Bonilla[1,2], Andy Challinor[2,5]

[1] International Center for Tropical Agriculture (CIAT). Km 17, Recta Cali-Palmira, Apartado Aéreo 6713, Cali, Colombia.

[2] CGIAR Program on Climate Change, Agriculture and Food Security.

[3] University of Vermont. 617 Main Street, Burlington, Vermont, 05405 , U.S.A.

[4] International Research Institute for Climate and Society, The Earth Institute, Columbia University, Palisades, N.Y, U.S.A.

[5] University of Leeds. Leeds LS2 9JT, United Kingdom.

Contact: Andy Jarvis, a.jarvis@cgiar.org.

International Centre for Tropical Agriculture (CIAT)

Km 17, Recta Cali-Palmira, Apartado Aéreo 6713. Cali, Colombia.

An integrated adaptation and mitigation framework for developing agricultural research: synergies and trade-offs

Andy Jarvis, Charlotte Lau, Simon Cook, Eva Wollenberg , James Hansen, Osana Bonilla, Andy Challinor

Abstract

Global food security is under threat by climate change, and the impacts fall disproportionately on resource-poor small producers. With the goal of making agricultural and food systems more climate-resilient, this paper presents an adaptation and mitigation framework. A road map for further agricultural research is proposed, based on the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). We propose a holistic, integrated approach that takes into account tradeoffs and feedbacks between interventions. We divide the agenda into four research areas, three tackling risk management, accelerated adaptation, and emissions mitigation, and the fourth facilitating adoption of research outputs. After reviewing specific technical, agronomic, and policy options for reducing climate change vulnerability, we acknowledge that science and good-faith recommendations do not necessarily translate into effective and timely actions. We therefore outline impediments to behavioural change and propose that future research overcomes these obstacles by linking the right institutions, instruments, and scientific outputs. Food security research must go beyond its focus on production to also examine food access and utilization issues. Finally, we conclude that urgent action is needed despite the uncertainties, trade-offs and challenges.

Introduction

The global environment currently supports nearly 7 billion people through a range of ecosystem services that include food production, water supply and sanitation. By 2050, the global population is projected to grow by another 2 to 4 billion (FAO, 2006), and with it will come greater stresses on the natural environment. The challenges of limited resources and food security are further complicated by climate change. Even beyond the hundreds of millions of small-scale farmers, livestock keepers, and fishermen whose livelihoods depend on continued food production, end consumers will feel the effects of food supply shortages and price shocks, as occurred in the recent East Asian rice crisis in 2008 (Balfour, 2008) and Russian grain crisis in 2010 (Economist, 2010).

Agricultural and food systems are complex and dynamic. Many may now face climate variability beyond the current 'coping range'. Increasingly frequent and intense extreme weather events, exacerbated by climatic variability within and between seasons, create stresses on agriculture. Longer-term changes heighten concerns for food security, particularly for populations reliant on smallholder rainfed farming systems in the drier (i.e., sub-humid to arid) tropics (Parry *et al.*, 2005; Easterling *et al.*, 2007). The Inter-governmental Panel on Climate Change (IPCC) anticipates with high confidence that projected longer-term changes in the climate baseline, i.e. increased average temperatures and changes in rainfall regimes, will have further and significant consequences for food and forestry production (IPCC, 2007).

The IPCC predicts an approximate 50 percent decrease in yields from rainfed agriculture by 2020 in some countries (Working Group II, 2007), while other studies show an aggregate yield decline of 10 percent by 2055 for smallholder rainfed maize in Sub-Saharan Africa, Central America, and South America, representing an economic loss of about US$2 billion each year (Jones and Thornton, 2003). Likewise, more than half of the Indo-Gangetic Plains (IGP), currently a major wheat producing area, may become too heat-stressed for the crop by 2050 (Ortiz *et al.*, 2008). In short, despite significant uncertainties in the science, there is an emerging consensus that global food security is under threat from climate change.

Smallholder and subsistence farmers, pastoralists and fisherfolk are likely to be vulnerable to these impacts. Furthermore, limited empirical evidence suggests that, in rainfed farming systems, the costs are disproportionately borne by the poor (Rosenzweig and Binswanger, 1993; Zimmerman and Carter, 2003). Agricultural researchers and rural development practitioners therefore need to develop strategies and frameworks to address climate change threats to food security. Strategies will include no-regret, win-win solutions that have the immediate benefits of higher incomes, improved livelihoods, better food security, and greater environmental health. However, other solutions will require careful analysis of trade-offs. The unprecedented speed and extremity of predicted changes will require tough decision-making, preparatory policies, and enabling incentives—employed in an environment of uncertainty and trade-offs.

This paper outlines an adaptation and mitigation framework for agriculture and food security in developing countries. The framework has been developed as the road map for further agricultural research through the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), a research for development collaboration between the Consultative Group of International Agricultural Research (CGIAR) and the Earth System Science Partnership (ESSP). As an overview, it places Climate Risk Management (CRM), the focus of this special edition in the broader, integrated context of what needs to be done to tackle the agricultural challenges of climate change.

An Adaptation and Mitigation Framework

A multi-pronged approach is required to address the challenges of climate variability and climate change to food security. Taking this into account, we propose an adaptation and mitigation framework based on four principles:

1. In the short term, we must address and manage risk due to climate variability and its effects on food security;
2. We must explore how climate risk management can then develop into longer term adaptation to changes in climate baselines;
3. We must exploit the potential for emissions mitigation and carbon sequestration in developing country agriculture, while acknowledging that mitigation should not compromise food security or economic development; and
4. Both adaptation and mitigation efforts feed back into the earth system hence benefits of, and trade-offs between, likely adaptation and mitigation actions must be analysed and considered together.

An adaptation and mitigation framework based on these principles is outlined in Figure 1. The framework is discussed overall in this section, and subsequent sections address the four primary research thrusts outlined.

The overall goal of the framework is to convert agricultural and food systems into resilient and sustainable structures capable of confronting global change at multiple spatial and temporal scales and reducing the impact of agriculture on climate change. To do so, we divide the agenda into four primary research thrusts, the first three of which focus directly on interventions on the ground and the last of which promotes uptake of research results to maximize impact. The proposed interventions must then be trialled and evaluated holistically, noting tradeoffs and feedbacks in terms of the three principle developmental and environmental goals: improved environmental health, improved rural livelihoods, and improved food security.

Interventions can be divided into three interacting categories—climate risk management, progressive adaptation, and mitigation of net emissions—between which exist synergies and trade-offs. The dividing line between climate risk management and progressive adaptation is largely temporal—i.e., climate risk management refers to short-term strategies to cope with impacts, which may be insufficient in dealing with climate change further down the line. The difference can also be one of scale, as often long-term adaptation requires larger, more systemic and transformational change. Drawing from distinct bodies of knowledge, these three research themes form the backbone of effective adaptive agriculture—identifying and developing the instruments, technologies, practices, partnerships, and integrated strategies necessary to prepare rural communities for a variable and changing climate.

The fourth research thrust, “Integration for Decision Making”, grounds science and analysis in the global policy environment, via engagements with rural communities, policy makers, and relevant institutions. Effective and sustained communication with stakeholders is critical to building understanding of opportunities and constraints, as well as to developing the capacity to diagnose vulnerabilities, identify appropriate interventions, and to assess their relative effectiveness.

