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METRICS FOR ASSESSING THE ECONOMIC BENEFITS OF CLIMATE CHANGE POLICIES IN AGRICULTURE

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EXECUTIVE SUMMARY

Climate change will exacerbate concerns about agricultural production worldwide. Food security is prominent among the human activities and ecosystem services under threat from dangerous anthropogenic interference in the earth's climate. Current research confirms that, while crops would respond positively to elevated CO_2 in the absence of climate change, the associated impacts of high temperatures, altered patterns of precipitation, and possibly increased frequency of extreme events such as drought and floods will likely combine to progressively depress agricultural yields and increase production risks in many regions over time, as the severity of climate change increases.

It is important for policy makers to develop, together with agricultural stakeholders, a set of metrics for analysing the magnitude and timing of climate change impacts on agriculture. Such metrics can be used to facilitate the evaluation of policy options, assess the long-term risks of climate change, and to identify potential thresholds beyond which significant adaptation of management techniques may no longer be sufficient to maintain system productivity and income. Impact metrics can help decision makers to evaluate, quantify, and communicate the benefits of climate change policies on agricultural systems. A cohesive set of metrics for climate change and agriculture can also further facilitate operational definitions of vulnerability thresholds for agricultural systems, helping to elucidate connections across biophysical and socio-economic variables.

This report proposes a general framework to develop metrics useful to decision-makers in the analysis of the benefits of climate policies on the agricultural sector. The framework is based on research findings from the impacts assessment community and has been informed by experts and stakeholders via a workshop and a survey. The proposed general framework for such metrics identifies biophysical factors, agricultural system characteristics, socio-economic data, and climate policy as key categories for analysis, and relates them to vulnerability criteria of agricultural systems in terms of their exposure, sensitivity, adaptive capacity, and synergy with mitigation strategies under climate change.

Based on the framework, a set of metrics is developed, comprised of variables that can be easily extracted from current models and used to obtain consistent and comparable information on climate change impacts and benefits in both monetary and non-monetary terms. Specifically, this report focuses on the development of metrics for regional, national, and global scales, characterizing the short-term (20-30 years) and long-term (80-100 years) impacts of climate change on agriculture. Specifically, we propose the following explicit metrics: crop suitability, crop yield and water stress as biophysical indicators; land resources, regional cereal production and water resources as agricultural system characteristics; economic value, land value, and a nutrition index assessing number of people at risk of hunger, as socio-economic indicators; and finally mitigation potential, as a measure of competition and/or synergies between adaptation and mitigation strategies.

This report also identifies a number of gaps in the current studies. Additional work is necessary to evaluate the proposed metrics and to test the framework across a range of agricultural systems, socio-economic pathways, and climate change regimes. A number of improvements will be needed to the current agronomic and economic model simulations that use these metrics to address key uncertainties in assessing the benefits of climate policies. In particular, these relate to the representation in such models of the effects of climate extremes (heat waves, droughts, and floods), pest and disease interactions, and the impacts of elevated CO_2 levels on crops.

GLOSSARY OF TERMS

- **Adaptation -** Adjustment in natural or human systems in response to climatic changes.
- **Autonomous - Private Adaptation** - Adaptation that is initiated and implemented by individuals, households or private companies.
- **Planned, or Public Adaptation** - Adaptation that is initiated and implemented by governments at all levels. Public adaptation is usually directed at collective needs.
- **Adaptation Assessment -** The practice of identifying options to adapt to climate change and evaluating them in terms of criteria such as availability, benefits, costs, effectiveness, efficiency, and feasibility.
- **Adaptive Capacity -** The ability of a system to adjust to climate variations, to take advantage of opportunities, or to cope with potential damages.
- **Afforestation/Reforestation -** Planting of new forests on lands that either historically were never forests, or were forests but were changed to a different land use.
- **Baseline -** The baseline (or reference) is the state of a system against which change is measured. It might be defined with respect to either currently observed data, or future projections.
- **Bioenergy -** Energy generated from organic matter or combustible oils produced by plants.
- **Carbon Dioxide Fertilization -** The enhancement of plant growth as a result of increased elevated atmospheric carbon dioxide concentration.
- **Carbon Sequestration -** The process of reducing atmospheric concentrations of CO_2 by increasing the carbon content of a natural or artificial pool other than the atmosphere.
- **Climate -** Statistical description of relevant weather quantities, in terms of their mean and variability, over a period of time ranging from months to millennia. The standard averaging period defined by the World Meteorological Organization is thirty years.
- **Climate Projection -** A computed response of the climate system to future emissions or concentrations of greenhouse gases and aerosols, and other radiative forcing, often based on climate models.
- **Climate Variability -** Climate variability refers to variations in the mean state of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).

- **Crop Model -** A set of mathematical equations that estimate agricultural production of crops as a function of soil, climate and management resources at local, regional and global scales. Dynamic crop models include DSSAT (Decision Support Systems for Agro-Technology Transfer); EPIC (Erosion Productivity Impact Estimator), and AEZ (Agro-ecological Zone modeling system).

- **Drought -** The phenomenon that exists when precipitation has been significantly below normal recorded levels, causing serious imbalances that adversely affect land resource production systems.

- **Emission Scenario -** A plausible representation of the future development of greenhouse gas emissions and other anthropogenic forcing, based on socio-economic scenarios.

- **Exposure -** The nature and magnitude of climatic variations experienced by a system.

- **Extreme Event -** An event that is rare within its statistical reference distribution over a certain period of time (e.g., rainfall over a season; frequency of floods, droughts, etc).

- **Feedback -** A process that triggers changes in a second process that in turn influences the original one; a positive feedback intensifies the original process, and a negative feedback reduces it.

- **Food Insecurity -** A situation that exists when people lack secure access to sufficient amounts of safe and nutritious food. It may be caused by the unavailability of food, insufficient purchasing power, inappropriate distribution, or inadequate use of food at the household level.

- **Global Circulation Model -** A numerical representation of the climate system based on the physical, chemical, and biological properties of its components, their interactions and feedback processes. Output from General Circulation Models, also commonly referred to as Global Climate Models (GCM), is often used as input in impact assessment studies.

- **Impact Assessment -** The study and quantification of potential consequences of climate change on natural and human systems at local, regional or global scales.

- **Impacts -** Consequences of climate change on natural and human systems. Depending on the consideration of adaptation, one can distinguish between potential impacts and residual impacts.

- **Integrated Assessment -** A method of analysis that combines results and models from the physical, biological, economic, and social sciences, and the interactions between these components, in a consistent framework to evaluate the status and the consequences of environmental change and the policy responses to it.

- **Kyoto Protocol -** A binding agreement under the UN Framework Convention on Climate Change committing industrialised countries to reduce anthropogenic greenhouse gas emissions in the period 2008-2012 by 5% overall with respect to 1990 emissions.

- **Market (Monetary) Impacts -** Impacts on ecosystems, sectors and people that can be directly expressed as monetary costs or benefits - for example, changes in the food supply, price of agricultural goods, or land value.

- **Metrics -** A set of measurements of observed and simulated quantities, facilitating objective and replicable descriptions of complex systems and the tracking of how they change over time.

- **Mitigation -** An anthropogenic intervention aimed at reducing the severity of climate change by controlling the earth's radiative forcing.

- **Non-Market (non-monetary) Impacts -** Impacts that affect ecosystems, sectors and people, which are not easily quantifiable in monetary terms - for example, increases in risk of hunger.

- **Phenology -** Study of crop development, from plant emergence to maturity.

- **Policy Benefits -** The avoided damage costs or the accrued gains, measured in either monetary or non-monetary impacts, following the adoption and implementation of adaptation or mitigation measures.

- **Policy Costs -** Costs, measured in either monetary or non-monetary impacts, of planning, preparing for, facilitating, and implementing adaptation and mitigation measures, including transition costs.

- **Projection -** Potential future evolution of a set of quantities, often computed with the aid of a model.

- **Ricardian -** A modeling approach used to evaluate the economic value of agricultural productivity by equating it to the value of the underlying land resources, and by expressing the latter as a function of its agro-climatic suitability, assuming long-term equilibrium of the underlying statistical data.

