Chapter 1: Climate change, food security and trade: An overview of global assessments and policy insights

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chapter 1

Climate change, food security and trade: An overview of global assessments and policy insights

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main chapter messages

- Convergent results are showing that climate change will fundamentally alter global food production patterns, with negative crop productivity impacts likely expected in low latitude and tropical regions but somewhat positive in high latitude regions.

- Water mediates much of climate change impact on agriculture and increased water scarcity in many regions of the world present a major challenge for climate adaptation, food security and nutrition. Tackling the climate-food-water-trade nexus requires deploying coherent cross-sectoral, national, and regional strategies.

- Climate impacts on future food supply strongly suggest an enhanced role for trade with expanded flows from the mid-to-high latitude regions to the low latitudes regions, where production and export potential could be reduced. Progress on climate-compatible trade policies requires resolving the trade versus environment trade-offs and ensuring that future trade rules are more aligned with climate objectives.

- Combatting climate change goes hand in hand with alleviating poverty which requires mainstreaming climate responses within pro-poor development strategies. Mainstreaming should promote 'no regrets' actions that target improved resiliency to current and future climate impacts, especially for the poor and most vulnerable groups.

- Robust and reliable science-based evidence is critical to the development of policies to address climate impacts on food security and trade. A strategic and structured dialogue is required between science and policy and between global and regional impact research with local validation to support policy action.

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A. PART ONE

Climate change impact modelling – current status and future direction

Future land use and food security will be determined largely by the dynamics and interactions of agricultural markets, climatic suitability, adaptive capacity and direct interventions along the supply chain. Perhaps more than any other major economic sector, agriculture is highly dependent on local climatic conditions and is therefore expected to be highly sensitive to changes in climate that are expected in coming decades. This sensitivity is compounded by increasing pressure on the global agricultural system to meet food security objectives and, for some countries, to contribute also to national energy budgets through bioenergy production.

Rapid increases in global demand for agricultural commodities for food, animal feed and fuel are driving dramatic changes in the way we think about crops and land use. Along with recent supply side shocks driven by extreme weather events and other disasters, these conditions have led to increasingly wild swings in agricultural commodity markets that have some stakeholders concerned. In recent years, additional stresses on the land-food system are coming from some of the very mitigation strategies meant to slow climate changes before irreversible impacts occur. Many of the proposed strategies rely heavily on net emissions reductions through terrestrial biosequestration from modified farming practices, reducing application of inorganic fertilizer, avoiding deforestation or increasing afforestation and displacing fossil fuel energy with biomass and biofuel crops.

Conversion of natural lands to crop and/or livestock production as well as intensifying production on existing agricultural lands will have significant consequences for the environment, such as degradation of soil and water resources, increased greenhouse gas emissions and regional climate effects. Typical farming practices have been shown to reduce soil carbon by as much as 50-66 percent from natural levels [1] and there is little evidence that management practices which could stop or reverse these trends are gaining much traction. It has long been known [2] that direct effects of land-cover change on, for example, surface albedo[4] and evapotranspiration can be significant drivers of regional patterns of warming and can even have significant implications for changes in global mean variables. These environmental issues pose questions with regard to trade-offs of food and biomass production and increase the threat of environmental limitations on future increases in food production.

A1. Robust results from existing climate change impact studies

A1.1 Global impacts of climate trends

Overall expected patterns of climate impacts have been largely stable since the first global scale analyses [3]. Climate impacts in low-latitude regions, given present-day levels of management and technology, are clearly expected to be negative, even at low levels of warming. Impacts in the mid to high latitudes are expected to be more mixed, especially at lower levels of warming. Some high-latitude regions are expected to benefit [4] – sometimes substantially – from warmer temperatures and longer growing seasons; however, other environmental conditions, such as soil quality issues in the far north, will likely constrain expansion.

Recent summary results from the Intergovernmental Panel on Climate Change Fifth Assessment (IPCC AR5) [5] and global model

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[4] The ratio of reflected radiation from the earth's surface to incident radiation upon it.

results from the Inter-Sectoral Impacts Model Intercomparison Project (ISI-MIP1) [4, 6, 7] have largely verified these overall patterns and extended them to cover more regions, more crops and higher temperatures. These studies have also added more information regarding the potential for adaptation to ameliorate some portion of likely climate impacts to food production [5, 6]. Adaptive changes in management – especially planting dates, cultivar choice and sometimes increased irrigation – have been studied to varying extents and are generally estimated to have the potential to increase yields by about 7-15 percent on average [5], though these results depend strongly on the region and crop being considered and many questions remain. Increasing the concentration of atmospheric carbon dioxide (CO_2) is widely accepted to have a positive stimulating effect on crop yields under a broad range of other conditions, primarily through increasing the efficiency of photosynthesis, especially in C_3 crops (which include wheat, rice and soybeans). The magnitude of this effect, especially in environments with high stress from nutrient, or other, deficiencies, is still a field of active study and debate.

A1.2 Strengths and weaknesses of common model types

A wide array of models has been applied to the study of climate impacts, at decadal to multidecadal time scales. Models can generally be distinguished as primarily mechanistic or primarily empirical, though most of them fall somewhere between these extremes. Mechanistic models are usually based on field-scale crop models developed over many decades and tend to have the most complex process representations, especially with respect to parameterizing farm management, soil dynamics and genetic properties of different crop cultivars [8-11]. Dynamic global vegetation models have generally evolved from the opposite direction, starting with global-scale land models, often coupled with global earth systems models. Researchers have added crops and related processes to these models using representations of varying complexity, typically with a focus on better representing crucial exchange processes (e.g. carbon, water and energy balance) between land and atmosphere [12-17]. Purely empirical models are used to study global climate impacts, typically at national or continental scales [18, 19]. These models are useful for capturing in-sample processes and representing hidden variables, but pose challenges for estimation of climate impacts at long time scales, where regimes of atmospheric carbon, technology, management and climate may be fundamentally different from the recent historical past. A newer class of models, called large-area crop models, uses relatively simple representations of key crop processes to produce flexible models that can be statistically calibrated at large scales to capture hidden variables and better reproduce historical trends [20-23].

The scale of application of models and model-based assessments also leads to various trade-offs. Field-scale assessments of climate impacts often benefit from very high quality input and reference data, available at only a handful of experimental sites around the world [e.g. 24]. In addition, the relative simplicity of model execution and data management for these highly localized studies makes it possible to consider many different models and explore detailed subseasonal process differences and uncertainties. Global models require consistent global datasets of climate, soils and management. Many such datasets have been developed for continental or global-scale applications [25-28], but there are often trade-offs in terms of quality and representational complexity in the process of compiling these data.

Bio-economic models of agriculture and food systems (also called agro-economic models) apply results from biophysical model applications within an economic modelling framework (typically a partial or general equilibrium model) [29-35]. These models generally use simple representations of food production and climate impacts combined with representations of economies, populations, markets and other demand forces. These models make it possible to parameterize technological change and adaptation in response to prices in a way that is not possible in a purely biophysical assessment.

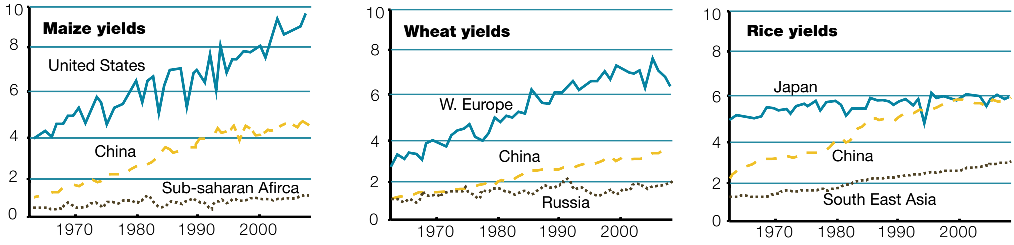
A1.3 Other drivers of productivity

For over 30 years it has been generally accepted that trends towards increasing temperatures and changing precipitation patterns in agricultural areas will have major, generally negative, implications for cropland productivity and will increase stress on global food production in the coming decades. In addition to these changes, a number of other related changes in the biosphere could ameliorate or compound these impacts. In fact, it has been suggested that the food security implications of changes in the severity, frequency and extent (both spatially and temporally) of drought events [36] may affect more people in the future than any other climate-related impact [37], though much work is still needed to understand how climate trends will produce precipitation extremes. On the other side of the ledger, increasing concentrations of CO_2 in the atmosphere – the very same phenomenon that drives global warming – can have a positive effect on the capacity for photosynthesis and water-use efficiency. These effects vary quite substantially among different crops, especially between those that use C_3 and C_4 pathways for photosynthesis, and among different regions, depending on the local aridity and the prevalence of other constraining stressors such as nitrogen availability.

For every aspect of future crop production and climate impact, technology and local management practices do and will play a crucial role, and the interactions of environmental, technological and management changes must be better understood and better modelled. Technological change in the agricultural sector proceeded unevenly in the twentieth century (Figure 1) [38]. Maize yields have increased steadily in the United States and China over the last 50 years and show little sign of slowing. Indeed, average yields of maize in the United States surpassed 10.3 tonnes per hectare in 2009, and these increases are expected to continue, at least over the short to medium term [39]. At the same time, average yields in sub-Saharan Africa have been mostly flat, growing

figure 1

The evolution of average yields for three staple cereal crops in three regions important to global trade and the food, feed and fuel supply [41]. In each plot, the major producer with the highest average per hectare yield is shown (**solid blue line**), along with the producer for whom yields have grown by the highest fraction in the 50-year period (**dashed yellow line**), which is China in all three cases, and an additional region (**dotted black line**) that, while still important to the global supply, has shown substantially lower average yields and a generally slower pace *of increase* (and thus presumably has much room to grow given the right conditions)



from around 1 tonne per hectare in the 1960s to barely more than 1.5 tonnes per hectare over the last decade. In the case of wheat, average yields in Western Europe have tripled since 1960, but have been largely flat with high volatility since the mid-1990s, potentially indicating a slowing of yield growth [40]. Chinese wheat yields are still significantly lower than those obtained in Western Europe, and are increasing steadily with little sign of slowing. Yields in Russia, meanwhile, have been largely flat for over 30 years but have significant potential for growth.