Managing risk: the challenges of climate variability

In response to climate variability, risk-averse small producers often employ conservative coping strategies *ex-ante*—sacrificing appropriate investment, intensification and adoption of innovation to protect against the threat of shocks (reviewed in Barrett *et al.*, 2007; Hansen *et al.*, 2007)—and in turn causing rural poverty to persist. Moreover, despite hedging against risk, farmers are still exposed to uninsured climate shocks such as droughts or floods, whose damage to health, productive assets and infrastructure can affect livelihoods long after the stress has ceased (McPeak and Barrett, 2001; Dercon, 2004). Without effective intervention, projected increases in climate variability can be expected to intensify the cycle of poverty, natural resource degradation, vulnerability and dependence on external assistance. Managing current climate risk, the specific focus of this special edition, is therefore integral to a comprehensive strategy for adapting agriculture and food systems to a changing climate. Given pressing current development challenges and a 2015 deadline for the MDG targets, management of current climate risk also offers attractive win-win opportunities for developing countries to contribute to articulated immediate development priorities, while reducing vulnerability to a changing climate.

Climate risk management (CRM) is emerging as a promising framework for engaging climate in development. CRM includes systematic use of climate information in planning and decision making, climate-informed technologies that reduce vulnerability to climate variability, and climate-informed policy and market-based interventions that reduce risk to vulnerable rural populations. In doing so, it aims to address the full range of variability, balancing protection against climate-related hazards with efforts to capitalise on opportunities arising from more favourable climatic seasons. CRM also requires serious attention to the policy and institutional environment in which information is used and adaptations are made.

Where they are skillful, seasonal climate predictions appear to offer substantial potential to improve risk management, but seldom reach poor smallholder farmers in a usable form, i.e. within a comprehensive package of information and support (Vogel and O'Brien, 2006; Hansen *et al.*, 2006; Patt *et al.*, 2007; Hansen *et al.*, 2007, Hansen *et al*.,2011, this issue). If historical precedent is indicative, the potential benefits of such systems are enormous. In Mali, where the national meteorological service was launched some 25 years ago, farmers receive three-tiered information packages including seasonal forecasts, forecasts for the next 3 days, and 10-day bulletins with agriculture-specific information. Participating farmers have benefited from significantly higher yields and incomes of up to 80 percent more than non-participants (Moorhead, 2009). Such examples exemplify how better use of historic and monitored weather data, combined with agricultural simulation models (for example Dixit *et al*., 2011, Gathenya *et al*., 2011, Stern and Cooper, 2011, all this issue), can permit the *ex ante* quantification of climate-induced risk and give decision-makers the tools to prioritize the interventions with higher probabilities of success. Further research can also be done to monitor and predict the spread of pests and diseases affecting plants (see Farrow *et al*., 2011, this issue), livestock and humans.

Recent agricultural economics literature on poverty traps (see Barrett *et al.* 2001; McPeak and Barrett, 2001; Santos and Barrett, 2005; Carter and Barrett, 2006) describes bifurcated wealth dynamics: households fall into one of two different "clubs," separated by threshold lines above which asset accumulation occurs and below which a cycle of poverty reigns.

Poverty traps explain why climate variability more strongly impacts households in the lower, structurally poor club, both before and after weather shock. *Ex-ante*, risk aversion can minimize asset accumulation. *Ex-post*, the biophysical effects of the shock itself, as well as the coping mechanisms of farmers (e.g. liquidating assets to smooth consumption), can push vulnerable households back under the critical asset threshold and into the poverty trap (Barrett *et al.*, 2007).

As such, poverty traps demonstrate the need for providing:

1) Low-risk liquidity (e.g. certain microfinance programs) to those in the poverty trap , allowing poor households to accumulate assets, take advantage of returns to scale, and overcome minimum barriers to entry for creating added value (e.g. cheese derived from milk) (Barrett *et al.*, 2001), and

2) Risk transfer products (e.g., rainfall-indexed insurance) to all vulnerable populations to prevent households from slipping or falling further into the poverty trap (Santos and Barrett 2006).

These financial instruments can help farmers overcome long-standing information asymmetries and show promise for addressing risk-related constraints to adoption of new technologies, rural poverty reduction, and food security. The rapid resurgence of interest in such products is therefore justifiable, but important knowledge gaps regarding the logistics of implementation still exist (Barrett *et al.*, 2007).

Risk can also be reduced through non-financial means. There is substantial scope for using climate information to better target engineering projects (e.g., irrigation systems and flood-protective coastal walls); manage grain storage, trade and distribution (e.g., Arndt and Bacou, 2000; Hill *et al.*, 2004); and better target external assistance for emerging food crises (Haile, 2005). Research should address critical knowledge gaps related to: targeting, package design, institutional challenges to implementation at scale, managing basis risk, and implications of advance information. In all cases, investment in resources is necessary to test, improve and refine the proposed risk management approaches.

Adaptation to progressive climate change

Food systems naturally evolve and adapt, responding to short-term dynamics such as climate variability. In this way, many of the projected impacts of climate change are amplifications of the substantial challenges that climate variability already imposes. The risk management measures detailed above simply improve upon traditional knowledge and conventional adaptation strategies. However, the key challenge for both food security and the agricultural economy is to accelerate food system adaptation enough to anticipate and keep up with progressive climate change. Accomplishing this task requires a multi-pronged strategy: analysis of farming systems; generation and use of new technologies; and changes in agricultural practices including diversification of production systems, improved institutional settings, enabling policies, and infrastructural improvements (Tubiello *et al.* 2008; Beddington, 2010). In sum, accelerated adaptation requires larger, structural changes.

Future farming and food systems will have to be better adapted to a range of abiotic and biotic stresses to cope with the direct and indirect consequences of a progressively changing climate, e.g. higher temperatures, altered precipitation patterns and rising sea levels. Germplasm improvement, natural resource management, advanced agrichemicals and enhanced agro-biodiversity have a proven track record of decreasing susceptibility to individual stresses, and will offer increasingly important solutions for adapting to progressive climate change (Jackson *et al.*, 2007). However, technical innovations will not be sufficient on their own. Strengthening the adaptive capacities of farmers and other land users requires a variety of strategies ranging from altering the crop calendar to diversifying production systems, all of which must be reinforced by enabling institutional settings. Adaptive management to continually refine these strategies will be required, and can be supported by the predictive capacity of downscaled global climate models, e.g. forecasts on precipitation, coupled with more effective communication with end users.

Intensively managed cropping systems offer a variety of entry points to adjust to projected climate change (Aggarwal and Mall, 2002; Easterling *et al.*, 2003; Butt *et al.*, 2005; Travasso *et al.*, 2006; Challinor *et al.*, 2007, Howden *et al.*, 2007). Breeding and marker-assisted selection have been important mechanisms for achieving yield improvements for most crops as long as suitable megavarieties are available that can be used for introgressing improved genes (Bennett, 2003). In natural resource management, conservation agriculture offers resource-poor farmers a set of possible options to cope and adapt to climate change (Thomas *et al.,* 2007). Improved water management will represent the key adaptation strategy in both irrigated and dryland agriculture. Emphasis will also be given to crop production systems located in the delta regions, e.g. IGP mega-deltas, to sustain high production potentials under sea level rise (Wassmann and Dobermann, 2007).