- **Resilience -** Amount of change a system can undergo without changing state.

- **Scenario -** A plausible, simplified description of future socio-economic and technological development.

- **Sensitivity -** The degree to which a system is potentially affected by the climate variations it is exposed to.

- **Socio-Economic Scenarios -** Scenarios concerning future conditions in terms of population, gross domestic product and other socio-economic factors relevant to understanding the implications of climate change. See SRES.

- **SRES -** Population, GDP and emission scenarios defined within the Special Report on Emissions Scenarios (SRES). Four families of SRES socio-economic scenarios, identified as A1, A2, B1, and B2, represent different world futures in two distinct dimensions: economic versus environmental concerns, and global versus regional development patterns.

- **Stakeholders -** Person or entity holding grants, concessions, or any other type of value that would be affected by a particular action or policy.

- **Threshold -** A discontinuity in an impact chart that separates values with no significant system change from values associated with significant change.

- **Uncertainty -** An expression of the degree to which a value (e.g., the future state of the climate system) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from quantifiable errors in the data to ambiguously defined concepts or terminology, or uncertain projections of human behavior.

- **Under-nutrition -** The result of food intake that is insufficient to meet dietary energy requirements continuously, poor absorption, and/or poor biological use of nutrients consumed.

- **Vulnerability -** The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate variations.

- **Water Stress -** A crop is water stressed whenever actual ET is lower than potential ET. A region is water stressed if the available freshwater sup ply relative to water withdrawals acts as an important constraint on development. Withdrawals exceeding 20% of renewable water supply has been used as an indicator of water stress.

1. Introduction

Climate change impacts on agriculture have local, regional, and global dimensions (IPCC, 2001). The nature of those impacts will depend upon how much and how rapidly the climate changes over time and on how natural and human systems respond to such change. In particular, responses to such impacts depend on the capacity of agricultural systems to adapt to changed conditions as a function not only of climate, but also of socio-economic conditions, technological progress and agricultural markets. It is therefore useful to develop, a set of metrics for analysis of the magnitude and timing of such impacts, so that the benefits of climate policies on agriculture–- can be assessed within coherent frameworks, providing for both non-monetary and monetary estimation (Corfee-Morlot and Agrawala, 2004). Working together with agricultural stakeholders and decision-makers, the identification of such metrics can facilitate elaboration of adaptation and mitigation responses to climate change across local, national, regional and global scales. A cohesive set of metrics for climate change and agriculture further facilitates operational definitions of vulnerability thresholds, reflecting a level of change beyond which adaptation can no longer be an effective response, for agricultural systems.

The objective of this work is precisely to develop the general framework needed to develop such metrics, as well as to provide a first explicit set of metrics for analysis of impacts on agricultural systems. We do this by focusing on metrics that relate directly to simulation models, so they can be used to easily extract information from available impact assessment studies. Previous work has shown the importance of a multi-scale approach to metrics needed for climate policy analysis (Jacoby, 2004); therefore, within our approach, we select a set of metrics that span multiple spatial and temporal scales, i.e., from local to regional and global, as well as bridging short-term and long-term information on impacts.

Agricultural production systems integrate agronomic (e.g., climate, soils, crops and livestock) and economic elements (e.g., material, labour, energy inputs, food and services outputs). These systems are affected by socio-economic and cultural processes at local, regional, national, and international scales, including markets and trade, policies, trends in rural/urban population, and technological development. This report focuses mainly at national to regional (here intended as supra-national) and global scales, while bearing in mind that decision-makers may require information at more local scales as well. In order to consider issues relevant to this report, an international workshop on “Agricultural Impact and Adaptation Metrics” was held at Columbia University, Center for Climate Systems Research, on June 5-6 2006, with participants from government and technical experts in agricultural systems from the U.S., Slovakia, Ukraine, Italy and southern Mediterranean, Uruguay and Latin America (Appendix A). In addition, a survey questionnaire was distributed among several US and international experts (Appendix B). The purpose of the workshop and the survey was to help develop a coherent analytical framework, within which metrics relevant to different nations and regions could be identified, and to discuss methods for their development and application.

This study provides background and methods relevant to the development of metrics that assess impacts on the agricultural sector arising from potential changes in mean and distribution of potential temperature and precipitation changes over the next 100 years, by focusing on both short-term (20-30 years) and long term (80-100 years) horizons. Section 2 below provides a review of recent studies of climate impacts on agriculture, needed to elaborate metrics; Section 3 discusses criteria for metric development; Section 4 recommends a generalized framework for analysis and applications, providing explicit examples at national to regional and global scales. Section 5 provides a quantitative example of metrics computation using impact data form a published integrated assessment study. Appendixes A and B provide a summary of the workshop discussions and the results of a survey of experts and stakeholders. Appendix C provides details of the models used in evaluating metrics.

2. Impacts and adaptation in agriculture: an overview

Climate change will exacerbate concerns about agricultural production worldwide. At the regional and global scale, food security is prominent among the human activities and ecosystem services under threat from dangerous anthropogenic interference in the earth's climate (IPCC 2007; Millennium Ecosystem Assessment 2005; Watson et al. 2000; article II, UNFCCC). At the national scale, countries are concerned about potential damages that may arise in coming decades from climate change impacts, since these are likely to affect domestic and international policies, trading patterns, resource use, regional planning, and welfare. To this end, tools needed to estimate benefits of avoided impacts due to climate mitigation and adaptation policies to the agricultural sector.

Current research confirms that while crops would respond positively to elevated CO_2 in the absence of climate change (e.g., Ainsworth and Long 2005; Kimball et al. 2002; Jablonski et al. 2002), the associated impacts of high temperatures, altered patterns of precipitation, increased water demand, and possibly increased frequency of extreme events such as drought and floods will likely combine to progressively depress yields and increase production risks in many regions over time, as the severity of climate change increases (e.g., IPCC 2007, 2001b).

The recent IPCC (2007) provides a number of important conclusions. At the plot level, and without considering changes in the frequency of extreme events, moderate warming may benefit crop and pasture yields in temperate regions, while it would decrease yields in semi-arid and tropical regions. Specifically, as shown in Figure 1, modelling studies indicate small beneficial effects on crop yields in temperate regions corresponding to local mean temperature increases of 1-3ºC and associated CO_2 increase and rainfall changes. By contrast in tropical regions, models indicate negative yield impacts for the major cereals even with moderate temperature increases (1-2^{o}C). Further warming projected for the end of the 21st century has increasingly negative impacts in all regions. At the same time, farm-level adaptation responses may be effective at low to medium temperature increases, allowing to cope with up to 1-2 ^{o}C local temperature increases, an effect that can be seen as "buying time" (Tubiello et al., 2007; Howden et al., 2007).

Increased frequency of extreme events, such as heat stress, droughts and floods would negatively affect crop yields and livestock beyond the impacts of mean climate change, however, creating the possibility for surprises. The impacts on crop yields discussed above would then be larger, and occurring earlier, than predicted using changes in mean variables alone. More frequent extreme events may lower long-term yields by directly damaging crops at specific developmental stages, such as temperature thresholds during flowering, or by making the timing of field applications more difficult, thus reducing the efficiency of farm inputs (IPCC, 2007).