Rice, the most important staple food crop for a huge portion of the global population, shows a very different profile from the other major cereals. Japan, long the world leader in rice yields, has seen yield growth slow to a crawl over the last 50 years. China, which is both the world's largest producer and largest consumer of rice, saw average yields double from 1960 to 1980 but has struggled to keep up yield growth rates since then and has also seen flat yield trends since the mid-1990s. There is still some potential for increased rice yields in South and Southeast Asia, however, with each region accounting for about a quarter of global rice production and averaging 3.5-4 tonnes per hectare in recent years. While in gross terms this is substantially less "slack" than is implied by low yields in maize and wheat crops in large potential bread baskets such as sub-Saharan Africa and Russia, recent trends towards increased rice yields in these areas show that at least here the lower-yielding regions are moving in the right direction.

Substantial yield gaps, defined as the difference between potential and actual yields, caused by imperfect cropland management [42], exist in most parts of the world as a result of market conditions, the availability of resources such as irrigation and fertilizers, and degradation due to poor soil management. The International Food and Policy Research Institute's International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) takes the spatial study of climate change impacts beyond analysis of the impacts of climate on key crops at a national level by adding additional analysis that examines global trends and other factors that are changing with the climate, including gross domestic products (GDPs), populations, and agricultural technology development and use (Thomas and Rosegrant, Chapter 5). The model identifies hotspots under climate change where large losses in production are projected to occur, but also areas of climate opportunity, which may have large gains, and/or areas that were previously unsuitable but can become suitable for crop production at some point. Identification of these climate change hotspots could then provide important information for national policy, as they could be used to aid targeting of resources for adaptation (through policy intervention) or provide incentives, over the longer term, for climate adaptation research – for example, to develop agricultural technologies for the hotspot regions. In extreme cases, hotspots may provide forewarning of areas where agriculture could be untenable in the future, leading to shifts out of agriculture or migration away from the hotspot. Areas identified as climate opportunities, in contrast, could become the focus for inward investment in agriculture and food sectors.

Historically, there have been fewer assessments of climate change impacts on livestock than on the arable sector. Calculation of the uncertainty in livestock projections needs to account for impacts on both feed and fodder, as well as uncertainties in meat and dairy production. For livestock systems based on grazing, Havlik and colleagues (Chapter 6) identified two major sources of uncertainty: which particular crop/grass growth model was used in the impact assessment; and what assumptions were made about the magnitude of the CO_2 fertilization effect on grass growth. They concluded that climate change impacts on grass yields, allowing for these uncertainties, may substantially alter the relative competitiveness of the different systems and hence the overall outcome for the livestock sector in the future. However, projected changes in global milk and meat production by 2050 attributable to direct climate change impacts were comparatively small compared with other influences on demand for these products. Global price changes differed by up to 10 percent from the baseline scenario. More substantial differences in uncertainty were found at a regional scale. Climate change effects were most uncertain in the Near East & North Africa and in sub-Saharan Africa. For example, in the Near East & North Africa, the change in ruminant meat production due to climate change varied by +/-20 percent, depending on the scenario. In sub-Saharan Africa, the effects were the most uncertain, but also potentially the most severe; ruminant production could increase by 20 percent but it could also decrease by 17 percent, with most yield scenarios projecting monogastric meat production to fall by more than 30 percent (Chapter 6).

A2. Current modelling challenges

A2.1 Mechanisms requiring improved understanding

Many aspects of modern global agricultural impact models and assessments deserve further study and improvement, especially with regard to the effect of increasing atmospheric CO_2 on plant growth, grain formation and crop water use efficiency. Increasing the level of CO_2 improves the efficiency of photosynthesis, directly stimulating plant growth. It also reduces sensitivity to drought conditions by improving the efficiency with which crops use the water available in the soil, and can even improve nitrogen use efficiency [43]. These factors can have a compensatory effect on climate impacts, especially in regions where other potential stressors, such as soil quality and availability of key nutrients, are not constraining. These benefits may come with trade-offs in terms of food quality, however. Recent work has found that, in addition to increased caloric productivity, elevated CO_2 conditions have substantial negative implications for food nutrition content, with a 40-50 percent increase in CO_2 leading to a 5-10 percent reduction in the concentrations of zinc, iron and protein in some crops [44].

Together, these factors will have significant, and potentially transformational, implications for global food and nutrition security and large-scale drought sensitivity. However, global models used to assess climate impacts on crops disagree significantly on the strength of CO_2 fertilization effects, with their inclusion doubling or even tripling the range of outcomes within the model ensemble [4]. These differences are closely linked to whether a given model represents the nitrogen cycle and what assumptions are made about fertilizer application rates and nitrogen availability, now and in the future.

A2.2 Data requirements for model improvement

Perhaps the most important factor limiting the improvement of field-scale crop models is the existence and availability of experimental data, especially for conditions well outside normal experience, such as from large increases in CO_2 or extreme temperatures. Availability of data from Free-Air CO_2 Enrichment (FACE) experiments [43, 45] is beginning to address this issue but many more experiments are needed for many more crops under many different conditions to understand the complex interactions among Carbon, Temperature, Water and Nitrogen (CTWN) [46]. Global-scale impact modelling poses additional challenges. Assessments require high-resolution data on daily weather, soil and environmental conditions, crop-specific cultivation areas, irrigation and fertilizer use and local cropping calendars. High-quality reference data are also necessary to facilitate evaluation of models at the scales of interest. Finally, many applications require long time series of these types of data in order to evaluate distributions, trends and extremes. Recently, significant progress has been made on many of these data requirements, notably including global high-resolution time series reference data from subnational statistics [47] and hybrid algorithms combining national statistics and remotely sensed measures of plant growth [48].

A2.3 Accounting for management changes and other human responses

Technological changes, mainly in the form of new cultivars, field management practices and industrial production techniques for inorganic fertilizers, have led to huge increases in yield in the developed world since the end of World War II. Most assessments of the future socio-economic conditions of the global population assume that crop yields in developed countries will continue to increase linearly or even exponentially, and that crop yields in developing countries will soon begin to accelerate, meeting or even exceeding their pace of growth in the developed world. The recent historical record on growth rates in yield, however, is more mixed (as summarized in Section A1.3, in [38, 40] and Figure 1). Yield gaps in the developing world are generally estimated to be 50 percent or more of potential yields [49]. Recent work suggests that average maize yields in sub-Saharan Africa could be doubled by an increase of fertilizer application to about 50 kg/ha nitrogen [50]. While modest by global and developed world standards, this level would nevertheless require an increase in fertilizer availability of more than seven times the current level in sub-Saharan Africa and, given present day capacities, this increase is unlikely to be attained in the near future.

Much work is also still needed to identify how the options for agricultural development and adaptation and other likely sociotechnical changes might interact with climate changes in the coming decades. Towards this goal, the Agricultural Model Intercomparison and Improvement Project (AgMIP) has developed protocols [51] for the creation of Representative Agricultural Pathways (RAPs), story lines and scenario information products for the future of agricultural systems that are consistent with the Shared Socio-economic Pathways [52, 53] and the Representative Concentration Pathways [54, 55] created for the IPCC AR5 process. RAPs are being developed for many different systems and modelling purposes, at scales ranging from individual farms to national and global food systems.

A3. Future research areas

A3.1 Multimodel assessment and intermodel comparison: benefits and limitations

Increasingly, the above considerations have driven interest in scientific assessments of agricultural production, demand, markets and land-use trends. Many collaborative initiatives and institutions around the world have undertaken large-scale projects to address underlying scientific questions about productivity and environmental sustainability, as well as to gather, produce and distribute the technology, data and information products required by stakeholders and policy-makers. To be credible, these assessments must account simultaneously for the socio-economic drivers of demand, the environmental limitations and changes from a warming climate, and the potential and limitations for sociotechnical adaptations to vulnerabilities and impacts. To be maximally useful, they must additionally be able to address the major underlying uncertainties in the system and deliver information products and impact measures across a wide range of spatial and temporal scales.

Examples of ongoing collaborative initiatives include: AgMIP [51]); ISI-MIP [56]; and the Modelling European Agriculture with Climate Change for Food Security project (MACSUR, [57]). AgMIP includes many and various protocol-driven climate scenario simulation exercises for historical model intercomparison and future climate change conditions. It involves ecophysiological and agricultural economics modelling groups, by extending the multimodel applications from global circulation models to ecophysiological and economic trade and impact models [51].

ISI-MIP takes a similar protocol-driven approach to AgMIP, expanding the sectoral coverage to include hydrology, biomes and health impacts of climate change. MACSUR is a modelling network focusing on impacts of climate change on European agriculture [57]. MACSUR integrates models covering livestock, crops and economics to describe how climate variability and change will affect regional farming systems and food production in Europe in the short and long terms.

A3.2 Country-scale assessments: data requirements and successful case studies

Because of the current international nature of agricultural markets and the relevance of global change drivers (climate, population, consumption and regulation), food security and land-use change dynamics must be evaluated at the global scale. The effects of food insecurity and environmental impacts, however, are largely experienced locally and confronted by decision-makers at national or regional scales. For this reason, assessments of impacts and adaptation potential are also needed at national and even sub-national scales. For these assessments to be useful at the level expected by policy-makers and stakeholders at the regional scale, they require higher resolution (in space and time) data with improved representations of local management practices and potential adaptation options (e.g. [58-61] in sub-Saharan Africa, [62, 63] in South America, [64-66] in South Asia and [67] in East Asia).