Adaptation for livestock production include a variety of management options ranging from adjusted stocking rates to supplementary feeds, e.g. climate-tolerant legumes (Adger *et al.*, 2003; Howden *et al.* 2007). For pastoralists, however, adaptation options are very limited, and mobility is an important strategy to cope with climate variability. This will remain an important feature in the future (Oba, 2001), although mobility in many places may suffer because of other pressures such as population increase and land rights issues (see Ouma *et al*., 2011, this issue). Aquaculture is an important, high-protein food source in many developing countries and may become even more important as a form of agricultural diversification and a means to improve food security and nutrition (Allison and Horemanns, 2006; Allison *et al.*, 2007).

Several adaptation strategies have been suggested for managed forests, but large areas of forests in developing countries receive minimal direct human management, which limits adaptation opportunities (FAO, 2000). Even in more intensively managed forests where adaptation activities may be more feasible, the long lag times between planting and harvesting trees will complicate decisions, as adaptation may take place at multiple times during a forestry rotation (Working Group II, 2007).

In places where changes in climate are extreme and agriculture becomes impossible despite adaptation strategies, support and training will be necessary to help smallholders and farm workers take up offfarm employment. Where these are large populations, policy-makers should draft *ex-ante* local or regional strategies for economic adaptation. On the flip side, warmer and wetter climates may transform some currently non-arable landscapes into potentially productive croplands, especially in places at higher altitudes and latitudes. Taking advantage of these emerging agricultural opportunities will require a wide range of tools: technology and financial transfer; preparation for potential migration corresponding to geographical shifts in suitable areas; cooperation and coordination; among others.

In all, a holistic approach to adaptation to progressive climate change still needs to be developed—one that considers the interactions of different technical, institutional, and policy sectors, and the potential need for incentives or aid. This would allow for the development of adaptation options that go beyond sector-specific management and lead to more systemic changes in resource management and allocation, such as targeted diversification of production systems and livelihoods (Howden *et al.*, 2007). Some example s of adaptation options are provided in Figure 2.

Mitigation that contributes to adaptation

Poor smallholders can hardly be held accountable for climate change, but agriculture does contribute 10–12 percent of total global anthropogenic emissions of greenhouse gases (Verchot, 2007). For the non-CO2 greenhouse gases (GHGs) (principally methane and nitrous oxides), emissions are highest in developing countries and expected to grow rapidly in the coming decades (Verchot, 2007; Smith *et al*., 2008). Furthermore, the pressures to expand agriculture in many developing countries contribute to carbon emissions through deforestation and unsustainable land management practices. Smith *et al*. (2008) estimated that mitigation interventions, many of which can enhance on-farm productivity and contribute to poverty alleviation, are able to offset up to 24 to 84 percent of global agricultural emissions (which account for 5.1-6.1 gigatons yr^{-1}).

Natural resource management can thus have both mitigation and adaptation potential, e.g., by improving nitrogen use efficiency or reducing water dependence. Precision fertilizer use, for example, can raise yield-to-emission ratios (Pretty *et al.,* 2003), while Wassman *et al.* (2009) report that mid-term drainage and intermittent irrigation of rice paddies may reduce methane emissions by over 40% without compromising yields. Soil carbon sequestration via management of crop residues can also improve resilience by boosting water retention, as well as soil fertility and stability (Lal, 2004). Silvo-pastoral systems decrease methane production, while often improving feed use efficiency and ensuring ample feed availability in the face of climate variability (Murgueitio *et al.*, 2010). Incentive-based mechanisms such as the Clean Development Mechanism (CDM) and the new UN initiative Reducing Emissions for Deforestation and Forest Degradation (REDD+), as well as growing voluntary carbon markets, provide opportunities for smallholder farmers to reduce GHG emissions and move to more sustainable land management practices. These new market opportunities also offer farmers a means to bolster their food and livelihood security through diversified income sources. In this way, community forestry or agroforestry can produce income, ensure wood supply, and conserve ecosystems. However, in many cases, monitoring, reporting and verification (MRV) tools must be improved and more extensively applied to qualify for international payment schemes (Eriksen, 2009; Negra and Wollenberg, 2011). Smallholders in developing countries may also not be able to afford the up-front costs of project development, data may not be available or sufficient, and land rights or boundaries may be communal or unclear.

Smaller local programs with lower transaction costs may warrant research and financial support. One example is Socio Bosque in Ecuador, which pays individual landowners or indigenous communities annual monetary sums for each hectare of forest they voluntarily pledge to protect. Such programs use neither close vigilance nor exact calculations of carbon sequestered. Regardless, their apparent efficacy merits greater attention. Other emerging market opportunities may exist for certifying products as water-efficient, sustainable or organic.

Critical evaluations of these win-win situations have been largely neglected (Klein *et al.*, 2007), as the adaptation and mitigation communities have tended to operate in isolation. Therefore, research is needed that explores and exploits these synergies, while also analysing the inevitable trade-offs between environmental and livelihood benefits (Stoorvogel *et al.*, 2004). The identification and promotion of best management options require an integrated, systems-level framework on agriculture and climate change. The food security externalities of large-scale biofuel production is one such example where careful evaluation is required.

Integration for decision making

It is essential that knowledge generation through research on risk management, progressive adaptation and pro-poor mitigation is linked with a sound diagnostic and decision making structure that will enable and ensure on-the-ground change. Targeting food security, poverty reduction and sustainable natural resource management interventions that are robust in the face of a changing and uncertain climate requires a strong *ex-ante* analytical capacity to diagnose points of vulnerability and assess the impacts and trade-offs between socioeconomic and environmental goals associated with alternative strategies. A strong analytical and diagnostic framework, grounded in the global change policy environment and supported by effective engagements with rural communities and institutional and policy stakeholders, is therefore essential. This implies engagement in the dialectic discourse between global policy and science—through which the political climate increasingly shapes the opportunities for and constraints to local and national-scale action, but can also be responsive to and influenced by the sound scientific evidence, e.g. the outputs from the other research themes. Responding to climate change and improving food security requires that stakeholders develop their capacity to anticipate and plan for uncertain and changing conditions. Successful mitigation and adaptation will entail not only individual behavioral changes, but also changes in technology, institutions, agricultural and socio-economic systems. These changes cannot be achieved without improving interactions between scientists and decision-makers at all levels of society, to better match supply and demand of information, to develop and share appropriate adaptation tools, and to continually assess and address the need for new resources and information (Moser and Dilling, 2007). Vogel *et al*. (2007) note that the attempt to produce ‘useful’ science often occurs separately from the study of the science-practice interface. Consequently, decision-makers and managers do not receive or use the information that is produced, and vulnerability to environmental change may remain high, despite new scientific knowledge. These authors point to the need for improved communication and engagement, because both the science and the practices change as the result of increased researcher-stakeholder interactions, “sometimes in unexpected or unintended ways” (Vogel *et a*l., 2007, p. 351). Strategies may include participation, integration, social learning, and negotiation. An important point emphasised by van Kerkoff and Lebel (2006, p. 445) is that “the unique contribution of research-based knowledge needs to be understood in relation to actual or potential contributions from other forms of knowledge.”