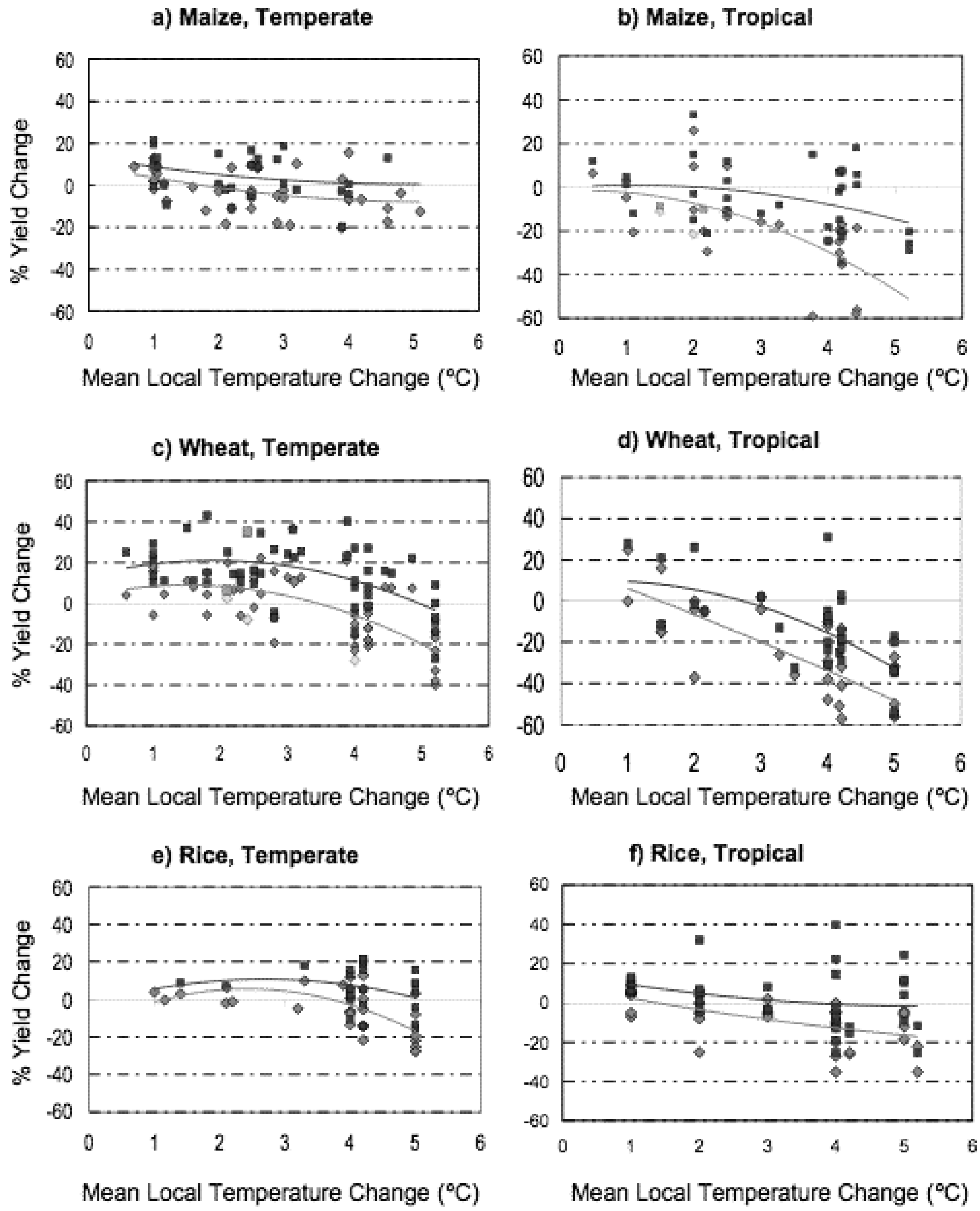


Figure 1 a-f. Sensitivity of cereal yield to climate change against mean local temperature change, expressed as increases compared to 1980-1999 climatology. Responses include cases without adaptation (orange dots) and with adaptation (green dots). Adaptation represented in these studies included changes in planting, changes in cultivars, and shifts from rainfed to irrigated conditions. Source: IPCC (2007).

The impacts of climate change on crop yield have implications for regional and global food supply. However, in order to make realistic predictions, it is necessary to also consider key socio-economic factors, such as the interplay of land, capital and labour in response to population growth, technological and economic development. This is because, from an economic perspective, food demand is relatively price-inelastic and commodity supply is relatively price-elastic, so that, globally, actual commodity production needed to meet a given demand may not be very sensitive to changes in crop yields, at least within a set range (Reilly et al., 2007). Most importantly, trends in the socio-economic factors we discussed above are likely to impact agriculture over and above the projected climate change signals (e.g., Reilly et al., 2007; Schmidhuber and Tubiello, 2007; Tubiello et al., 2006). For instance, pressures from growing population and increasing income alone imply a doubling of current global cereal demand by

2080, requiring an increase in production from 2 to slightly over 4 billion tonnes, with consequent pressure on crop productivity and land utilization patterns (e.g., Fischer et al., 2005). In addition, continuation of recent dietary trends in many developing countries–in the last three decades, average daily per capita intake has risen globally from 2,400 to 2,800 calories—spurred by economic growth, improved production systems, international trade, and globalization of food markets, may significantly increase the shares of meat, fat, and sugar in total food intake compared to current, again resulting in significant pressures on land use and crop productivity (e.g., Fischer et al. 2005). At the same time, increased global trade may lessen negative climatic impacts, by moving food from climate-advantaged to climate-disadvantaged regions. However, the ability to cope with trade mechanisms may depend on the vulnerability of the whole economy to shocks in the agriculture sector. Some developing countries are highly dependent on agriculture, in terms of employment, income and international trade. In particular, some countries, especially the least developed, will not be able to replace exports of agricultural goods by other exports. This could endanger their ability to import goods, including food, that are essential for their economy.

Within this context, analyses of the impacts of climate, CO_2, and other environmental changes on food supply must include, in addition to effects on crop yields, explicit representations of land availability as well as the market dynamics of demand and supply (Tubiello et al. 2007). Integrated assessment studies focusing on quantifying impacts of climate change on food production dynamics must therefore link agro-ecological dynamic crop production modules to economic models that can simulate the evolution of agriculture regionally and globally - including the important role played by world trade - as a function of different socio-economic scenarios (Fig. 2). It is only within such frameworks that one can hope to realistically quantify the impacts of climate change, and likely adaptation processes such as crop management changes and economic adjustments, necessary to compute the benefits of climate policy.

In general, conclusions in IPCC (2007) confirm that, once economic considerations are taken into account, global climate impacts on food production are small, albeit with significant regional variation. Specifically, developing countries are more vulnerable to climate change than developed countries, because of the predominance of agriculture in their economies, the scarcity of capital for development and dissemination of adaptation measures, often-warmer baseline climates, already stressed, marginal production environments, and heightened exposure to extreme events. In particular, climate change may result in 5-170 million people additionally at risk of hunger by 2100, depending on assumed socio-economic scenario (see also: Schmidhuber and Tubiello, 2007). The IPCC (2007) concludes that among developing countries, sub-Saharan Africa is projected to be the most negatively affected region, with significant increases in the share of people at risk of hunger, and decreased quality of land and water resources. Mediterranean countries are expected to experience severe droughts leading to potential abandonment of agricultural land and desertification.

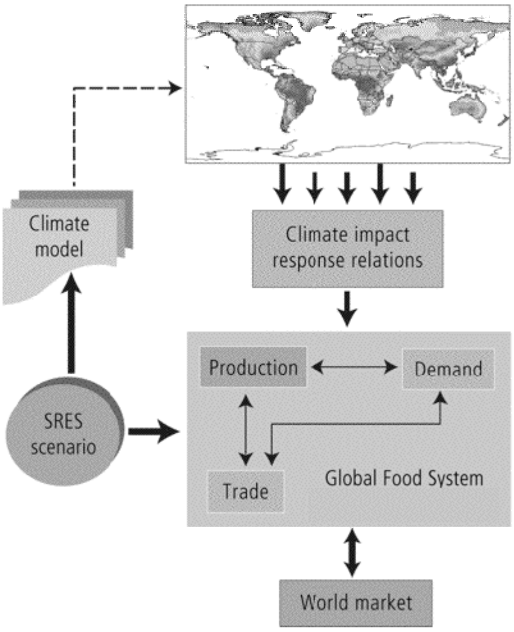
Finally, the recent IPCC (2007) indicates the possibility for negative surprises. All global integrated studies considered above do not consider increases in the frequency of extreme events. Yet these could have significant consequences even within integrated models. It was computed that, under scenarios of increased heavy precipitation, production losses due to excessive soil moisture—already significant today—would double in the U.S. to $ 3 billion per year in 2030 (Rosenzweig et al., 2002). Furthermore, the impacts of climate change on irrigation water requirement may be larger than assumed in current models. A few new studies have further quantified the impacts of climate change on regional and global irrigation requirements, estimating an increase of crop irrigation requirements of +5% to +8% globally by 2070, with larger regional signals, e.g., +15% in southeast Asia. Fischer et al., (2007) estimated increases in global net irrigation requirements of +20% by 2080, with larger impacts in developed vs. developing regions, due to both increased evaporative demands and longer growing seasons under climate change Recent regional studies have likewise underlined critical climate change/water dynamics in key irrigated areas, such as in North Africa and southeast Asia.