A3.3 Model projections and uncertainty

Crop models, especially when run at global scale, are highly complex models that differ widely in terms of process representations, functional implementations, data input choices and basic assumptions. Even with the same version of the same basic underlying model, for example (as in the case of the Economics and Policy Innovations for Climate-Smart Agriculture (EPIC) and Global EPIC (GEPIC) modelling groups from the AgMIP/ISI-MIP Phase 1 Fast-Track), results often differ substantially [4], due to different assumptions about planting dates and fertilizer application rates, different choices for the functional representation of key processes such as evapotranspiration, and different implementations of the same functional representation (e.g. different choices of parameter values). To begin to understand these differences, the Global Gridded Crop Model Intercomparison (GGCMI), launched by AgMIP in 2013, is carrying out a set of simulation experiments run with harmonized data for a number of the key inputs that drive model differences, including planting dates, growing season length, fertilizer application rates and atmospheric CO_2 concentration pathways [68].

A3.4 Incorporating current and future resource constraints

Concern has been growing recently over constraints to agricultural production and productivity growth caused by the availability of key resources such as land, fresh water and fertilizers. These resource constraints are likely to compound the negative effects of climate change in many regions and hamper efforts at adaptation [6]. Climate change will directly affect the availability of resources such as fresh water for irrigation [69], and sociotechnical changes such as population growth and new energy technologies will directly affect the supply and availability of other key resources, such as land. Evaluation of resource availability and constraints must therefore be done within a broad multisector context that includes assessments by, for example, hydrological models, agro-economic and integrated assessment models, and ecosystem models. ISI-MIP has made some progress in this direction already, including agro-economic, hydrology and biome models in the fast-track phase, and the next round of coordinated assessments should provide greatly improved capacity as a result of the addition of new impact sectors such as forestry, biodiversity and energy systems models.

A3.5 Emerging and unknown future technologies

Technological change is typically incorporated in climate impact assessments through relatively simple parameterizations of productivity growth in agro-economic models, using a method that assumes that the effects of technological and environmental changes on productivity are completely separable [16]. However, the interactions between technology and environment are usually more complex. For example, new tillage practices can reduce the exposure of top soil to the air, reducing evaporation, improving soil moisture characteristics and reducing sensitivity to drought and heat. Breeding can lead to new cultivars that send roots down faster and deeper, increasing access to water in the soil profile, or that are more robust to underwater submergence conditions [70] that could become more common in a future climate. For these reasons, technological change should be included directly in biophysical impacts models and assessments through trends in model parameters and inputs. Getting this right will require renewed engagement between modellers, agronomists, and crop breeders.

A3.6 Improving economic modelling of climate impacts in agriculture

Improving economic analysis as part of modelling climate impacts in agriculture requires several model improvements. First, it is necessary to improve representation and integration of biophysical processes into economic models. This requires that economists increasingly work with researchers from other disciplines, recognizing that climate change impacts and their analysis pose a multidimensional problem. Also required is the ability to model extreme events and variable climate conditions, as opposed to the usual treatment of gradual climate change, which is much harder to detect but for which most Integrated Assessment Models (IAMs) are designed. Economic models also need to systematically quantify uncertainties related to structure and parameters and to frame economic conclusions in the context of known model limitations. Expressing the model results in probabilistic terms helps decision-makers to understand the risks of under- or overinvesting in adaptation to high- or low-probability climate change outcomes.

A3.7 Economic modelling of climate and trade

Trade is increasingly a subject of analysis within the economic modelling of climate change. Economic models show that trade can cushion against the large production shocks resulting from climate change and, if unrestricted, trade is expected to increase to compensate for production shortages or shifts in production patterns across regions due to climate [71-77]. However, the empirical evidence is incomplete and fraught with the usual caveats related to uncertainty vis-à-vis future climate outcomes and developments in climate and trade policy. More robust trade analyses in the context of climate change should integrate direct climate impacts on agricultural productivity, demand-side drivers (e.g. consumer diets, labelling, subsidies), resource constraints (such as climate-induced irrigation water shortages), as well as climate policies (e.g. carbon taxes, standards, ecolabelling). Moreover, the two-way linkage between climate and trade is not a settled issue as there remain a number of unanswered questions related to the environmental impact of increased trade (such as indirect land-use change from biofuel trade expansion).

B. PART TWO

Critical issues at the interface of climate and food security

Robust trends on global agricultural productivity are emerging from the growing literature on climate impact assessments, with clear indications of differential responses across regions. While climate change effects on agriculture will be felt everywhere, some regions will be more negatively affected than others, while some regions may benefit from climate warming – up to a point. Convergent results are showing negative effects on food supply in tropical zones but some positive effects in high-latitude regions. Moderate warming may benefit crops in the mid and high latitudes in the short term. However, any warming in seasonally dry and low-latitude regions would decrease yields. Densely populated developing countries in these regions are vulnerable to increased food insecurity [78].

These global trends present the world with multiple global challenges (globalization, sustainability, climate change, increased inequality) locked in increasing interdependence. The first global challenge is how to minimize, if not reverse, the negative impacts of climate on global food supply. Second, climate change is likely to exacerbate the growing inequality as the brunt of the negative climate effects is expected to fall on those countries that are least developed and most vulnerable. For these countries, low levels of economic development, weak institutions, and limited human and financial capital all contribute to limited resilience capacity. The third challenge is how to develop climate-compatible growth strategies that do not conflict with mitigation goals required to minimize further warming. Fourth is how to sustain policy commitments in a world increasingly defined by uncertainty, climate variability and greater policy interdependence.

B1. Climate and nutrition:

Improving analysis of climate-nutrition-health links

Adverse global impacts of climate change on health, including through malnutrition, are gaining increased attention. For example, in Kenya, a positive relationship has been observed between regional trends in climate (rising temperatures and declining rainfall) and childhood stunting since 1975 [80]. Climate-induced health risks develop from a variety of sources, including climate influence on food yields, water supply and quality, and infectious diseases, as well as the adverse health effects of social disruptions, migration and conflicts. In addition to adverse effects on food supply and adequate nutrition, climate change is likely to exacerbate global health concerns such as: increased incidence of new influenza virus strains; decline of available seafood proteins due to ocean warming, acidification and overfishing; and worsening freshwater shortages and resulting displacements and conflicts [80]. Some populations, especially in the least-developed countries, will be more negatively affected than others. Low-income and remotely located populations are more vulnerable to physical hazards, undernutrition, diarrhoea and other infectious diseases. Populations in low-lying islands and coastal areas, like Bangladesh, are also vulnerable to increased storm surges and flooding as the sea levels rise [80].

There is relatively little research on the implications for food quality and possible implications on human nutrition. A recent study reported that C_3 grains (e.g. wheat, rice) and legumes have lower concentrations of zinc and iron when grown under field conditions with elevated CO_2 levels [44]. C_3 crops other than legumes also have lower concentrations of protein. Analysis of food balance sheets from the Food and Agriculture Organization of the United Nations (FAO) found that in 2010 roughly 667 million people were living in countries whose populations received at least 60 percent of their dietary zinc and iron from C_3 grains or legumes. Similarly, 1.9 billion people who lived in these countries received at least 70 percent of one or both of these nutrients from these crops [44]. In the case of reduced proteins, the health implications from consuming non-leguminous C_3 plants are not uniform across regions and depend on local food patterns. In India, where up to a third of the rural population is at risk of not meeting protein requirements, and who depend on C_3 plants, decreased protein content due to higher CO_2 levels may have serious health consequences [44]. An extensive meta-analysis, covering 7761 observations and 130 species/cultivars, corroborated these findings [81]. This study found that elevated CO_2 reduces the overall mineral concentrations (by 8%) and increases the total non-structural carbohydrates (mainly starch and sugars) in C_3 plants. These results offer the first robust documentation of the adverse nutritional impact of climate change, which can exacerbate the prevalence of "hidden hunger" and obesity.

In the economic realm, the IMPACT modelling framework provides projections of climate impacts beyond production changes, all the way to nutrition outcomes. For example, the number and share of children who are malnourished in Africa is projected to be higher with climate change than without climate change, but both the number and share of malnourished children would fall between 2010 and 2050 as incomes rise for other reasons (Chapter 5, Table 13). However, more systematic probing of the nutritional implications of climate impacts on food security is required to generate the evidence required for appropriate policy response.

B2. Climate and water: *Growing need for systematic climate-food-water analysis*

Much of the climate change impact on agriculture is mediated through water. In many regions of the world, increased water scarcity under climate change will present a major challenge for climate adaptation. It is of paramount importance to address the implications of future water availability for food security and, by extension, nutrition and health. This requires improved modelling of hydrological processes and climate impacts on water dynamics at appropriate scales. It is also important to address the economics of water use, taking into account the special nature of water as a resource requiring a balanced approach between market instruments and institutional structures.

Hydrological modelling is a growing field of research. Improvements in downscaling techniques are making it possible to reconcile the scale gaps between large-scale climate impacts and local-scale hydrological processes. Interlinked models have also been designed to reconcile the scale difference between the basin-level hydrological models and the more aggregate (or national) level economic models. As water availability has become a global concern in light of climate change, more quantitative global hydrological and economic models are required to help facilitate global policy dialogue on water issues. Recent work has assessed the global impact of diet change on the blue (irrigated) and green (rainfed) water footprints of food consumption [82]. The study showed that when the dietary guidelines are followed, gradually limiting the amount of total protein intake from animal products to 50 percent, 25 percent, 12.5 percent and finally 0 percent reduced water consumption by 6 percent, 11 percent, 15 percent and 21 percent for green water, and by 4 percent, 6 percent, 9 percent and 14 percent for blue water, respectively [82]. These results suggest that reducing animal products in the human diet offers the potential to save water resources, up to the amount currently required to feed 1.8 billion additional people globally.

Economists argue for higher reliance on water markets and water pricing regimes as an effective adaptation tool to help facilitate water use by considering higher-value uses. At the same time, water is not a typical commodity, but a resource whose use is geographically bound, and whose access is determined by rights (not just by market value) and managed through public institutions.