Given the complex, dynamic and uncertain nature of climate change and its interactions with other social, economic and political processes driving agricultural development and food security, innovative methods and tools need to be developed to improve communication between researchers and stakeholders. An example of such a tool is the “learning wheel,” developed as part of the Integrated Natural Resource Management (INRM) task force of the CGIAR (Campbell *et al*., 2006a, b). This tool is based on principles and operational guidelines that present a new way of approaching research and development. Research must further develop and apply such approaches given the novel challenges that climate change introduces to resource management. This should draw upon experiences of how farmers and communities already adapt to climate variability and extreme events, and assess the role and relevance of such local and traditional knowledge. In a similar vein, communication and exchange with stakeholders in the food system must take into account the diversity of cultural and cognitive frameworks for understanding climate change, including how they relate to different beliefs, values and worldviews (Orlove *et al*., 2004; Roncoli, 2006). Osbahr *et al*., (2011, this issue) and Rao *et al*. (2011, this issue) illustrate the importance of this point through case studies from Uganda and Kenya which examine farmers' perceptions of climate risk and change compared with the outputs of climate risk and trend analyses of long-term historical weather data from nearby recording stations. A focus on communication and understanding the information needs of stakeholders is a minimum requirement for ensuring that research results are used by decision makers, as stakeholders will only utilize information that they find credible, legitimate and relevant to the problems they face.

Synergies, Trade-offs, and Transitions

Production systems will need to transition from managing risk of climate variability to adapting to long-term climate change and reducing net emissions, yet little is known on whether this transition occurs naturally, or whether some risk management strategies progressively become less capable of adapting to progressive changes in the baseline and in extreme cases may even contribute to maladaptation. In some instances, mitigation activities can act as a vehicle to effectively bridge short-term management and long-term adaptation. We postulate that there are three basic scenarios, which provide a framework for analysing synergies and trade-offs among adaptation, risk management and mitigation.

Case 1. Transition (win-win-win)

This is the best-case scenario in which risk management strategies smoothly contribute to progressive adaptation, all the while mitigating climate change (**Figure 4**). There are no real tradeoffs. An example would be payments for carbon sequestration-related ecosystem services (PES), which reduce risk by offering immediate financial capital relief, mitigate by increasing carbon storage, and adapt by creating incentives and opportunities to diversify and further invest in agricultural and non-agricultural income sources.

Case 2. Disjointed adaptation (win-win)

In this case, risk management does not easily transition into transformational adaptation, but there are synergies between each of these and mitigation (**Figure 5**). As a result, it is possible that mitigation strategies can act as a bridge. Sometimes this situation can be self-supporting, for instance in the case of silvo-pastoral systems, where climate-tolerant legumes provide additional fodder (risk management), biomass sequesters carbon (mitigation), and the landscape is transformed into an improved natural resource base (adaptation). In other cases, the situation precariously hinges on continued political and institutional support: for example, subsidies conditional on eco-friendly agriculture (mitigation) can supply immediate liquidity (risk management) but not necessarily help farmers prepare for changed climate baselines (adaptation).

Case 3. Disjointed adaptation (no win-win)

This is the worst-case scenario, in which there are always trade-offs, no opportunities for win-win, and no smooth transition from risk management to progressive adaptation (**Figure 6**). For example, a small producer farming on land that will become unsuitable for agriculture in 2050 might have no clear long-term adaptation strategies. He/she might therefore move locations, thus deforesting land for his crops or logging to make his non-farm livelihood. External aid and incentives are therefore necessary to help affected parties and encourage them to adapt in sustainable ways.

The interface between risk management, adaptation to progressive change, and mitigation is a priority area of research with many knowledge gaps. What causes a farming system to fall into one of the three cases is likely to be a combination of existing resource endowments, institutional and scientific support, together with the willingness of stakeholders to change behaviour. In this sense, underlying both adaptation and mitigation research, as well as Integration for Decision Making, must be a framework and strategy to overcome behavioural path dependence in individuals and institutions.

Overcoming Behavioural Inertia and Effecting Change

The drivers of behavioural change represent yet another important knowledge gap. The IPCC 4th assessment reverts to basic theory (e.g. Raiffa, 1968) to explain the process of making decisions under uncertainty. A more robust way of looking at this is to ask: If the need for adaptation is so obvious, why does it not happen? Further, are societies adapting quickly enough? Accelerated adaptation risks an initial capital investment but ultimately yields benefits. Slow, or non-adaptation avoids early investment but ultimately exhausts capitals as productivity remains consistently below potential.

Parry, *et al.* (2007) list five impediments to behavioural change, and in the context of climate change adaptation and mitigation, we re-work these into four umbrella constraints:

1. **Uncertainty about outcomes of different decisions,** rooted in *ignorance* about the scale, distribution, and production impacts of climate change (e.g., as a scientist with limited ability to predict, or as a farmer with little access to such information); and inability to manage *variability* of projections or information;
2. **Cognitive problems and differing perceptions of vulnerability or risk**, resulting from *poor resilience science* that can analyze socio-ecological processes in conjunction, *myopia* in terms of time (thinking short-term) or space (thinking locally), *disagreement* between agents, *cultural barriers* to change, and *translational difficulties*, e.g., between scientists, policy-makers, and farmers;
3. **Lack of compelling motive or incentives**, due to *lack of ecosystem valuation*, *inadequate or unfavourable market value chain links*, and *risk aversion*, especially to investment in new technologies in the context of climate variability; and
4. **Lack of capacity**, related to an *inadequate asset base to invest*, *lack of organizational capacity* at any/all scales, and *institutional failure*, i.e. their absence, incompetence/poor fit, and/or perceived illegitimacy.

The challenge for the research community, then, is to identify which behaviours are inhibiting or supporting adaptive change, scan for the institutions involved, look for “instruments” of change (e.g., technologies, policy, law), and then finally strategize as to how science can support or improve those instruments to encourage accelerated adaptation. As an example, Figure 7 shows how various components in this scheme can be linked to enable PES.

Taking a Food Security Perspective

At its most simplified level, food security generally refers to the sufficient production of food for the world population. However, the more nuanced definition of food security includes four key dimensions, only one of which is availability (production); the other three are stability, access and utilization (Schimidhuber and Tubiello, 2007). Agricultural adaptation to climate change therefore must guarantee *stable* production, which in turn feeds rural incomes and gives people adequate resources to *access* and purchase food. Where there is insufficient food for a household due to climate change impacts, *utilization* may also be affected, as certain members (e.g., men) within a family are often prioritized (Lambrou and Nelson, 2010). On a global scale, this is obviously true as well: adequate production for the world population does not mean all sub-populations can acquire and allocate food properly. As areas of suitability change and mobility becomes a potential adaptation strategy, adequate support must be given to the access side of food security as well, with all the relevant policy implications (e.g., regarding global trade, national subsidies, food relief, conditional cash transfer, gender- or vulnerable population-focused programs *etc.*). In many cases, ensuring food security may also require further data collection on household priorities and decision-making processes, which can then be applied as inputs for bio-economic, farm-level vulnerability mapping.

Closing Knowledge Gaps

The research agenda for climate change adaptation and mitigation is as complex as it is important. Scientists must build integrated models reflecting biophysical, socioeconomic, and behavioural factors, which together can reasonably predict tipping points in food systems and develop science-based plans and strategies to prevent or overcome climate-related constraints. In formulating recommendations, scientists, policy-makers and farmers alike must take advantage of institutional learning, including traditional knowledge of coping mechanisms and adaptation strategies. Indeed, knowledge sharing will be an important strategy as climate zones migrate.