In this paper we focused on integrated assessment studies for agriculture that, while characterized by sufficient regional detail, also maintained a global economic framework for analysis that included food trade (e.g., Tubiello and Fischer, 2006; Parry et al. 2005; Fischer et al. 2005; Parry et al. 2004; FAO 2003; Fischer et al., 2002). These studies provide the ability to assess both regional and temporal dynamics of agricultural impacts over the 21st century. We also review another important category of models, so-called Ricardian (e.g., Mendelsohn and Nordhaus, 1999; Schlenker et al., 2005). We argue however that despite representing an interesting alternative approach with a powerful treatment of adaptation, they are less useful for metrics, as they provide more static-equilibrium analyses that are regionally limited and do not consider explicitely the effects of regional and global trade.

Hitz and Smith (2004), using a subset of the studies we considered, defined a first set of impact metrics that included crop yield by crop, cultivated land area, and number of people at risk of hunger. These authors mapped these impact metrics against global mean temperature (GMT) change, viewed as a single proxy for the time-evolution of climate change over this century. These analyses, and previous summary efforts such as the IPCC TAR (2001), suggested that global agricultural production may suffer little, or even benefit, from climate impacts in the coming two or three decades, or up to about 2.5°C warming - with positive effects of elevated CO_2 on crops overriding negative temperature signals. However, as global temperature increases past this level, global impacts turn negative in all regions. While maintaining a focus on GMT as climate change proxy, our efforts are an attempt to refine their analysis by adding both regional and temporal depth to the impacts analysed, by means of a larger set of metrics.

Figure 2. Socio-economic SRES scenarios determine both climatic and market conditions in integrated agro-economic assessments. Climatic impacts on agricultural production–calculated with crop models - are passed on to agricultural economics and trade models to determine overall impacts on world food systems.

Impact assessment studies need to consider the role of adaptation as a means to minimize



negative impacts and to take advantage of potential benefits of climate change on human activities and ecosystems (Table 1). *Adaptation* to climate change can be defined as the range of actions taken in response to changes in local and regional climatic conditions (Smit et al., 2000). These responses include both *autonomous adaptation* actions, i.e., those taken independently by individual actors such as single farmers or groups such as agricultural organizations, as well as *planned adaptation* actions, i.e., climate-specific infrastructure development, regulations and incentives put in place by regional, national and international policies in order to complement, enhance and/or facilitate response by farmers and organizations (Table 2). In terms of the multiple factors impinging on agriculture, as discussed, system responses to socio-economic, institutional, political or cultural pressures may outweigh response to climate change alone in driving the evolution of agricultural systems (de Loe et al., 2000).

Table 1. **Examples of climate change agricultural impacts and responses**

System Impact	**Possible Adaptation Response**
Biomass increase under elevated CO_2	Cultivar selection to maximize yield
Acceleration of maturity due to higher temperature	Cultivar selection with slower maturing type/ crop shifts
Heat stress during flowering and reproduction	Early planting of spring crops
Crop losses due to increased variability Drought/flooding	Crop mixtures/rotation/change in soil and water management; Advanced warning systems
Increased competition/pests	Land and input management/Biotechnology

Autonomous adaptation can help offset negative climate change impacts and take advantage of positive changes. When summarized across many adaptation studies, there is a tendency for the benefits of adaptation to be greater with moderate warming (<2°C) than with greater warming and under scenarios of increased rainfall than those with decreased rainfall (Howden et al., 2007). IPCC (2007) indicates that benefits of adaptation vary with crop, between tropical and temperate regions and with temperature and rainfall changes (Fig. 1). Specifically, the benefits of adaptation for rice and maize appear to be smaller than those for wheat. In general with adaptation, temperatures increases (with respect to 1980-1999) beyond which yields start to decline were extended to 4.5-5°C in temperate regions and to 1.5-3°C in tropical region (Howden et al., 2007). Warming beyond these ranges would exceed adaptive capacity in either region.

Additional measures, planned ahead of time at local, regional, national and international levels may be needed in order to facilitate farmers' responses. Many options for policy-based, planned adaptation to climate change have been identified for agriculture. These can involve adaptation activities such as developing infrastructure, capacity building in the broader user community and institutions and in general modifying the decision-making environment under which management-level, autonomous adaptation activities typically occur. The process of 'mainstreaming' adaptation into policy planning in the face of risk and vulnerability at large is an important component of planned adaptation (Howden et al., 2007).

Many adaptation frameworks have been developed in the last decade, with contributions from both social and physical scientists (e.g., Burton et al., 2002, Howden et al., 2007, IPCC, 2007). The consensus appears to be that products developed under such theoretical frameworks should be closely aligned to the needs of agricultural decision-makers, and consider different levels of engagement. Involving the stakeholders from project inception is critical to achieving effective outcomes.

A*daptive capacity* of a system, in the context of climate change, can be viewed as the full set of system skills – i.e., technical solutions available to farmers in order to respond to climate stresses – as determined by the socio-economic and cultural settings, plus institutional and policy contexts, prevalent in the region of interest. The concept of adaptive capacity is a theoretical one, i.e., it is not easily measurable. While adaptive capacity can in principle be defined *within* a theoretical framework, it is actual adaptation responses that can be measured and evaluated, in a cost-benefit fashion or some other monetary or non-monetary approach. They can also be used to test previously defined adaptive capacity, by adding information on system's response to surprises and reducing uncertainties.

Table 2. **Adaptation approaches to climate impacts on agriculture**

Approach	**Definition**	**Operation**
Autonomous	Actions that can be taken by farmers and communities independently of policy, based on a set of technology and management options available under current climate	Crop calendars shifts (planting, input schedules, harvesting) Cultivar and crop changes Management Changes Diversifying Income Seasonal Climate Forecasts
Planned	Actions that require concerted action from local, regional and or national policy	Land-use incentives, Irrigation infrastructure, Water pricing, Efficient water use technologies; Germplasm development programs Transport and storage infrastructure; Revising land tenure arrangements including attention to property rights; Accessible, efficient markets for products and inputs (seed, fertilizer, labor etc) and for Financial services including insurance.

Recent studies have also emphasized the concept of *vulnerability* of an agricultural system (e.g., Kates et al. 2000) - as a function of exposure of that system to climate hazards, its intrinsic sensitivity to that exposure, and its adaptive capacity:

$$\text{Vulnerability} = f\,(\text{Exposure, Sensitivity (Exposure), Adaptive Capacity})$$

Using the equation above, vulnerability of given systems could be estimated for a range of climates by keeping adaptive capacity fixed while varying system exposure and sensitivity; changes in socio-economic backgrounds would modify adaptive capacity.

As climate changes are realized and climate policies adopted in the coming decades, mitigation actions to reduce greenhouse gas emissions will be implemented at the same time as adaptation responses. Recent work shows that significant efforts will be required to find the right synergies between adaptation and mitigation efforts. Rosenzweig and Tubiello (2007) presented a number of instances in which adaptation and mitigation may be at odds with each other, for example in regions with competition for land between food crops and biofuel or carbon-sequestration plantations. Other mitigation strategies, such as no-till agriculture for enhanced carbon sequestration, may in contrast have synergies with adaptation and reduce system vulnerability by increasing soil water-retention properties and minimizing erosion.