Water economics present a number of modelling challenges because water is a resource whose use can be optimized in part through market instruments but which requires strong institutional structures to ensure people's rightful and equitable access to water. Modelling economics of water requires improved specification of the level and structure of water prices, the scope of water trading between users and across basins and the costs of water infrastructure investments. A key challenge is the availability of data, which are localized and managed by subnational agencies and lack consistency across regions. More importantly, economic water modelling improvements require including the political economy dimension of water markets (e.g. non-price water conservation mandates, legal property rights regimes).

B3. Climate mitigation and food security:

Co-benefits versus trade-offs

Climate change mitigation measures that affect food security involve reducing emissions from many sources. Several technologies targeting adaptation can also have mitigation co-benefits. Examples include new varieties with higher yields and enhanced pest and drought resistance, carbon sequestration and ability to survive on marginal lands.

Climate change mitigation and adaptation have revived discussion about the role of agricultural biotechnology and its potential to intensify production of food while reducing pressure on cropland. However, the potential value of biotechnology has been contested, and its dissemination is limited by demands for product labelling and other environmental approvals and controls under the Biosafety Protocol of the United Nations Convention on Biodiversity. Whether biotechnology can find a place among mitigation measures to combat climate change remains an open question.

Biofuel production falls at the interface between renewable energy and climate mitigation. Support to biofuel production in the last two decades, especially in the United States and Western Europe, was prompted in part as a contribution to climate mitigation. However, biofuels have become controversial, especially in relation to indirect land-use change and its association with increased carbon emissions (linked to deforestation). While awaiting economic breakthroughs for second-generation biofuels, current biofuel production from crops (rapeseed, maize, canola, sugar cane, soy, palm oil) is expected to continue over the medium term. Given that the net effect on mitigation of current biofuels is still uncertain, many countries have taken a more cautionary approach. Earlier drives for biofuel investments in developing countries have been scaled back due to concerns over food security conflicts. In the area of research, modelling biofuels within integrated assessment models requires more detailed account of land-use change effects. Also required are further advances in analysing climate-energy-food linkages and taking into account policy instruments and technology advances.

Nitrogen fertilizer – a critical input for agricultural productivity for non-legume crops – also presents a trade-off in terms of climate mitigation. Reducing emissions related to the production and use of nitrogen fertilizer will increase its cost, reduce its use and hence prevent yield gains required for intensification. There are, in fact, multiple trade-offs. The first is between food production and climate mitigation. Another trade-off is between intensifying agricultural production with the use of fertilizers, which lessens land pressure (hence lowering emissions), or reducing emissions from fertilizer production, resulting in stagnant yields and higher pressure on forests and grasslands. Clearly a balanced approach is required, one that ensures fertilizers remain affordable to farmers but with improvements in use efficiency (through better fertilizer delivery technologies) that would allow for lower fertilizer use without negatively affecting yield.

B4. Climate and trade: *Understanding the trends and tackling trade-offs*

Climate change fundamentally alters global food production patterns and, given the fact that impacts are expected to be worse in low-latitude regions, climate change is likely to exacerbate existing imbalances between the developed and developing world. For crop impacts at least, there is now a coherent pattern of yield changes across the world, with yields expected to increase in some higher latitude regions until about the mid-century before declining, but with almost immediate declines in yields across the tropics [83]. Spatial differences are also observed at regional and subregional scales, particularly where there are substantial differences in elevation. The impacts of climate change (and of climate mitigation policies [84-87]) thus have a major impact on patterns of global trade [88].

It is clear from climate change impact assessments to date that trade will probably expand under climate change. Trade flows would increase from mid to high latitudes towards low-latitude regions, where production and export potential will be reduced [78]. Climate change is also projected to cause wide variations in the net global food supply as the result of a higher frequency of droughts and extreme weather events [78]. Climate change can transform trade by altering the comparative advantages, while more frequent extreme weather patterns have an adverse impact on trade by disrupting transportation, supply chains and logistics [89].

Trade can also affect climate change. Increased economic activity, including trade, also increases greenhouse gas emissions. In many developing countries that have weak enforcement of environmental protection, growing demand for food crops drives the expansion of production for exports (maize, rice, biofuel feedstocks). In other cases, unregulated exports of forest products can exacerbate deforestation, land degradation and loss of biodiversity.

Global markets can play a stabilizing role for prices and supplies and provide alternative food options for negatively affected regions by changing conditions or by finding regions where food can be produced more efficiently (both in terms of environmental and economic costs). However, trade alone is not a sufficient adaptation strategy, owing to several trade-offs. First, there is serious tension between trade versus the environment. Second, dependence on imports to meet food needs may increase the risk of exposure to higher market and price volatility that is expected under climate change. A recent example can serve as an illustration of future trends. The extreme heat and wildfires in western Russia in the summer of 2010 destroyed one-third of that country's wheat yield, and the subsequent ban on exported grain contributed to a rise in the price of wheat worldwide, exacerbating hunger in Russia and in low-income urban populations in countries such as Pakistan and Egypt [80].

The spatial dimension of climate change impacts will be critical to the development of trade policies. Müller and Elliott (Chapter 2) show how the impacts of climate change on the production of food calories could vary spatially by the end of the century. They attribute uncertainties in these projections to patchy coverage of data for model calibration and testing, lack of knowledge of management practices across the modelling domain and limited physiological understanding of crop response to elevated CO_2. They conclude that "consideration of various scenarios on future agricultural management is crucial" to the assessment of future agricultural productivity under climate change.

In addition to the direct impact of climate change on primary production, changing socio-economics can alter comparative advantages and trade flows, and potentially alter future international competitiveness and agrifood trade patterns (see Ahammad, Chapter 10). Model projections of imports and exports under climate change showed differences across scenarios due to non-climate economic, demographic and technology assumptions. However, Ahammad identified common trends across climate change model runs, such as the continued importance of the United States as a net exporter of coarse grains and oilseeds in 2050 and that net trade for the fast-growing developing economies and exports were both projected to decrease by much less than the projected decline in production attributable to climate change. Various projections for trade in China showed contrasting responses on trade, highlighting an important area in which the evidence is uncertain.

B5. Climate and poverty: *Mainstreaming adaptation into development*

Combating climate change must go hand in hand with alleviating poverty. Adverse effects of climate are greater among the poor in developing countries, who are highly dependent on climate-sensitive natural resources yet have the least adaptive capacity to cope with climate impacts. There is general agreement that development investments in climate change impact are competing with efforts to eradicate poverty over the medium term [91].

Consequently, there is increasing support for mainstreaming climate change responses within human development and poverty alleviation rather than pursuing separate climate and poverty tracks and risking potentially negative outcomes for one or the other of these goals. Such mainstreaming would require policies that can achieve co-benefits for poverty alleviation, climate adaptation and greenhouse gas emission reduction [92, 93, 94]. Mainstreaming involves the integration of information, policies and measures to address climate change in ongoing development planning and decision-making. Mainstreaming should create "no regrets" opportunities for achieving development that are resilient to current and future climate impacts for the most vulnerable groups, and avoid potential trade-offs between adaptation and development strategies, which can result in maladaptation [91].

Given that the task of alleviating poverty is itself formidable, adding climate adaptation and mitigation hugely complicates the process, requiring an innovative framework commensurate with the complexity at hand yet tractable to achieve results. While there is no single methodology to achieve this, some basic concepts exist that can guide mainstreaming adaptation [92]. First among these is the view that climate adaptation is inseparable from the cultural, economic, political, environmental and developmental contexts in which it occurs. Second, responses to climate change often cross spatial and jurisdictional boundaries, requiring coordination to avoid maladaptation. Third, because of positive feedback loops, system trajectories are path-dependent and difficult to change. Fourth, contested rules, values and knowledge cultures determine social decision-making processes which respond to change [95]. These basic guidelines clearly suggest a paradigm shift between research, policy and practice [92] so that adaptation pathways must be able to trigger a change along each of three components. Such a shift also means that processes and tools must be developed among all the key stakeholders who can facilitate and manage the contested decision-making arena [92].

In practice, how mainstreaming is achieved depends on the adaptation approach taken – that is, technology-based (impacts-based) or development-based (vulnerability-based) [91]. Under the former, mainstreaming ensures that projections of climate change impacts are considered in the decision-making about climate investments (known as "climate-proofing"). With the development-based view, adaptation goes beyond "climate-proofing" and recognizes the implication of many actors and the importance of an enabling environment. This approach emphasizes the need to remove existing financial, legal, institutional and knowledge barriers to adaptation, and to strengthen the capacity of people and organizations to adapt. A review by the World Resources Institute of over 100 "adaptation" interventions found that adaptation and development are not totally separable. These interventions lie along a continuum, from those that overlap almost completely with development practices that build general resilience to those that are focused more specifically on climate change impacts. [96]

As an illustration of adaptation mainstreaming, a recent study from Bangladesh describes a framework that follows a linear sequence of stages, starting with raising awareness, scientific capacity building, generating evidence and conducting pilot studies to inform and engage the decision-makers in policy planning [91]. Building awareness is a critical first step towards generating enough interest on the part of decision-makers to demand climate vulnerability information. It is necessary to generate evidence that can show how and why climate vulnerability is a problem requiring integration into development decisions. Locally developed information is more likely to be relevant to the decision-making contexts of country decision-makers. Investing in building national capacity is required to generate locally appropriate evidence that is connected to the body of international climate science. For least-developed countries, technology transfer is a critical requisite for successful adaptation strategy and requires creative options to relax the patents and other intellectual property protection constraints to technology transfer from advanced countries to developing countries [97]. The next stage in the framework calls for pilot studies to inform policy-makers and to generate incentives to incorporate the lessons learned into policy planning. The final stage involves the full integration of climate change adaptation into policy and planning across different sectors and scales, requiring investment planning that combines "climate proofing" with building resilience among the climate-vulnerable poor. It is at this stage that government stakeholders and decision-makers become fully engaged in adaptation planning.