There are also considerable uncertainties regarding the magnitude and direction of climate change, particularly at the downscaled, local level. Going forward, researchers must continue to refine these projections using a range of approaches and relate them to agricultural productivity. In doing so, scientists should clearly indicate the levels of comprehensiveness and probability for all projections, as well as acknowledge the inevitability of unanticipated effects. This in turn presents challenges in the communication of scientific research results to broader stakeholder groups and decision makers.

In addition to the climate-based uncertainties are the complex human geographies of food systems, with all their cross-cutting externalities, positive and negative, and feedback loops that extend far beyond the agricultural realm. Intensification of food production methods may have repercussions on consumers' health (Matson et al., 1997; Global Environmental Change and Human Health, 2007). Migration of displaced farmers may lead to political disputes. It is in this somewhat unpredictable sociopolitical space that truly integrated adaptation pathways must be developed.

These uncertainties and trade-offs, however, do not preclude the necessity of acting despite all unknowns. Indeed, they provide greater incentive for ensuring that we construct the most flexible, durable, and climate-resilient food systems possible. Adaptation, like the processes of climate change and the moving parts of food systems, must be dynamic.

Conclusions

This paper has outlined a framework for research on climate change and food systems from a pro-poor perspective. The inherent complexities and inter-relations between the climate system and food security means that science must make a great effort to take a holistic view to adaptation and mitigation research, and make significant effort to understand the trade-offs and synergies involved in interventions aimed at addressing the climate crisis. The research agenda outlined forms the road map for the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), a major collaboration between the CGIAR centres and the Earth System Science partnership (ESSP).

Bibliography

Adger, W.N., Huq, S., Brown, K., Conway, D. & Hulme, M. (2003). Adaptation to climate change in the developing world, *Progress in Development Studies* 3: 179-195.

Aggarwal, P.K & Mall, R.K. (2002). Climate change and rice yields in diverse agro-environments of India. II. Effects of uncertainties in scenarios and crop models on impact assessment, *Climate Change* 52: 331-343.

Allison, E.H. & Horemans, B. (2006). Putting the principles of the Sustainable Livelihoods Approach into fisheries development policy and practice. *Marine Policy* 30:757-766.

Allison, E.H., Andrew, N.L. & Oliver, J. (2007). Enhancing the resilience of inland fisheries and acquaculture systems to climate change. ICRISAT. *SAT e Journal* 4(1). Penang, Malaysia.

Arndt, C. & Bacou, M. (2000). Economy wide effects of climate variability and prediction in Mozambique, *American Journal of Agricultural Economics* 82:750-754.

Balfour, F. (2008). Understanding the global rice crisis. *Bloomberg Businessweek*, 28 April 2008.

Barrett, C.B., Barnett, B.J., Carter, M.R., Chantarat, S., Hansen, J.W., Mude, A.G., Osgood, D.E., Skees, J.R., Turvey, C.G., & Ward, M.N. (2007). Poverty traps and climate and weather risk: Limitations and opportunities of index-based risk financing. *IRI Technical Report* 07-03.

Barrett, C.B., Bezuneh, M. & Aboud, A. (2001). Income diversification, poverty traps and policy shocks in Cote d'Ivoire and Kenya. *Food Policy* 26:367-384.

Beddington, J. (2010). Food security: Contributions from science to a new and greener revolution, *Philosophical Transactions of the Royal Society* 365: 61–71.

Bennett, (2003). Opportunities for increasing water productivity of CGIAR crops througb plant breeding and molecular biology. In *Water Productivity in Agriculture: Limits and Opportunities for Improvement* (Eds J.W. Kijne, R. Barker & D. Molden). CAB International.

Butt, T.A., McCarl, B.A., Angerer, J., Dyke, P.T. & Stuth, J.W. (2005). The economic and food security implications of climate change in Mali, *Climatic Change* 68: 355-378.

Byerlee, D. de Janvry, A., Sadoulet, E., Townsend, R. & Klytchnikova, I (2008). *World development report 2008: Agriculture for development*. Washington, DC: The World Bank.

Campbell, B., Jürgen, H., Sayer, J., Ann, S., Richard, T. & Wollenberg, E. (2006a). What kind of research and development is needed for natural resource management? *Water International* 31:343-360.

Campbell, B., Jürgen, H., Sayer, J., Ann, S., Richard, T. & Wollenberg, E. (2006b). Navigating amidst complexity: Guide to implementing effective research and development to improve livelihoods and the environment. Center for International Forestry Research, Bogor, Indonesia.

Carter, M.R. & Barrett, C.B. (2006). The economics of poverty traps and persistent poverty: An asset-based approach. *Journal of Development Studies* 42:178-199.

Carter, M.R. & Barrett, C.B. (2006). The economics of poverty traps and persistent poverty: An asset-based approach. *Journal of Development Studies* 42:178-199.

Challinor, A.J., Wheeler, T.R., Craufurd, P.Q., Ferro, C.A.T. & Kassam A. (2007). Assessing the vulnerability of food crop systems in Africa to climate change, *Climatic Change* 83: 381-399.

Dercon, S. (2004). Growth and shocks: Evidence from rural Ethiopia, *Journal of Development Economics* 74 (2): 309- 329.

Dixit, P.N., Cooper, P.J.M., Rao, K.P. & Dimes, J. (2011) Adding value to field-based agronomic research through climate risk assessment: A case study of maize production in Kitale, Kenya. *Experimental Agriculture*. This issue.

Easterling, W.E., Aggarwal, P.K. , Batima, P., Brander, K.M., Erda, L., Howden, S.M. , Kirilenko, A. , Morton, J., Soussana, J.-F. , Schmidhuber, J. & Tubiello, F.N. (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*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 273-313.

Easterling,W.E., Chhetri, N. & Niu, X.Z. (2003). Improving the realism of modeling agronomic adaptation to climate change: simulating technological submission, *Climatic Change* 60 (1-2): 149-173.

The Economist (2010). Don’t starve they neighbor: How to rebuild confidence in food markets after this summer’s spike in wheat prices, *The Economist*, 9 September 2010.

Eriksen, P.J. (2009). Conceptualizing food systems for global environmental change research. *Global Environmental Change* 18:234-245.

FAO (2000) Global forest resources assessment. FAO Forestry Paper 140, Food and Agriculture Organization of the United Nations, Rome.

FAO (2006). World Agriculture: towards 2030/2050, Interim Report, Food and Agriculture Organization, Rome.

Farrow, F., Musoni, D., Cook, S., & Buruchara, R. (2011) Assessing the risk of root rots in common beans in East Africa using simulated, estimated and observed daily rainfall data. *Experimental Agriculture.* This issue.

Gathenya, M., Mwangi, H., Coe. R and Sang, J. (2011). Climate- and land use-induced risks to watershed services in the Nyando River Basin, Kenya. *Experimental Agriculture*. This issue

Giddens, A. (2009). *The Politics of Climate Change*. Cambridge and Oxford, UK: Polity Press.

Global Environmental Change and Human Health (2007). Science Plan and Implementation Strategy. Earth System Science Partnership (DIVERSITAS, IGBP, IHDP, and WCRP) Repost No. 4; Global Environmental Change and Human Health Report No.1.