Both adaptation and mitigation solutions will deliver avoided impact benefits in the agricultural sector. While many studies have attempted to compare impacts simulated with and without implementation of local adaptation solutions, little has been done in the area of quantifying impacts under scenarios with and without global mitigation—for instance, by investigating when and how negative impacts may be lessened as a result of stabilizing atmospheric CO_2 concentrations. Nonetheless, initial results from recent impact assessment studies indicate that while there are significant benefits to limiting emissions and concentrations of GHG, the regional and temporal distributions of such benefits are uncertain, due to complex interactions of CO_2 effects, climate outcomes, and socio-economic factors, so that concerted efforts are likely to be needed to redistribute risk and benefits globally (Parry et al., 2005; Tubiello and Fischer, 2006). We will provide an example based on these results, showing how an explicit set of metrics can be used to evaluate regional and temporal characteristics of the benefits of climate policies.

3. Selected methodological issues in economic policy assessment

While the literature on climate change impacts on agriculture at local to regional and global scales is extensive, there is currently a need to develop an analytic framework - i.e., a system of metrics that goes beyond a simple, global mean temperature change proxy - that would allow for more complete, yet still easy-to-understand comparisons of research results across scales, regions and models (Corfee-Morlot and Agarwala, 2004; Jacoby, 2004). The focus of this study is precisely the development of impact metrics that can be used by policy analysts and decision-makers to extract information from research studies, in order to estimate the economic benefits and evaluate the effectiveness of climate change policies needed to facilitate response actions at regional, national and global scales.

The metrics to be developed, to be referred herein as climate change impact and adaptation metrics, should thus focus on key agricultural system characteristics helping to quantify, using both monetary and non-monetary terms, severity of impacts; system capacity to respond to climate change; and adaptation options that minimize risk and/or maximize benefits. In addition, such metrics should help national policy-makers and regional planners to assess the vulnerability of their agricultural systems to increasing degrees of climate change, and to identify thresholds beyond which current coping capacity and autonomous adaptation should be complemented by planned adaptation responses at local to regional levels, involving significant changes in management practices (Jones, 2003; 2001).

If metrics are to be policy relevant, they should communicate in a simple and concise manner a sense of how important the observed and projected impacts are, including their temporal and spatial distribution; to what extent local adaptation (or global mitigation) measures can be effective; and ultimately the extent to which people should care (Jacoby, 2004). For instance, climate stress insurance indicators - a set of metrics developed by the World Bank's Agriculture and Rural Development Department - respond to the following criteria: 1) observable and easily measured in a timely manner; 2) objective; 3) transparent; 4) independently verifiable; and 5) stable but flexible over the long-term (World Bank, 2005).

Similarly, criteria for developing metrics can be expressed as:

1) Relevant for assessing impacts and responses to climate change in both non-monetary and monetary terms;

2) Appropriate for global, regional and/or national-level planning, including adaptation responses; and

3) Computationally easy with respect to observed and/or model-generated data.

Impact and Policy Assessment

While observed data can be used to calculate metrics and to assess system vulnerability over past and current reference periods, models are necessary to project impacts of future climate change and socio-economic development on agricultural systems, and to derive associated metrics for estimation of climate benefits. As shown in Table 4, two distinct model classes are useful to estimate metrics in agriculture: dynamic crop/agro-ecosystem models (with or without coupling to economic trade models) and Ricardian economic approaches.

Dynamic crop models such as DSSAT (Tsuji et al., 1994), EPIC (Williams et al., 1995), AEZ (Fischer et al., 2002a), are biophysical representations of crop production, simulating in daily to monthly time-steps the relevant soil-plant-atmospheric components that determine plant growth and yield, and including explicit representation of land and plant management. These models may be used to compute seasonal dynamics of crop yield, as well as its inter-annual variability, at local, regional and global scales under current and future climate conditions (see, e.g., Rosenzweig et al, 1995; Tubiello and Ewert, 2002; Fischer et al., 2002b). Importantly, these models allow for in-depth sensitivity analyses of the effects on crop yield of alternative management practices, from planting and harvesting methods to fertilization and irrigation schedules, including use of cultivars with specific genetic, phenotypic and phenology characteristics. Such models can also be coupled to agricultural-economic models, such as BLS (Fischer et al., 2002a) and FARMer, (Darwin, 2000) to estimate current and future food demand, production and trade, as a function of agro-climatic and socio-economic factors (i.e., Rosenzweig and Parry, 1994; Fischer et al., 2002b; Fischer et al., 2005; Parry et al., 2005).

Dynamic crop models may be used to routinely provide non-monetary assessments of many key metrics, namely: crop yield; its long-term means and variability (CV); local to regional production levels - when coupled to a GIS with extensive information on soil and climate distribution; irrigation water requirements; and impacts of increased frequency of extreme events. When coupled to economic models with extensive description of the agricultural sector, they also allow for monetary assessments of these metrics, as well as for the computation of additional metrics that are important to policy assessment, i.e., the value of land and production at risk, and nutrition index.

Table 4. **Examples of models, including their inputs and outputs for assessment of climate impacts on agriculture**

MODEL	INPUTS							OUTPUTS									
	BIO		AGS		SCE		PL	BIO			AGS			SCE			PL
Dynamic Crop	Soil	Cl.	Irr.	N	P	GDP	CS	Suit.	Y	WS	Ld	Pr	WR	$Pr	$Ld	NI	CS
DSSAT	X^{ab}	X^{ab}	X^{ab}	X^{ab}			X^{ab}		Y^{ac}	Y^{ac}		Y^{c}	Y^{c}				Y^{ac}
EPIC	X^{ab}	X^{ab}	X^{ab}	X^{ab}			X^{ab}		Y^{ac}	Y^{ac}		Y^{c}	Y^{c}				Y^{ac}
AEZ	X^{b}	X^{b}	X^{b}	X^{b}				Y^{bc}	Y^{bc}	Y^{b}		Y^{c}	Y^{c}				
Econ. Trade																	
BLS			X^{c}	X^{c}	X^{c}	X^{c}					Y^{c}	Y^{c}	Y^{c}	Y^{c}	Y^{c}	Y^{c}	
FARMer	X^{b}		X^{c}	X^{c}	X^{c}	X^{c}		Y^{b}			Y^{c}	Y^{c}	Y^{c}	Y^{c}	Y^{c}	Y^{c}	
Ricardian																	
Mendelsohn	X^{c*}	X^{c}				X^{c*}									Y^{c}		
Schlenker	X^{c*}	X^{c}	X^{c}			X^{c*}									Y^{c}		

Notes:

Input and Output data types: BIO=biophysical; AGS=Agricultural Systems; SCE=Socio-Economic; PL=Policy

Input data category: Soil=Soil Parameters; Cl.=Climate; Irr=Irrigation type and schedule; N=N Fertilization type and schedule; P=Population data; GDP=National GDP; CS=Carbon Sequestration techniques.

Output data category: Suit.=Crop suitability index; Y=Crop yield (mean and CV); WS=Water stress; Ld=Land resources; Pr=Regional crop production (mean and CV); WR=Water resources; $Pr=Value of production (e.g., agricultural value added) at risk; $Ld=Value of land at risk; NI=Nutrition Index; CS=Amount of carbon sequestered.

[a] Farm level; [b] Geo-referenced grid; [c] Administrative level

*Not a generic input; Variables used only to determine region-specific regression model

Ricardian approaches provide assessments of monetary impacts on agricultural systems, i.e., with relation to possible metrics, production and land value at risk under climate change, considered one single aggregated variable. Importantly, these monetary assessments are comprehensive of all possible adaptation responses to climate change, as the statistical approach assumes efficient geographic re-distribution of agricultural activity following new climate regimes.

Although both modeling approaches are useful for assessing agricultural systems under climate change, it is only with crop/agro-ecological models that it is possible to identify and evaluate explicitly the farm-level responses that are of key importance to regional to national level strategies. Dynamic crop models can be used to successfully identify thresholds of needed management change; to predict when such thresholds might be reached; and to assess robustness of specific adaptation strategies. To this end, these models are quite useful in computing many of the metrics of importance to decision-making, especially at local to regional level; they provide answers to the following questions: How vulnerable are given local or regional agricultural production systems to climate change? What are some of the adaptation strategies and what are their effects? Coupled to trade models, these models can further address questions regarding the linkages between regional agricultural production, trade, food supply, and nutrition levels.