As our understanding of climate and food security increases, we need to steer it beyond crop yield impacts and expand the debate into new drivers of food productivity (biotechnology, bioenergy and trade). Climate impact on food security should be broadened systematically to include nutrition and health. Of particular relevance is the need to broaden the crop coverage to include crops important for regional (not necessarily global) food security, as well as other land- use enterprises (livestock, agroforestry). Climate impact should also be linked with poverty alleviation and sustainability of resources (water, soils, nitrogen fertilizer). Climate impact science also needs to become more systems-based and multidimensional. For example, addressing the health risks of climate change requires a cross-sectional approach because health risks are tied to such sectors as water, agriculture and energy. Improved frameworks are necessary to examine cross-sectoral linkages such as climate-food-trade [79], climate-nutrition-health, climate-food-water and climate-food-energy. In addition, global climate impact analysis should "come down to earth" and be validated at the local level, accounting for spatial variability, possible adaptation responses, local resource availabilities and constraints, and socio-economic determinants.

C. PART THREE

Policy messages, communication and the need for two-way science-policy dialogue

C1. Matching evidence on climate impacts to the needs of policy-makers

Robust and reliable evidence is critical to the development of policies to address climate impacts on agriculture, food and trade. When used effectively, evidence can be used to guide decisions on policy, highlight options for policy action and also identify areas where insufficient evidence currently exists. However, the interaction between those generating evidence (climate science) and the needs of those developing policy is not straightforward. This section considers which factors contribute to an effective science-policy dialogue and highlights examples from this volume of evidence about climate impacts on agriculture, food and trade that are relevant to policy. It concludes with a recommendation for a forum to enable more effective dialogue between science and policy.

There is often a mis-match between the type of evidence produced from the climate impact research community and what is needed for policy development. This can be illustrated with two contrasting examples. The first is that primary evidence, as it is produced, is often too detailed. At the time of publication of the first report of the IPCC in 1990 (with a supplement in 1992) [98], little was known about the impacts of human-induced climate change on agricultural crops and livestock. The synthesis of climate science knowledge by the IPCC prompted crop scientists to begin investigating the direct effects of warmer temperatures, changed rainfall patterns and elevated concentrations of CO_2 on the growth of crops. Over the next two decades many thousands of research papers reported findings on the direct impacts of climate change on all of the world's major food crops in many different countries and regions. This work provided a wealth of detail, but on its own the evidence is not easily interpreted by those looking for high-level conclusions on climate impacts across the sector to guide policy formulation. Instead, it is the syntheses of primary research that more closely meet the policy need for robust and coherent statements of evidence from the underpinning science. Good examples of evidence syntheses include: the "impacts" chapters of the subsequent IPCC reports, most recently in 2014 [99]; a systematic review of crop impacts in Africa and Asia [100]; and a recent meta-analysis of climate change impacts on crops [101]. These syntheses of knowledge provide robust statements of current evidence that can be used with a degree of confidence by those looking for summaries of the state of evidence on climate impacts. A number of such statements regarding climate impacts on food security were recently proposed [83].

The second example of a mis-match between evidence needs for policy and research knowledge is that the evidence is often not specific enough to base policy and operational decisions on it. This may seem to contradict the first point – that research evidence is too detailed – but it is a different issue, best illustrated through an example. Knox and colleagues [100] reviewed all studies to date of climate impacts on the major food crops across Africa and South Asia using systematic review criteria as a quality filter. A range of modelling methods, time periods and ensemble sizes (from a single climate model to ensembles of 20 or more climate models) were included. They found that average crop yields were projected to decline across both regions by 8 percent by the 2050s. Across Africa, yields were projected to change by -17 percent (wheat), -5 percent (maize), -15 percent (sorghum) and -10 percent (millet), and across South Asia by -16 percent (maize) and -11 percent (sorghum) under climate change. No mean change in yield was detected for rice. These are all clear and robust statements of impact for crops and regions for which there is good coverage in the evidence base. However, for many crop and country combinations there was not enough evidence to draw any general conclusions; thus, the authors concluded that the evidence was either inconclusive, absent or contradictory for rice, cassava and sugar cane. Those looking for evidence for important African staples such as yam, millet and bananas on which to base climate adaptation policies will find almost nothing on which to base policy advice.

Those that work on the science-policy dialogue are not necessarily drawn from only research institutions or policy organizations. Instead there are a raft of intermediary organizations, such as think tanks, civil society organizations and consultancies, that synthesize, filter, reinterpret and reorganize evidence to aid the uptake of information into policy. For example, the Climate

Development and Knowledge Network [102] combines research, advisory services and knowledge management in support of locally owned and managed policy processes. Where these organizations also act as portals, they can facilitate sharing of evidence, experiences and lessons from past and current policy initiatives.

A common barrier to the uptake of evidence into policy is that the evidence does not meet, or is not presented in a way that meets, the information needs of those developing policy. Often the research community does not start by defining the information needs of the policy community, but instead works from the evidence in search of applications in policy. Such an approach is often ineffective and will also contributes to a mis-match of information with needs for evidence. The way in which science is communicated for policy development is different from a simple technical summary of the research. For example, the IPCC Summaries for Policy-makers are quite different from the Technical Summaries, even though both are based on the same synthesis of evidence. Effort invested in matching the form of evidence communication to the needs of the intended reader is clearly worthwhile.

Finally, the timing of evidence for policy is absolutely critical. Evidence needs to adjust to policy and political cycles. Many policy-advising intermediary organizations have addressed these communication barriers to provide finer-level and more rapid analyses tailored to specific policy requirements for information and knowledge.

C2. Policy insights on climate change impacts under uncertainty

Most policies have to cope with levels of uncertainty in the evidence base they use. This is definitely the case for climate adaptation policies, perhaps more so than in other policy areas. Uncertainties for climate policy arise regarding greenhouse gas emission scenarios and from the climate and crop models that are used to form projections of future impacts. Numerical methods can be used to better define the boundaries of uncertainty, by running ensembles of climate models [103] or by systematically varying parameters within climate [104] or crop models [105], but considerable uncertainty in projections will still remain. Rötter and Höhn (Chapter 4, Figure 1) show how uncertainties and errors in climate change impact modelling are propagated along the impact modelling chain.

Policy advice will often define options for action. A robust assessment of the uncertainties in impact projections can contribute to at least a qualitative statement of the risks about individual policy options. Indeed, the absence of any statement of uncertainty implies that each option is equally uncertain. However, it is likely that the precision of these statements will at most be approximate. The calibrated language used by the IPCC to communicate uncertainties in climate science and impacts evidence is a good example [106]. Confidence in IPCC conclusions from the evidence is a product of the degree of expert agreement and the completeness of the evidence base. The likelihood of particular conclusions is defined by a seven point scale – from exceptionally unlikely (0-1% probability) to virtually certain (99-100% probability). The guidelines conclude with the recommendation for contributing authors to “communicate uncertainty carefully, using calibrated language for key findings, and provide traceable accounts describing your evaluations of evidence and agreement” [106].

Within the climate impacts research community, formal treatment of uncertainties is often done well, particularly with regard to direct climate impacts on crops or livestock and in cases where these uncertainties are of biophysical origin [107, 108]. However, policies for the agricultural sector or for food trade have to consider a much wider range of uncertainties from political, economic and social sources that are often far harder to foresee and account for than those from biophysical sources. Simulation modelling of possible impact and adaptation pathways can help to at least explore uncertainties in these possible "futures". Examples include the Special Report on Emissions Scenarios (SRES) socio-economic pathways developed for the IPCC reports [109], and similar approaches used for the Millennium Ecosystem Assessment [110]. However, simply defining a specific set of possible socio-economic pathways constrains the exploration of uncertainties to those within the boundaries of these projected futures. Lioubimtseva *et al*. (Chapter 6) conclude that economic and institutional changes in Russia, Ukraine and Kazakhstan have dominated historic changes in grain exports, although there is also an impact of weather variability. The projected effects of climate change by 2020 on grain exports in Russia, Ukraine and Kazakhstan differed in direction – i.e. decreased exports for Ukraine, increased exports for Russia and Kazakhstan – and in magnitude, between SRES B2 and A2 socio-economic scenarios (Table 12, Chapter 6).

Climate change as a result of human activities will produce changes in both the mean and variability of climate. Changes in variability add a further dimension to policy development, introducing an element of risk management for adaptation responses and the possibility of threshold events, such as shocks to primary productivity, price or demand for food products [83]. Risk-based approaches to climate adaptation have been developed in response to the challenges of sea-level rise, but climate risks in the agriculture and food sector are inherently more complex.

The concept of resilience came from ecology and describes the ability of an ecological system to recover from a shock, climatic or otherwise. In recent years, those working on adaptation to climate change have applied these concepts to other natural and social systems. The thinking is that better resilience to climate variability and change can be increased through building biological and institutional capacity to respond to shocks, by investing in infrastructure, social protection measures and so on. An appealing aspect of this approach is that it does not matter what the precise degree of projected climate change is, a more resilient society should be better prepared for climate change impacts.

Any effective development intervention to address adaptation should be able to evaluate its outcomes. For adaptation to climate change this is difficult. Waiting until the year 2030, for example, is not a useful strategy. This is a current topic of debate, but a resilience approach seems to address well the problems of making decisions in the face of uncertainty around climate change and its impacts and the challenges of local-scale vulnerability. However, to date there are very few examples of evaluation of resilience of communities and societies in practice. Resilience is often evaluated with respect to climate variability in the current climate, but when we expect a change in the mean and variability of climate in the future, how effective can this evaluation be? Risk management options for agriculture under climate change still constitute an important gap in the evidence. Indeed Rötter and Höhn (Chapter 4) conclude that there is a "lack of a comprehensive, well-tested methodology for the assessment of multiple risks to crop production under climate change".