Haile, M. (2005). Weather patterns, food security and humanitarian response in sub-Saharan Africa. *Philosophical Transactions of the Royal Society B* 360: 2169–2182.

Hansen, J.W., Baethgen, W., Osgood, D., Ceccato, P. & Ngugi, R.K. (2007). Innovations in climate risk management: protecting and building rural livelihoods in a variable and changing climate. *Journal of SemiArid Tropical Agricultural Research 4(1).*

Hansen, J.W., Challinor, A., Ines, A.V.M., Wheeler, T & Moron, V. (2006b). Translating climate forecasts into agricultural terms: advances and challenges, *Climate Research* 33:27-41.

Hansen, J.W., Mason, S.J., Sun, L. & Tall, A. (2011) Review of Seasonal Climate Forecasting for Agriculture in Sub-Saharan Africa. *Experimental Agriculture.* This issue.

Hill, H.S. J., Mjelde, J.W., Love, H. A., Rubas, D.J., Fuller, S.W., Rosenthal, W. & Hammer, G. (2004). Implications of seasonal climate forecasts on world wheat trade: a stochastic, dynamic analysis, *Canadian Journal of Agricultural Economics* 52: 289-312.

Howden, S.M., Soussana, J.F., Tubiello, F.N., Chhetri, N., Dunlop, M. & Meinke, H. (2007). Adapting agriculture to climate change. *Proceedings of the National Academy of Sciences* 104:19691-19696.

Intergovernmental Panel on Climate Change (IPCC). In *Climate Change 2007: Fourth Assessment Report, Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY: Cambridge University Press.

Jackson, L.E., Pascual, U. & Hodgkin T. (2007). Utilizing and conserving agrobiodiversity in agricultural landscapes. Agriculture, Ecosystems, and Environment 121: 196–210.

Jones, P.G. & Thornton, P.K. (2003). The potential impacts of climate change on maize production in Africa and Latin America in 2055. *Global Environmental Change* 13:51-59.Klein, R.J.T., Huq, S., Denton, F., Downing, T.E., Richels, R.G., Robinson, J.B., Toth, F.L. (2007). Inter-relationships between adaptation and mitigation; in *Climate Change 2007: Impacts, adaptation and vulnerability.* Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Eds M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden & C.E. Hanson). Cambridge, UK and New York: Cambridge University Press.

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science* 304:1623-1627.

Lambrou, Y. & Nelson, S. (2010). Farmers in a changing climate: Does gender matter? Food security in Andhra Pradesh, India. FAO. Rome, Italy.

Matson, P., Parton, W., Power, A. & Swift, M. (1997). Agricultural intensification and ecosystem properties. *Science* 277: 504–509

McPeak, J.G. & Barrett, C.B. (2001). Differential risk exposure and stochastic poverty traps among East African pastoralists. *American Journal of Agricultural Economics* 83:674-679.

Moorhead, A. (2009). Climate, agriculture and food security: A strategy for change. Alliance of the CGIAR Centers.

Moser, S.C. & Dilling, L., eds. (2007). *Creating a Climate for Change: Communicating Climate Change and Facilitating Social Change*. Cambridge: Cambridge University Press.

Murgueitio, E., Zoraida, C., Uribe, F., Calle, A. & Solorio, B. (2010). Native trees and shrubs for the productive rehabilitation of tropical cattle ranching lands. *Forest Ecology and Management*. Article in press.

Negra, C. & Wollenberg, E. (2011). Lessons from REDD+ for Agriculture. CCAFS Report no. 4. The CGIAR Research Program, Climate Change, Agriculture and Food Security (CCAFS). Copenhagen, Denmark.

Niles, J.O., Brown, S., Pretty, J., Ball, A.S. & Fay, J. (2002). Potential carbon mitigation and income in developing countries from changes in use and management of agricultural and forest lands. *Philosophical Transactions of the Royal Society A.* 360:1621-1639.

Oba, G. (2001). The importance of pastoralists' indigenous coping strategies for planning drought management in the arid zone of Kenya. Nomadic Peoples 5: 89-119.

Orlove, B., Broad, S. K. & Petty, A.M. (2004). Factors that influence the use of climate forecasts. *Bulletin of the American Meteorological Society* 85:1-9.

Ortiz, R., Sayre, K.D., Govaerts, B., Gupta, R., Subbarao, G.V., Ban, T., Hodson, D., Dixon, J.M., Iván Ortiz-Monasterio, J. & Reynolds, M. (2008). Climate change: Can wheat beat the heat? *Agriculture, Ecosystems & Environment* 126:46-58.

Osbahr, H., Dorward, P. Stern, R.D and Cooper, S.J. (2011) Supporting agricultural innovation in Uganda to climate risk: linking climate change and variability with farmer perceptions. *Experimental Agriculture.* This issue.

Ouma, R., Mude, A. & van de Steeg, J. (2011). Dealing with climate-related risks: some pioneering ideas for enhanced pastoral risk management in Africa. *Experimental Agriculture.* This issue.

Parry, M., Rosenzweig C. & Livermore, M. (2005). Climate change, global food supply and risk of hunger. *Philosophical Transactions of the Royal Society B* 360:2125-2138.

Parry, M.L. Canziani, O.F., Palutikof, J.P., van der Linden, P.J. & Hanson, C.E., eds. (2007). Contribution of Working Group II to the Fourth Assessment Report of the International Panel on Climate Change (Eds M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden & C.E. Hanson). Cambridge, UK and New York: Cambridge University Press.

Patt, A.G., Ogallo, L. & Hellmuth, M. (2007). Learning from 10 years of climate outlook forums in Africa. *Science* 318:49-50.

Pretty, J.N., Low, P.J., Ellis, J.R, & Hine, R.E. (2003). Reducing food poverty by increasing agricultural sustainability in developing countries. *Agriculture, Ecosystems and Environment* 95:217-234.

Rao, K.P.C., Ndegwa, W.G., Kizito, K. & Oyoo, A. (2011) Climate variability and change: Farmer perceptions and understanding of intra-seasonal variability in rainfall and associated risk in semi-arid Kenya. *Experimental Agriculture.* This issue.

Raiffa, H. (1968). *Decision Analysis: Introductory Lectures on Choices under Uncertainty*. Reading, MA: Addison-Wesley.

Roncoli, C. (2006). Ethnographic and participatory approaches to research on farmers' responses to climate predictions. *Climate Research* 33:81-99.

Rosenzweig, M.R. & Binswanger, H.P. (1993). Wealth, Weather Risk, and the Composition and Profitability of Agricultural Investments. *The economic journal* 103:56-78.

Santos, P. & Barrett, C.B. (2006). Informal insurance in the presence of poverty traps: Evidence from southern Ethiopia. USAID.

Schmidhuber, J. & Tubiello, F.N. (2007). Global food security under climate change. *Proceedings of the National Academy of Sciences* 104:19703-19708.

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). *Philosophical Transactions of the Royal Society B.* 363:798-813.

Stern, R.D. and Cooper, P.J.M. (2011) Assessing climate risk and climate change using rainfall data – a case study from Zambia. *Experimental Agriculture*. This issue

Stoorvogel, J.J., Antle, J.M., Crissman, C.C. & Bowen, W. (2004). The tradeoff analysis moel: Integrated bio-physical and economic modeling of agricultural production systems. *Agricultural Systems* 80:43-66.