Such models cannot, however, cover the entire range of possible adaptation solutions, or the mechanisms necessary for implementation. For this reasons, they may overestimate climate change impacts and their costs.

Ricardian models calculate the overall cost of impacts, and thus ultimately its overall system vulnerability, by considering all possible adaptation options. Within this context, they provide first-order, yet static analyses of the economic vulnerability of regionally or nationally aggregated production systems. These models are however of little dynamic value: they cannot provide any further insight with regards to which specific adaptation would actually work, how they would be distributed over a territory, their actual cost, nor when they should be considered for implementation. They also do not include the practical, institutional and technical constraints to such adaptation. These constraints arise, among other factors, from: (i) issues in the detection and attribution of climate change; (ii) culture and habits; (iii) the lack of know-how in some regions; (iv) the required amount of investment. For these reasons, they may provide overestimates of the uptake and effectiveness of adaptation when used to assess overall costs of climate change impacts.

In the vulnerability equation, these models estimate statistically the functional components of exposure and sensitivity to exposure of production systems, while taking adaptation capacity out of the equation entirely, by integrating over all possible response strategies. For these reasons, we consider Ricardian models to be not as useful in developing metrics leading to the analyses of benefits of climate change policies, as they lack temporal and spatial dynamics that are captured in the dynamic agro-ecosystem/agro-economic frameworks. The following section provides an example of how the dynamic models can be used to assess the benefits for agriculture (or rather for a subset of agricultural metrics) of policies aimed at mitigating climate change over time.

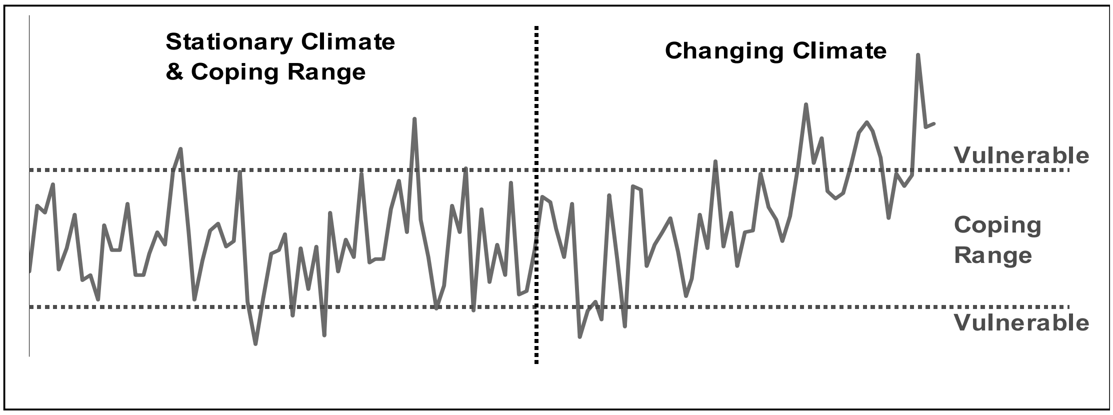
4. Metrics to assess the avoided impact benefits of policies

Review and discussion of specific metrics characteristics

Developing a set of metrics that would apply to all scales (local, regional, national, and global) would be extremely complex in practice. The expert and stakeholder workshop with participants from the case-study regions helped us to evaluate users' needs and the usefulness of the selected scales, and to develop a candidate set of metrics for practical application (See Appendix A). Recommendations from the survey/workshop suggested, first, to focus on national and regional (supra-national) scales for metrics development and application, in order to provide relevancy to policy makers. Importantly, metrics should help characterize the status of agricultural production systems currently and in coming decades, for both short-term (20-30 years) and long-term (80-100 years) horizons. Second, climate impacts, adaptation and mitigation potentials need to be assessed against the backdrop of socio-economic development. Third, metrics should analyse impacts of climate as well as benefits of adaptation strategies aimed at managing risk and maximizing benefits in coming decades. In addition to estimating benefits of climate policies, metrics can aid in the assessment of vulnerability of agricultural systems, helping to identify adaptation strategies needed to improve production under the different conditions of future decades. Finally, by assessing these metrics across different climate and emission scenarios, it will also be possible to use the same metrics to analyse the benefits of mitigation.

In addition, *vulnerability thresholds* may be derived from the impact metrics, as specific values of the proposed metrics beyond which the ability of a system to cope with a new climatic range is significantly diminished (e.g., Jones, 2004), e.g., the risk of production failures increases (Fig. 3). Changes in management practices may be necessary in such cases to restore system productivity. Thresholds for agricultural systems may be based on estimates of national-level inter-annual yield variability over long-term means. The coefficients of variation are a good indicator of a system's long-term viability. Likewise, physiological temperature thresholds for crop growth, especially during key phenological events such as flowering, can be used for analysis. At the socio-economic level, nutrition indexes, derived from comparing internal food supply, including trade, with calorie demand, provide important thresholds for malnutrition and risk of hunger (e.g., Fischer et al., 2005).

Figure 3. **Coping ranges and vulnerability thresholds under stationary and changing climate conditions (from Jones, 2003)**



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Time

Agricultural production metrics

Key characteristics of agricultural systems may be described by local, regional and global metrics based on the long-term sustainability of production. Long-term means (at least 20 years), and variability of yield and production, income, and aggregate value-added may be used for this purpose. Regional and national data on agricultural income and production, available from FAO and related studies (e.g., Bruinsma et al. 2003; Fischer et al., 2005, Parry et al. 2005) may be used to describe total and regional GDP, GDP/capita, share of agricultural GDP (agGDP) and agricultural GDP per capita; total and regional production of cereals and/or additional crops.

Another quite useful metric is the nutrition index, i.e., an indicator of the number of people at risk of hunger in a given region, computed as the sum of local production and net imports divided by total food demand (Bruinsma et al. 2003; Fischer et al., 2005). Temperature and precipitation (means and variability), are key determinants affecting the variability of agricultural output, including the extent of area planted and harvested, amount and schedule of inputs used (water, nitrogen, etc.); growing season length; and plant sensitivity to extremes.

Benchmarking the state of current and future agricultural systems is useful for comparisons across different production regions and future socio-economic scenarios. Criteria for system vulnerability can then be developed and evaluated through interactions with national and regional stakeholders and experts, as a function of their knowledge of production and societal trends of importance to agriculture in coming decades (See results of the workshop and the survey in Appendices A and B).

Proposed framework

Following the criteria identified in the previous sections and discussed among workshop participants, a general framework was developed for climate change impact and adaptation metrics for the assessment of climate policy benefits. We focus herein on metrics relevant to national and regional to global scales, allowing for estimates on both the near-term (20-30 years) and the long term (80-100), although metrics for other spatial and temporal scales can also be developed within this approach. In addition to helping decision-makers to evaluate the benefits of climate mitigation policies, this general framework may also be useful for planning and evaluating the costs and benefits of adaptation responses in the agricultural sector.

The framework identifies biophysical factors, socio-economic data, and agricultural system characteristics, as the key categories relating to vulnerability criteria of agricultural systems, expressed in terms of their exposure, sensitivity, adaptive capacity, and synergy with climate policy (Table 4). Specifically, metrics for biophysical factors may include indexes for soil and climate resources, crop calendars, water status, biomass and yield dynamics. An example of a biophysical indicators, for which a unitless measure of soil and climatic limitations to crop growth that can be easily calculated and applied to current and future climate projections is shown in Fig. 5. This figure shows the potential impacts of climate change on suitability classes for cereals in Sardenia, with low suitability classes extending to important areas of current production. Drought conditions, another example of a biophysical indicator, can be expressed as the ratio of actual versus potential evapotranspiration. Fig. 6 shows examples for Sardenia, where a water stress index was used to assess marginal production areas under current climate; and for the African continent, where a recurring drought index is used to define areas at risk of severe water stress. Metrics for agricultural system characteristics may be expressed as indexes for land resources, such as the percentage of arable land in use in a given region; inputs management, such as fertilizer and water applications; irrigation shares, i.e., the percentage of area or production that is irrigated within a region; and statistical production data.