C3. Harmonizing climate with trade policy

Policy tension between climate mitigation and trade-related economic growth is a necessary outcome that requires careful analysis and appropriate response. While climate science is indisputable, trade policy analysis in the context of climate change is far from conclusive and more analytical work is required to arrive at climate-compatible trade policies. In addition, the role of trade measures in the context of international negotiations on climate change stabilization is unclear. There is no consensus as to whether current World Trade Organization (WTO) trade rules can promote adherence to climate goals or are a threat to mutually agreed climate solutions [78]. Many of the hotly debated issues in the Doha

Round trade negotiations, including new special safeguard mechanisms, could take on renewed relevance when considering climate change. The proposal to expand the mandate of the Environmental Goods and Services negotiations to include all biofuels is another area of contention, despite its potential to advance more efficient and resource-friendly biofuel production, especially from second generation biofuels. Climate change also underscores the need to help developing countries deal with food and energy price increases, as well as volatile food supplies.

A number of climate change mitigation policies are potentially affected by trade rules [78]. Developed countries that impose national mitigation measures (such as carbon taxes, or cap-and-trade regimes) counter the potential shift of production ("leakage") overseas with unilateral import taxes. Without international agreement on climate policy, such measures would be challenged under WTO rules. Standards and certification systems can be important tools in climate change mitigation and adaptation. However, the use of standards, particularly by governments, may clash with WTO rules. Environmental payments for services, such as payments for forest and soil carbon sequestration, can also address climate change mitigation. However, if granted by governments, these payments could clash with WTO subsidy rules. These cases make clear the need to harmonize rules with climate objectives.

Progress on climate-compatible trade policy requires tackling the considerable apprehension that climate measures can distort trade, and alternatively, that trade rules could stand in the way of greater progress on climate change [90]. In the short term, opportunities for conflict exist as countries pursue unilateral policy choices to stabilize emissions through regulatory regimes, taxation and other instruments. In the longer term, trade rules that do not allow internalization of the cost of carbon would negatively affect climate change mitigation. Tariff structures could be tailored to internalize the cost of carbon and greenhouse gas emissions so that countries can assess higher tariffs on carbon-intensive goods than on goods with lesser carbon footprints [78]. Likewise, future climate change mitigation policies should include measures designed to internalize the environmental costs of resources.

C4. Recommendations for structured science-policy dialogue

Despite the very real uncertainties in the underlying science, decisions still need to be made by a whole range of decision-makers, from policy-makers to practitioners in the agricultural sector (Chapter 10). Decisions can only be made using the best evidence that is available at the time and they cannot wait until "perfect" knowledge is achieved. Wheeler and von Braun [83] provided examples of evidence statements that could be used by those making decisions as policy-makers and practitioners confronted with the prospect of climate change impacts on food security, despite very real uncertainties in current knowledge and future trends. These statements were:

1. Climate change impacts on food security will be worst in countries already suffering high levels of hunger and will worsen over time.
2. The consequences for global undernutrition and malnutrition of doing nothing in response to climate change are potentially large, and will increase over time.
3. Food inequalities will increase, from local to global levels, because the degree of climate change and the extent of its effects on people will differ from one part of the world to another, from one community to the next and between rural and urban areas.
4. People and communities who are vulnerable to the effects of extreme weather now will become more vulnerable in the future and less resilient to climate shocks.
5. There is a commitment to climate change of 20-30 years into the future as a result of past emissions of greenhouse gases that

necessitates immediate adaptation actions to address global food insecurity over the next two to three decades.

6. Extreme weather events are likely to become more frequent in the future and will increase risks and uncertainties within the global food system.

How can a structured two-way dialogue be achieved between science and policy for production and trade impacts of climate change? One possibility is to set up a structured forum dedicated to providing a portal to climate change impact evidence for agriculture and policy for trade and food security. Such a forum could focus on: the exchange and dissemination of knowledge of latest impact assessment models related to climate-food-trade, climate-food-water, Climate Adaptation and mitigation measures linked to food security, and climate adaptation mainstreaming into development. The forum should provide the scientific links between global and regional climate assessments and facilitate exchange of knowledge between international and regional research centres and between researchers and policy makers. The forum could also operate along specific regional themes focusing on hot spot areas, common regional problems (priority sectors of regional significance; regional water scarcity problems; soil fertility; regional capacity in research & development). The forum could also facilitate policy feedback back to science to improve data, information and knowledge related to future developments in agriculture in relation to climate change.

The forum should define a number of core principles to guide its ways of working including a firm commitment that evidence generation is demand-led by those in policy; robust and detailed assessments of uncertainties in evidence; and an emphasis on high standards of communication of evidence for policy. The forum should also build on and leverage expertise within existing knowledge networks, international organizations dedicated to climate change food security and specialized in adaptation, mitigation, water, trade and relevant policy analysis. We can be certain that climate change impacts on agricultural production and trade will be substantial, will change over time and will bring challenges to those making policy that have not been encountered to date. These features alone make the establishment of a structured forum dedicated to providing a portal to climate change impact evidence for agriculture and policy for trade and food security an urgent prerogative for policy development.

References

1. Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. *Science*, 304(5677): 1623-1627.

2. Henderson-Sellers, A. & V. Gornitz. 1984. Possible climatic impacts of land cover transformations, with particular emphasis on tropical deforestation. *Climatic Change*, 6(3): 231-257.

3. Rosenzweig, C. & M. Parry. 1994. Potential impact of climate change on world food supply. *Nature*, 367(6459): 133-138.

4. Rosenzweig, C., J. Elliott, D. Deryng, A. Ruane, C. Müller, A. Arneth, K. Boote, C. Folberth, M. Glotteri, N. Khabarov, K. Neumann, F. Piontek, T. Pugh, E. Schmid, E. Stehfest, H. Yang & J. Jones. 2014. Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proceedings of the National Academy of Sciences*, 111(9): 3268-3273.

5. Challinor, A., J. Watson, D. Lobell, S. Howden, D. Smith & N. Chhetri. 2014. A meta-analysis of crop yield under climate change and adaptation. *Nature Clim. Change*, 4(4): 287-291.

6. Elliott, J., D. Deryng, C. Müller, K. Frieler, M. Konzmann, D. Gerten, M. Glotter, M. Flörke,

Y. Wada, N. Best, S. Eisner, B. Fekete, C. Folberth, I. Foster, S. Gosling, I. Haddeland, N. Khabarov, F. Ludwig, Y. Masaki, S. Olin, C. Rosenzweig, A. Ruane, Y. Satoh, E. Schmid, T. Stacke, Q. Tang & D. Wisser. 2014. Constraints and potentials of future irrigation water availability on agricultural production under climate change. *Proceedings of the National Academy of Sciences*, 111(9): 3239-3244.

7. Pionteka, F., C. Müller, T. Pugh, D. Clark, D. Deryng, J. Elliott, F. González, M. Flörke, C. Folberth, W. Franssen, K. Frieler, A. Friend, S. Gosling, D. Hemming, N. Khabarov, H. Kim, M. Lomas, Y. Masaki, M. Mengel, A. Morse, K. Neumann, K. Nishina, S. Ostberg, R. Pavlick, A. Ruane, J. Schewe, E. Schmid, T. Stacke, Q. Tang, Z. Tessler, A. Tompkins, L. Warszawski, D. Wisser & H. Schellnhuber. 2014. Multisectoral climate impact hotspots in a warming world. *Proceedings of the National Academy of Sciences*, 111(9): 3233-3238.

8. Liu, J., J. Williams, A. Zehnder & H. Yang. 2007. GEPIC - modelling wheat yield and crop water productivity with high resolution on a global scale. *Agricultural Systems*, 94(2): 478-493.

9. Jones, J., G. Hoogenboom, C. Porter, K. Boote, W. Batchelor, L. Hunt, P. Wilkens, U. Singh, A. Gijsman & J. Ritchie. 2003. The DSSAT cropping system model. *European Journal of Agronomy*, 18(3-4): 235-265.

10. Xiong, W., J. Balkovič, M. van der Velde, X. Zhang, R. Izaurral, R. Skalský, E. Lin, N. Mueller & M. Obersteiner. 2014. A calibration procedure to improve global rice yield simulations with EPIC. *Ecological Modelling*, 273(0): 128-139.

11. Elliott, J., D. Kelly, J. Chryssanthacopoulos, M. Glotter, K. Jhunjhnuwala, N. Best, M. Wilde & I. Foster. 2014. The parallel system for integrating impact models and sectors. *Environmental Modelling & Software*, advance online publication.

12. Gueneau, A., C. Schlosser, K. Strzepek, G. Xiang & E. Monier. 2012. CLM-AG: *An agriculture module for the Community Land Model version 3.5.* MIT Joint Program on the Science and Policy of Global Change.

13. Drewniak, B., J. Song, J. Prell, V. Kotamarthi & R. Jacob. 2013. Modeling agriculture in the Community Land Model. *Geosci. Model Dev.*, 6(2): 495-515.

14. Van den Hoof, C., E. Hanert & P. Vidale. 2011. Simulating dynamic crop growth with an adapted land surface model - JULES-SUCROS: Model development and validation. *Agricultural and Forest Meteorology*, 151(2): 137-153.

15. Bondeau, A., P. Smith, S. Zahele, S. Schaphoff, W. Lucht, W. Cramer, D. Gerten, H. Lotze-Campen, C. Müller, M. Reichstein & B. Smith. 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology*, 13(3): 679-706.

16. Müller, C. & R. Robertson. 2014. Projecting future crop productivity for global economic modeling. *Agricultural Economics*, 45(1): 37-50.

17. Waha, K., L. van Bussel, C. Müller & A. Bondeau. 2012. Climate-driven simulation of global crop sowing dates. *Global Ecology and Biogeography*, 21(2): 247-259.

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

19. Schlenker, W. & D. Lobell. 2010. Robust negative impacts of climate change on African agriculture. *Environmental Research Letters*, 5(1): 014010.

20. Challinor, A., T. Wheeler, P. Craufurd, J. Slingo & D. Grimes. 2004. Design and optimisation of a large-area process-based model for annual

crops. *Agricultural and Forest Meteorology*, 124(1-2): 99-120.