Thomas, R. J., de Pauw, E., Qadir, M., Amri, A., Pala, M., Yahyaoui, A., El-Bouhssini, M., Baum, M., Iñiguez, L. and Shideed, K. (2007). Increasing the Resilience of Dryland Agro-ecosystems to Climate Change. *SAT eJournal* 4 (1): 1- 37.

Travasso, M.I., Magrin, G.O., Baethgen, W.E., Castaño, J.P., Rodriguez, G.R., Pires, J.L., Gimenez, A., Cunha, G. & Fernandes, M. (2006). Adaptation measures for maize and soybean in south eastern SouthAmerica. AIACC Working Paper No. 28, 38 pp.

Tubiello, F., Schmidhuber, J., Howden, M., Neofotis, P.G., Park, S., Fernandes, E. & Thapa, D. (2008). Climate Change Response Strategies for Agriculture: Challenges and Opportunities for the 21st Century. Agriculture and Rural Development Discussion Paper 42. World Bank.

UN (2009). State of World Population 2009: Facing a Changing World: Women, Population and Climate. UNFPA, New York, NY.

van Kerkhoff, L. & Lebel, L. (2006). Linking knowledge and action for sustainable development. *Annual Review of Environment and Resources* 31:445-477.

Verchot, L.V. (2007). Opportunities for climate change mitigation in agriculture and investment requirements to take advantage of these opportunities. A report to the UNFCCC Secretariat Financial and Technical Support Programme. Nairobi, Kenya.

Vogel, C. & O'Brien, K. (2006). Who can eat information? Examining the effectiveness of seasonal climate forecasts and regional climate-risk management strategies. *Climate Research* 33:111–122, 2006

Vogel, C.H., Moser, S.C., Kasperson, R.E., & Dabelko, G.D. (2007). Linking vulnerability, adaptation, and resilience science to practice: Pathways, players, and partnerships. *Global Environmental Change* 17:349-364.

Wassmann, R. & Dobermann, A. (2007). Climate change adaptation through rice production in regions with high poverty levels. SATe-J 4:1-24.

Wassman, R., Hosen, Y. & Sumeth, K. (2009). Reducing methane emissions from irrigated rice. In Nelson, G. (ed,), *Agriculture and Climate Change: An Agenda for Negotiation in Copenhagen*. 2020 Vision Policy Focus 16. IFPRI, Washington, D.C. Brief 3,

Working Group II. Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the International Panel on Climate Change (Eds M.L.

Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden & C.E. Hanson). Cambridge, UK and New York: Cambridge University Press.

Ziervogel, G. & Zermoglio, F. (2009). Climate change scenarios and the development of adaptation strategies in Africa: challenges and opportunities. *Climate Research* 40:133-146.

Zimmerman, F. & Carter, M. (2003). Asset smoothing, consumption smoothing and the reproduction of inequality under risk and subsistence constraints, *Journal of Development Economics* 71:233–60.

Figures

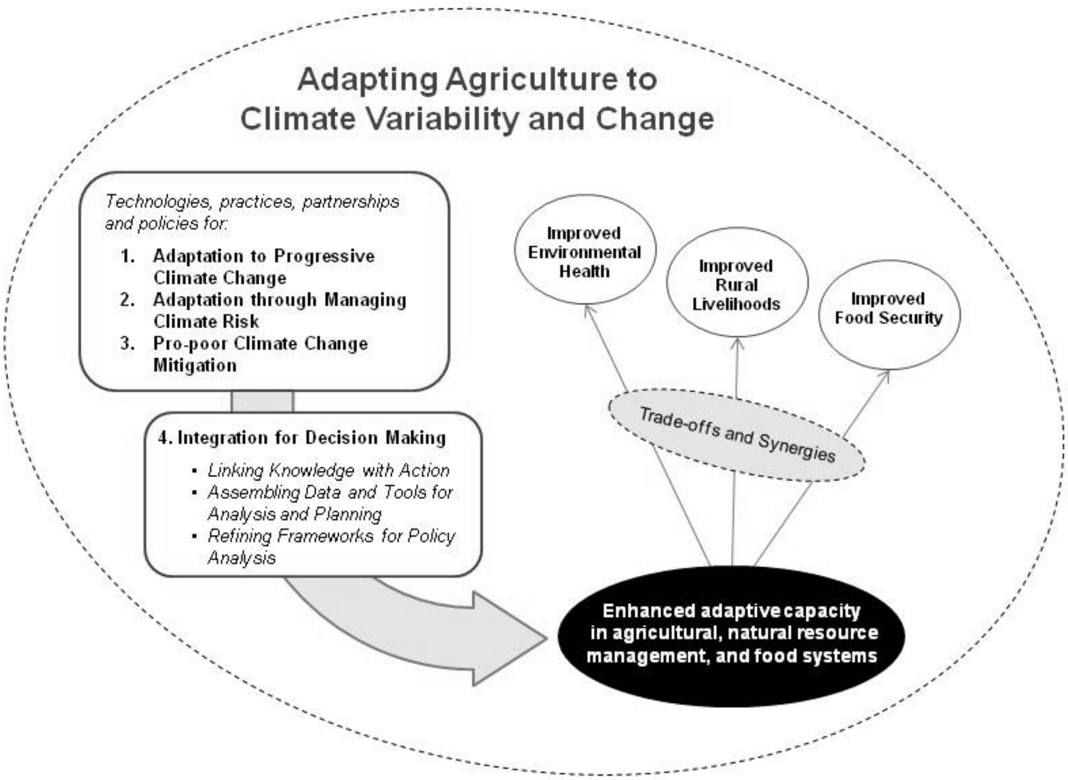

Figure 1. CCAFS framework for adaptation and mitigation research

Agricultural Toolbox

Risk Management	Progressive Adaptation
Inform	**Change Element**
• Climate forecasts, early warning systems • Training workshops on best practices	• Heat-, drought-, flood- tolerant crops • Resistant livestock
Engineer	**Change System**
• Irrigation, flood protection	• Change crop calendar phasing, timing • Introduce/Switch to different crops, products • Better agronomic practices
Hedge Risks	**Change Location**
• Diversification; spread /reduce investment • Insurance	• Upslope • Migrate
Get Financial Help	**Change Livelihoods**
• Subsidies • Microfinance • Aid	• Non-farm employment

Figure 2 Basic options for risk management and progressive adaptation.

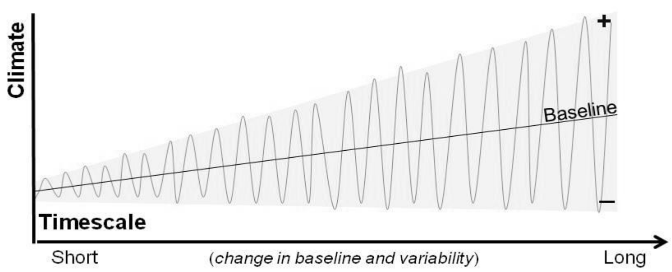

Figure 3 The combined effect of exacerbated climate variability and the change in baseline climate.