Metrics for socio-economic data include indexes describing rural welfare, reflected for instance in regional land and production values, total agricultural value added, or the agricultural share of GDP. They may include, importantly, nutrition indexes comparing regional calorie need versus food availability through local production and trade. Finally, they could indicate degree of protectionism and the status of crop insurance programs.

Finally, metrics for climate policies describe regional commitments to adaptation and mitigation policies, relevant to agriculture. For instance, such metrics measure land use and sequestration potential; number and type of Clean Development Mechanism (CDM) projects in place and committed land area; area planned for bio-energy production, etc. These may be useful for identifying potential synergies of mitigation with adaptation strategies within regions, helping to define how vulnerability may change with time.

Table 5. **General framework for agricultural metrics**

Categories	**Vulnerability Criteria**	**Measurement Class**
Biophysical indicators	Exposure	Soil and climate Crop calendar Water availability and storage Biomass/yield
Agricultural system characteristics	Sensitivity	Land resources Inputs and technology Irrigation share Production
Socio-economic data	Adaptive Capacity	Rural welfare Poverty and nutrition Protection and trade Crop insurance
Climate policy	Synergies of mitigation and adaptation	Kyoto commitment capacity Regional Support Policy, such as CAP Carbon sequestration potential CDM projects in place, planned Bio-energy Irrigation Expansion projects Land expansion plans Change in rotations/cropping systems

Figure 4. **Applications of a crop suitability index for Sardenia, Italy, under current and future climate. The figures show suitability for cereals under current (right) and future (left) climate conditions (Example provided by D. Spano, University of Sassari, Sardegna, Italy).**

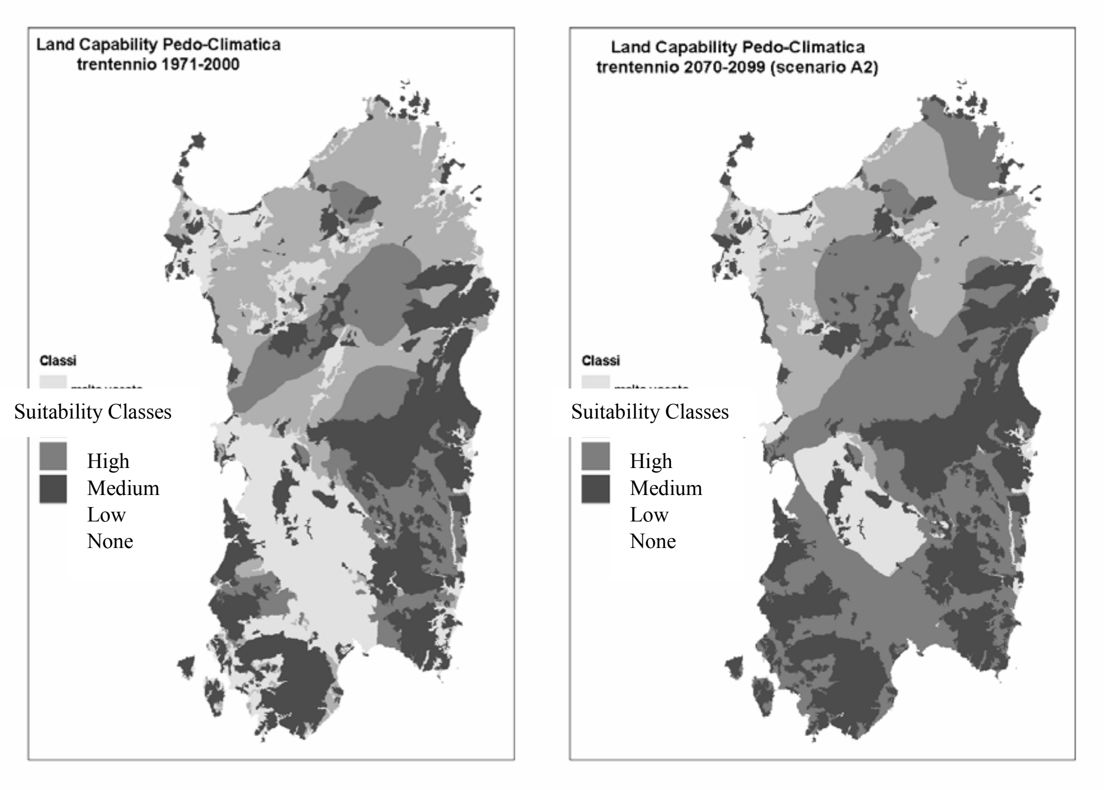
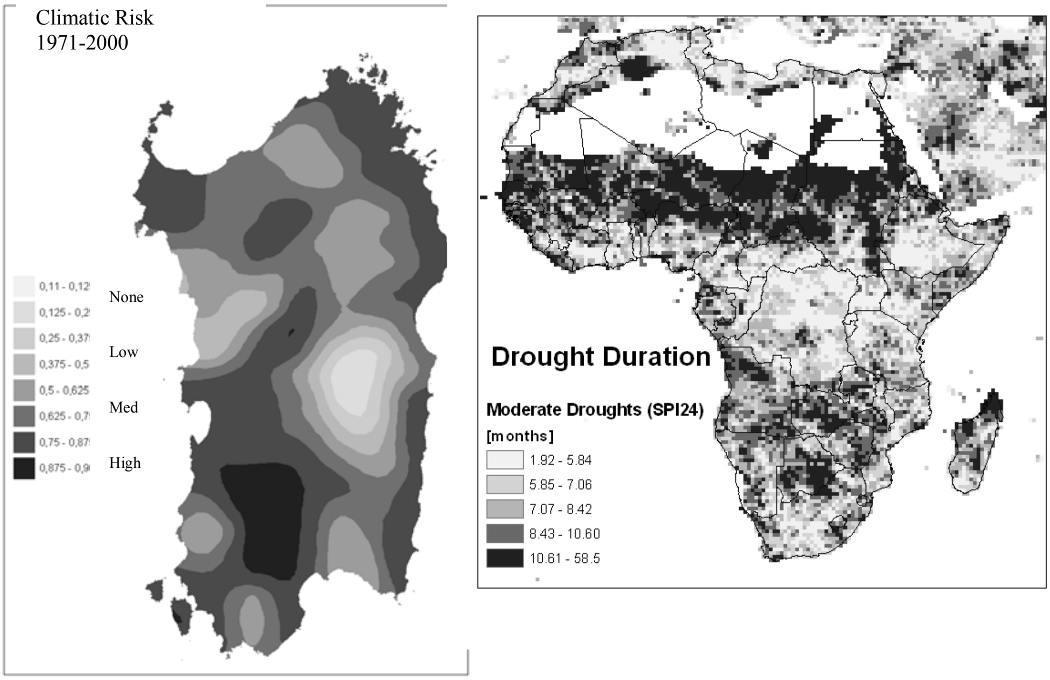


Figure 5. **Applications of a water stress/drought duration index for semi-arid and arid environments in two different regions. Computations of water stress in Sardenia (left) provided by D. Spano (University of Sassari, Italy); computations of drought duration in Africa (right) provided by A. Loetsch (World Bank).**



Based on the framework provided in Tab. 5 above, many potential metrics are available for system characterization .Here we propose a first set of metrics for policy applications, as shown in Table 6. The proposed set of metrics includes agricultural system characteristics, such as land resources regional cereal production, percent irrigated land, and a water index related to the ratio of water withdrawals to available renewable water resources; socio-economic data, such as aggregate economic value-added of production, land value at risk and a nutrition index related to number of people at risk of hunger; and finally, metrics for interactions with climate policy, such as competition for land for afforestation/reforestation or bio-energy projects for mitigation. Below we discuss how different types of impacts models could be used to estimate such metrics, and describe an application for using metrics for assessing benefits of climate mitigation policies on regional-to-global scales.