21. Tao, F., Z. Zhang, J. Liu & M. Yokozawa. 2009. Modelling the impacts of weather and climate variability on crop productivity over a large area: A new super-ensemble-based probabilistic projection. *Agricultural and Forest Meteorology*, 149(8): 1266-1278.

22. Tao, F., M. Yokozawa & Z. Zhang. 2009. Modelling the impacts of weather and climate variability on crop productivity over a large area: A new process-based model development, optimization, and uncertainties analysis. *Agricultural and Forest Meteorology*, 149(5): 831-850.

23. Deryng, D., W, Sacks, C. Barford & N. Ramankutty. 2011. Simulating the effects of climate and agricultural management practices on global crop yield. *Global Biogeochem. Cycles*, 25(2): GB2006.

24. Asseng, S., F. Ewert, C. Rosenzweig, J. Jones, J. Hatfield, A. Ruane, K. Boote, P. Thorburn, R. Rötter, D. Cammarano, N. Brisson, B. Basso, P. Martre, P. Aggarwal, C. Angulo, P. Bertuzzi, C. Biernath, A. Challinor, J. Doltra, S. Gayler, R. Goldberg, R. Grant, L. Heng, J. Hooker, L. Hunt, J. Ingwersen, R. Izaurralde, K. Kersebaum, C. Müller, S. Kumar, C. Nendel, G. O'Leary, J. Olesen, T. Osborne, T. Palosuo, E. Priesack, D. Ripoche, M. Semenov, I. Shcherbak, P. Steduto, C. Stöckle, P. Stratonovitch, T. Streck, I. Supit, F. Tao, M. Travasso, K. Waha, D. Wallach, J. White, J. Williams & J. Wolf. 2013. Uncertainty in simulating wheat yields under climate change. *Nature Climate Change*, 3: 827-832.

25. FAO/IIASA/ISRIC/ISSCAS/JRC. 2012. *Harmonized world soil database (version 1.2).* FAO, Rome, Italy and IIASA, Laxenburg, Austria.

26. Mueller, N., J. Gerber, M. Johnston, D. Ray, N. Ramankutty & J. Foley. 2012. Closing yield gaps through nutrient and water management. *Nature*, 490(7419): 254-257.

27. Potter, P., N. Ramankutty, E. Bennett & S. Donner. 2010. Characterizing the spatial patterns of global fertilizer application and manure production. *Earth Interactions*, 14(2): 1-22.

28. Sacks, W., D. Deryng, J. Foley & N. Ramankutty. 2010. Crop planting dates: an analysis of global patterns. *Global Ecology and Biogeography*, 19(5): 607-620.

29. Popp, A., H. Lotze-Campen & B. Bodirsky. 2010. Food consumption, diet shifts and associated non-CO_2 greenhouse gases from agricultural production. *Global Environmental Change-Human and Policy Dimensions*, 20(3): 451-462.

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

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

32. Havlík, P., H. Valin, A. Mosnier, M. Obersteiner, J. Baker, M. Herrero, M. Rufino & E. Schmid. 2013. Crop productivity and the global livestock sector: Implications for land use change

and greenhouse gas emissions. *American Journal of Agricultural Economics*, 95(2): 442-448.

33. Wise, M. & K. Calvin. 2011. GCAM 3.0 *Agriculture and land use: Technical description of modeling approach*. Pacific Northwest National Laboratory: Richland, WA, USA.

34. Hertel, T., J. Steinbuks & U. Baldos. 2013. Competition for land in the global bioeconomy. *Agricultural Economics*, 44(s1): 129-138.

35. Elliott, E., B. Sharma, N. Best, M. Glotter, J. Dunn, I. Foster, F. Miguez, S. Mueller & M. Wang. 2014. A spatial modeling framework to evaluate domestic biofuel-induced potential land use changes and emissions. *Environmental Science & Technology*, 2014.

36. Sheffield, J. & E. Wood. 2008. Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. *Climate Dynamics*, 31(1): 79-105.

37. Romm, J. 2011. Desertification: The next dust bowl. *Nature*, 478(7370): 450-451.

38. Ray, D., N. Ramankutty, N. Mueller, P. West & J. Foley. 2012. Recent patterns of crop yield growth and stagnation. *Nature Communications*, 3: 7.

39. Edgerton, M. 2009. Increasing crop productivity to meet global needs for feed, food, and fuel. *Plant Physiology*, 149(1): 7-13.

40. Lin, M. & P. Huybers. 2012. Reckoning wheat yield trends. *Environmental Research Letters*, 7(2): 024016.

41. FAOSTAT data, http://faostat.fao.org/ 2013.

42. van Ittersum, M., K. Cassman, P. Grassini, J. Wolf, P. Tittonell & Z. Hochman. 2013. Yield gap analysis with local to global relevance - A review. *Field Crops Research*, 143(1): 4-17.

43. Leakey, A., E. Ainsworth, C. Bernacchi, A. Rogers, S. Long & D. Ort. 2009. Elevated CO_2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. *Journal of Experimental Botany*, 60(10): 2859-2876.

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

45. Ainsworth, E.A. & S.P. Long. 2005. What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2. *New Phytologist*, 165(2): 351-371.

46. Ruane, A., S. McDermid, C. Rosenzweig, G. Baigorria, J. Jones, C. Romero & L. Cecil. 2014. Carbon–Temperature–Water change analysis for peanut production under climate change: a prototype for the AgMIP Coordinated Climate-Crop Modeling Project (C3MP). *Global Change Biology*, 20(2): 394-407.

47. Ray, D., N. Mueller, P. West & J. Foley. 2013. Yield trends are insufficient to double global crop production by 2050. *Plos One*, 8(6): 8.

48. Iizumi, T., M. Yokozawa, G. Sakurai, M. Travasso, V. Romanenkov, P. Oettli, T. Newby, Y. Ishigooka & J. Furuya. 2013. Historical changes in global yields: major cereal and legume crops from 1982 to 2006. *Global Ecology and Biogeography*, advance online publication.

49. Licker, R., M. Johnston, J. Foley, C. Barford, C. Kucharik, C. Monfreda & N. Ramankutty. 2010. Mind the gap: how do climate and agricultural management explain the 'yield gap' of croplands around the world? *Global Ecology and Biogeography*, 19(6): 769-782.

50. Folberth, C., H. Yang, T. Gaiser, K. Abbaspour & R. Schulin. 2013. Modeling maize yield responses to improvement in nutrient, water and cultivar inputs in sub-Saharan Africa. *Agricultural Systems*, 119(0): 22-34.

51. Rosenzweig, C., J. Jones, J. Hatfield, A. Ruane, K. Boote, P. Thorburn, J. Antle, G. Nelson, C. Porter, S. Janssen, S. Asseng, B. Basso, F. Ewert, D. Wallach, G. Baigorria & J. Winter. 2013. The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies. *Agricultural and Forest Meteorology*, 170: 166-182.

52. Kriegler, E., B. O'Neill, S. Hallegatte, T. Kram, R. Lempert, R. Moss & T. Willibanks. 2012. The need for and use of socio-economic scenarios for climate change analysis: A new approach based on shared socio-economic pathways. *Global Environmental Change*, 22(4): 807-822.

53. Moss, R., J. Edmonds, K. Hibbard, M. Manning, S. Rose, D. van Vuuren, T. Carter, S. Emori, M. Kainuma, T. Kram, G. Meehl, J. Mitchell, N. Nakicenovic, K. Riahi, S. Smith, R. Stouffer, A. Thomson, J. Weyant & T. Wilbanks. 2010. The next generation of scenarios for climate change research and assessment. *Nature*, 463(7282): 747-756.

54. van Vuuren, D., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G. Hurtt, T. Kram, V. Krey, J-F. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, S. Smith & S. Rose. 2011. The representative concentration pathways: an overview. *Climatic Change*, 109(1): 5-31.

55. Taylor, K., R. Stouffer & G. Meehl. 2012. An overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society, 93(4): 485-498.

56. Warszawski, L., K. Frieler, V. Huber, F. Piontek, O. Serdeczny & J. Schewe. 2013. The Inter-Sectoral Impact Model Intercomparison Project (ISI–MIP): Project framework. *Proceedings of the National Academy of Sciences of the United States of America*, early view.

57. Trnka, M., R. Rötter, M. Ruiz-Ramos, K-C. Kersebaum, J. Olesen & M. Semenov. 2014. Adverse weather conditions for wheat production in Europe will become more frequent with climate change. *Nature Climate Change*, 4 (doi: 10.1038/nclimate2242).

58. Müller, C., W. Cramer, W. Hare & H. Lotze-Campen. 2011. Climate change risks for African agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, 108(11): 4313-4315.

59. Crespo, O., S. Hachigonta & M. Tadross. 2011. Sensitivity of southern African maize yields to the definition of sowing dekad in a changing climate. *Climatic Change*, 106(2): 267-283.

60. Müller, C., K. Waha, A. Bondeau & J. Heinke. 2014. Hotspots of climate change impacts in sub-Saharan Africa and implications for adaptation and development. *Global Change Biology*.

61. Zinyengere, N., O. Crespo & S. Hachigonta. 2013. Crop response to climate change in southern Africa: A comprehensive review. *Global and Planetary Change*, 111(0): 118-126.

62. Marin, F. & G. Carvalho. 2012. Spatio-temporal variability of sugarcane yield efficiency in the state of São Paulo, Brazil. *Pesquisa Agropecuária Brasileira*, 47(2): 149-156.

63. Marin, F., J. Jones, A. Singels, F. Royce, E. Assad, G. Pellegrino & F. Justino. 2013. Climate change impacts on sugarcane attainable yield in southern Brazil. *Climatic Change*, 117(1-2): 227-239.

64. Koehler, A-K., A. Challinor, E. Hawkins & S. Asseng. 2013. Influences of increasing

temperature on Indian wheat: quantifying limits to predictability. *Environmental Research Letters*, 8(3): 034016.