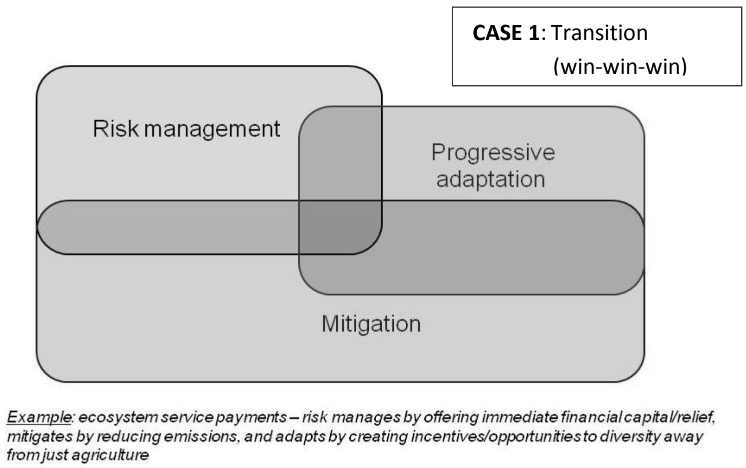

Figure 4 The triple win transition case, whereby risk management, progressive adaptation and mitigation all provide synergies.

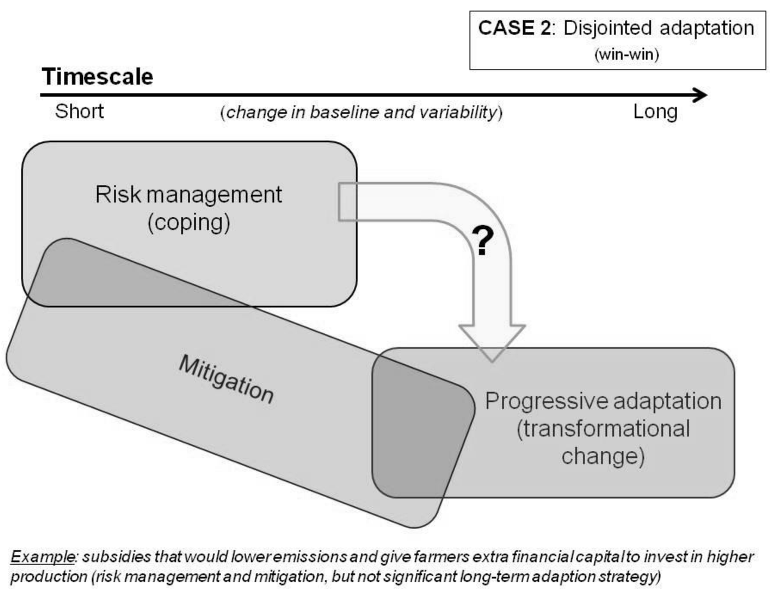

Figure 5 The second case of disjointed adaptation, but with opportunities of transitioning systems through mitigation actions.

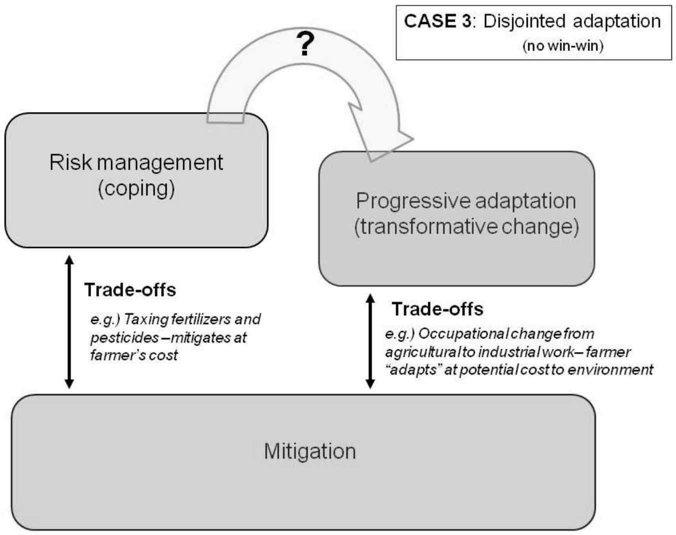

Figure 6 The third case of disjointed adaptation where all potential interventions require careful analysis of trade-offs.

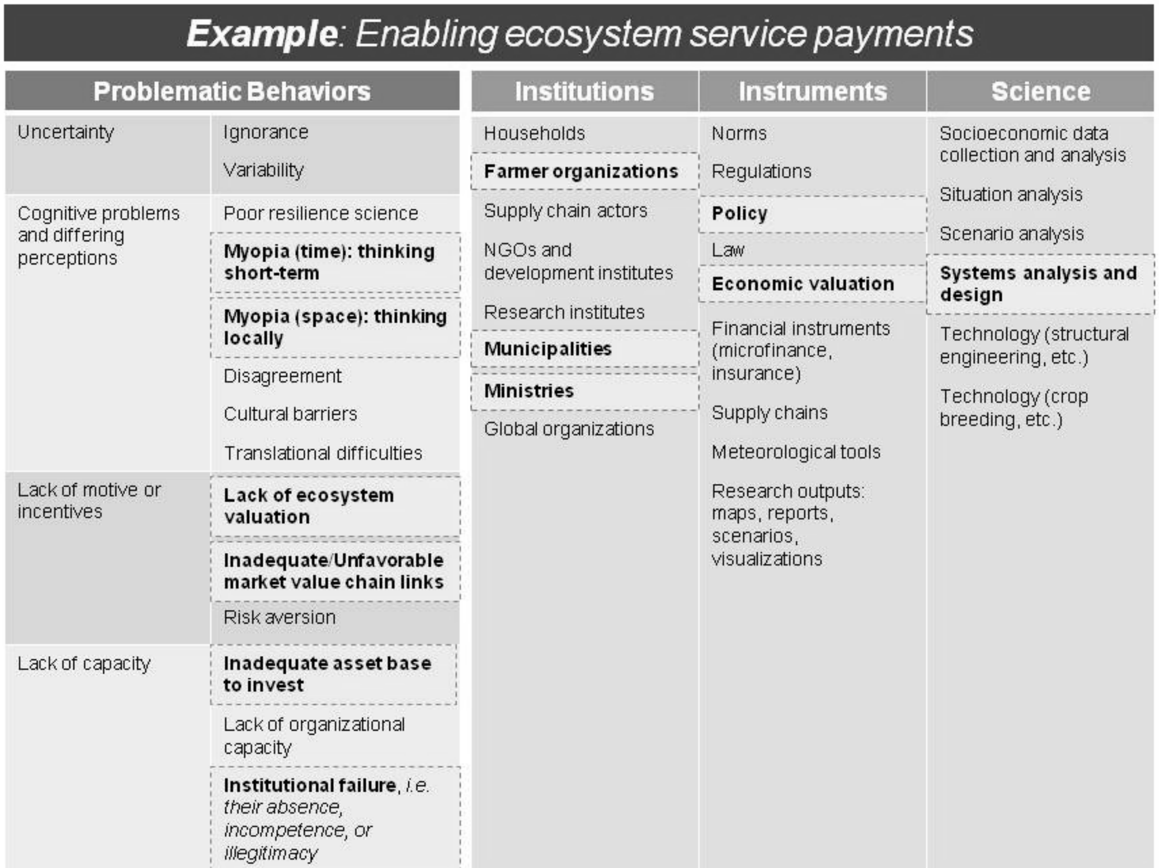

Figure 7. Dotted boxes show the behaviours, institutions, instruments, and science that can be linked to enable ecosystem service payment schemes.