65. Soora, N., P. Aggarwal, R. Saxena, S. Rani, S. Jain & N. Chauhan. 2013. An assessment of regional vulnerability of rice to climate change in India. *Climatic Change*, 118(3-4): 683-699.

66. Kumar, S., P. Aggarwal, D. Rani, R. Saxena, N. Chauhan & S. Jain. 2014. Vulnerability of wheat production to climate change in India. *Climate Research* 59(3): 173-187.

67. Yang, H. and X. Li. 2000. Cultivated land and food supply in China. *Land Use Policy*, 17(2): 73-88.

68. Elliott, J., C. Müller, D. Deryng, J. Chryssanthacopoulos, K. Boote, M. Büchner, I. Foster, M. Glotter, J. Heinke, T. Iizumi, R. Izaurralde, N. Mueller, D. Ray, C. Rosenzweig, A. Ruane & J. Sheffield. 2014. The Global Gridded Crop Model Intercomparison (GGCMI): Data and modeling protocol for phase 1 (v1.0). *Geoscientific Model Development*, in preparation.

69. Schewe, J., J. Heinke, D. Gerten, I. Haddeland, N. Arnell, D. Clark, R. Dankers, S. Eisner, B. Fekete, F. Colón-González, S. Gosling, H. Kim, X. Liu, Y. Masaki, F. Portmannn, Y. Satoh, T. Stacke, Q. Tang, Y. Wada, D. Wisser, T. Albrecht, K. Frieler, F. Piontek, L. Warszawski & P. Kabatt. 2013. Multimodel assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences*, 111(9): 3245-3250.

70. Xu, K., X. Xu, T. Fukao, P. Canlas, R. Maghirang-Rodriguez, S. Heuer, A. Ismail, J. Bailey-Serres, P. Ronald & D. Mackill. 2006. Sub1A is an ethylene-response-factor-like gene that confers submergence tolerance to rice. *Nature*, 442(7103): 705-708.

71. Al-Riffai, P., B. Dimaranan & D. Laborde. 2010. Global trade and environmental impact study of the EU biofuels mandate, *Final Report for the Directorate General for Trade of the European Commission*, International Food Policy Research Institute.

72. Banse, M., H. vanMeijl, A. Tabeau, G. Woltjer, F. Hellmann & P. Verburg. 2011. Impact of EU biofuel policies on world agricultural production and land use. *Biomass and Bioenergy*, 35(6): 2385–2390.

73. Calzadilla A., K. Rehdanz & R. Tol. 2011. Trade liberalization and climate change: A computable general equilibrium analysis of the impacts on global agriculture. *Water*, 3: 526-550. doi:10.3390/w3020526.

74. Keeney, R. & T. Hertel. 2011. The indirect land use impacts of United States biofuel policies: The importance of acreage, yield, and bilateral trade responses. *Amer. J. Agr. Econ*., 91(4): 895-909.

75. Liu, J., T. Hertel, F. Taheripour, T. Zhu & C. Ringler. 2014. International trade buffers the impact of future irrigation shortfalls. *Global Environmental Change*, 29: 22-31

76. Verma, M., T. Hertel & N. Diffenbaugh. 2014. Market-oriented ethanol and corn-trade policies can reduce climate-induced US corn price volatility. *Environ. Res. Lett*., 9: 064028 (10 pp.)

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

78. Earley, J. 2009. Climate change, agriculture and international trade: Potential conflicts and opportunities. *Biores*, 3(3).

79. Pitesky M., A. Gunasekara, C. Cook & F. Mitloehner. 2014. Adaptation of agricultural and food systems to a changing climate and increasing urbanization. Curr. *Sustainable Renewable Energy Rep.*, 1:43-50

80. McMichael A. 2013. Globalization, climate change, and human health. *New Engl. J. Med.*, 368: 1335-1343.

81. Loladze, I. 2014. Hidden shift of the ionome of plants exposed to elevated CO_2 depletes minerals at the base of human nutrition. *eLife* e:02245. DOI: 107554/Elife.02245

82. Jalava, M., M. Kummu, M. Porkka, S. Siebert & O. Varis. 2014. Diet change—a solution to reduce water use? *Environ. Res. Lett*. 9: 074016 (14 pp.)

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

84. Antle, J., S, Capalbo, E. Elliott & K. Paustian. 2004. Adaptation, spatial heterogeneity, and the vulnerability of agricultural systems to climate change and CO_2 fertilization: An integrated assessment approach. *Climatic Change*, 64(3): 289-315.

85. Elliott, J., F. Ian, K. Sam & J. Khun. 2013. Unilateral carbon taxes, border tax adjustments and carbon leakage. *Theoretical Inquiries in Law*, 14(1): 207-244.

86. Elliott, J., I. Foster, S. Kortum, T. Munson, F. Cervantes & D. Weisbach. 2010. Trade and carbon taxes. *The American Economic Review*, p. 465-469.

87. Elliott, J. & D. Fullerton. 2014. Can a unilateral carbon tax reduce emissions elsewhere? *Resource and Energy Economics*, 36(1): 6-21.

88. Hertel, T., M. Burke & D. Lobell. 2010. The poverty implications of climate-induced crop yield changes by 2030. *Global Environmental Change*, 20(4): 577-585.

89. East African Community. 2013. *Climate, food, trade: Where is the policy nexus*? Lessons from the East African Community. CUTS International, Geneva.

90. Wu M. & J. Salzman. 2014. The next generation of trade and environment conflicts: The rise of green industrial policy. *Scolarship Law Article*, 108(2). Duke University. (Online: http://scholarship.law.duke.edu/faculty_scholarship/3320/).

91. Ayers, J., S. Huq, M. Arif & S. Hussain. 2014. Mainstreaming climate change adaptation into development: A case study of Bangladesh. *WIREs Clim. Change*, 5:37-51. doi: 10.1002/wcc.226

92. Butler J., W. Suadnya, K. Puspadi, Y. Sutaryono, R. Wise, T. Skewes, D. Kirono, E. Bohensky, T. Handayani, P. Habibi, M. Kisman, I. Suharto, Hanartani, S. Supartarningsih, A. Ripaldi, A. Fachry, Y. Yanuartati, G. Abbas, K. Duggan & A. Ash. 2013. Framing the application of adaptation pathways for rural livelihoods and global change in eastern Indonesian islands. *Global Environmental Change*, pp:1-15.

93. Perch, L. 2011. *Mitigation of What and by What? Adaptation by Whom and for Whom? Dilemmas in delivering for the poor and the vulnerable in international climate policy*. Working Paper 79. International Policy Centre for Inclusive Growth, Brasilia, Brazil.

94. Smith, D. & J. Vivekananda. 2011. *Adapting to change: The linked challenges of building resilient communities*. Poverty in Focus No. 23. International Policy Centre for Inclusive Growth, Brasilia, Brazil, pp. 17-19.

95. Wise, R., I. Fazey, S. Stafford, S. Park, H. Eakin, A. van Garderen & B. Campbell. 2013.

Reconceptualising adaptation to climate change as part of pathways of change and response. *Global Environmental Change*, pp: 1-15.

96. McGray, H., A. Hammill & R. Bradley. 2007. *Weathering the storm: Options for framing adaptation and development*. World Resources Institute: Washington, DC.

97. Dutz, M. & S. Sharma. 2102. Green growth, technology and innovation policy. *Research Working Paper 5932*, World Bank, Washington DC.

98. Houghton, J., Callander, B. & S. Varney. 1992. *Climate change 1992: the supplementary report to the IPCC scientific assessment*. Cambridge University Press.

99. Porter J. and L. Xie (coordinating lead authors). 2014. Chapter 7: *Food Security and Food Production Systems, In IPCC: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., *et al*. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

100. Knox, J., T. Hess, A. Daccache & T. Wheeler. 2012. Climate change impacts on crop productivity in Africa and South Asia. *Environmental Research Letters*, 7(3): 034032.

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

102. http://cdkn.org/

103. Osborne, T., G. Rose, & T. Wheeler. 2013. Variation in the global-scale impacts of climate change on crop productivity due to climate model uncertainty and adaptation. *Agricultural and Forest Meteorology*, 170: 183-194.

104. Murphy, J., D. Sexton, D. Barnett, G. Jones, M. Webb, M. Collins & D. Stainforth. 2004. Quantification of modelling uncertainties in a large ensemble of climate change simulations. *Nature*, 430: 768-772.

105. Challinor, A., T. Wheeler, J. Slingo & J. Hemming. 2005. Quantification of physical and biological uncertainty in the simulation of the yield of a tropical crop using present-day and doubled CO_2 climates. Philosophical Transactions of the Royal Society B: Biological Sciences, 360: 2085-2094.

106. Mastrandrea, M., C. Field, T. Stocker, O. Edenhofer, K. Ebi, D. Frame, H. Held, E. Kriegler, K. Mach, P. Matschoss, G. Plattner, G. Yohe & F. Zwiers. 2010. *Guidance note for lead authors of the IPCC Fifth Assessment Report on consistent treatment of uncertainties. Intergovernmental Panel on Climate Change* (IPCC). Available at http://www.ipcc.ch.

107. Challinor, A., F. Ewert, S. Arnold, E. Simelton & E. Fraser. 2009. Crops and climate change: Progress, trends, and challenges in simulating impacts and informing adaptation. J*ournal of Experimental Botany*, 60(10): 2775-2789.

108. Challinor, A., T. Wheeler, C. Garforth, P. Craufurd & A. Kassam. 2007. Assessing the vulnerability of food crop systems in Africa to climate change. *Climatic Change*, 83(3): 381-399.

109. Gaffin, S., C. Rosenzweig, X. Xing & G. Yetman. 2004. Downscaling and geo-spatial gridding of socio-economic projections from the IPCC Special Report on Emissions Scenarios (SRES). *Global Environmental Change*, 14(2): 105-123.

110. http://www.millenniumassessment.org/en/Scenarios.html.