Table 6. **Proposed set of metrics for impact assessment**

	Metric	**Description (Units)**
Biophysical indicators	Crop suitability	Soil and climate factors (no single unit, i.e. different units for different factors)
	Crop yield	Seed Production (Tonne/ha)
	Water stress Index	Ratio of actual versus potential ET (no units–a ratio)
	Drought duration Index	Cumulative water stress over time (no units – a ratio)
Agricultural system characteristics	Land resources	Ratio of used vs. available land (no units – a ratio)
	Regional cereal production	Major cereal crops (Tonne/yr)
	Water resources	Irrigation requirements over availability (no unit – a ratio)
Socio-economic data	Economic value at risk	Net production value; agricultural GDP ($)
	Land value at risk	Land value of areas most affected ($)
	Nutrition index	Food demand over supply (no units – a ratio)
	Risk of hunger	Cumulative number of people whose calorie intake falls below a (FAO-defined) specific value (millions)
Climate policy	Mitigation potential	C-Sequestration committed (Tonne C yr^{-1})

5. Initial simulations and results

What are the implications for global and regional agricultural production of mitigating greenhouse gas emissions, and thus slowing climate change over time? By when and by how much do impacts get reduced? Where does it matter most?

We illustrate how these questions can be investigated given a specific socio-economic and emission scenario, within the context of some of the metrics proposed in Table 6. This example, which is only a technical simulation, is taken from work done in collaboration with the International Institute for Applied Systems Analysis (IIASA), using an agro-ecological dynamic crop model, the IIASA/FAO AEZ, in conjunction with IIASA's global economic and food system model, BLS, and is based on published results (Tubiello and Fischer, 2006). See Appendix C for further details on the modeling methodology.

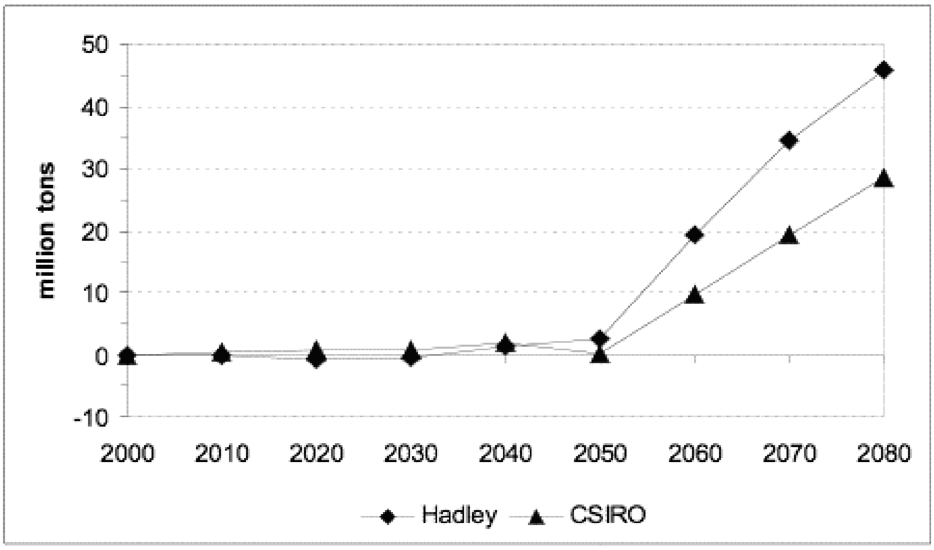
In order to estimate benefits of climate change policies, two distinct sets of climate simulations were analyzed within a SRES A2 storyline: 1) A *non-mitigated* scenario, with emissions reaching above 25 GT C per year and atmospheric CO_2 concentrations over 800 ppm CO_2 by 2100, and corresponding to a 4°C global mean temperature change above 1960-1990 levels; and 2) A *mitigation policy scenario*, with emissions progressively reduced below 1990 levels and CO_2 concentrations stabilizing at 550 ppm by 2100, corresponding to a 2.3°C global mean temperature change above 1960-1990 levels. With respect to climate change and socio-economic impacts, key trends expected over the 21st century for food demand, production and trade were computed, with specific attention given to potential monetary (aggregate value added, agricultural GDP) and human (risk of hunger and malnutrition) implications of climate mitigation.

Simulations with the AEZ-BLS system contained a number of advanced adaptation responses under either of the two scenarios considered. Adaptations considered included agronomic adjustments to changed growing conditions, such as changes in crop calendars (e.g., anticipation of planting for spring cultivars; adjusted harvesting schedules, etc.); and changes in crop varieties and species that better suit the changed climate; as well as adjustments in multi-cropping in tropical regions. Management adaptation only involved modification of irrigation regimes over land already irrigated; irrigation was however not extended to new areas in need, nor were fertilizer applications modified.

As shown in Fig. 6 for cereal production and Fig. 7 for number of people at risk of hunger, the results suggest that mitigation policies could have significant positive effects on agriculture, compared to unmitigated climate change. Specifically, within the emission scenario considered, the results indicate that avoiding a global mean temperature increase of about 1.7°C by 2100 through mitigation could deliver a range of benefits in the 2080 timeframe. These include global economic costs of climate change impacts on agriculture, though relatively small in absolute amounts, could be reduced by roughly 75-100% by mitigation (Table 7); and the number of additional people at risk of malnutrition due to climate change could be reduced by 80-95% by mitigation.* In addition, significant geographic and temporal differences were found. By the end of the century, regional effects of climate change and mitigation often diverge from global net results, with some regions worse off under the mitigation scenario, compared to the unmitigated case. Global and regional effects of mitigation in earlier decades, up to about 2050, were often found to be insignificant, and in early decades sometimes even negative, i.e., worse than under unmitigated climate change.

Figure 6. **Effects of climate mitigation on aggregate regional cereal production, defined as the difference of impacts with and without stabilization, as computed by the BLS model over time, for selected decades into the future. Positive values correspond to benefits. a) Net global effect of mitigation; b) Data is aggregated into industrialized (IND) and developing (DC) regions (From Tubiello and Fischer, 2006).**

a) Global effect of mitigation on cereal production



b) Regional effects of mitigation on cereal production

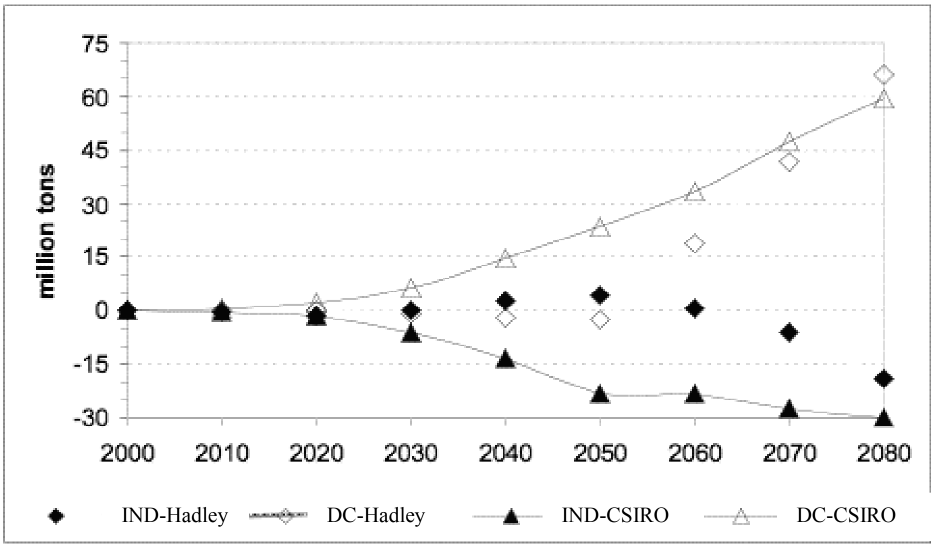


Table 7. **A measure of benefits of climate mitigation policies, expressed as economic impacts on global and regional agricultural GDP (billion US $, constant 1990 prices). The data represent the difference between mitigated and non-mitigated climate change scenario A2 under two climate scenarios, Hadley and CSIRO (from Tubiello and Fischer, 2006).**

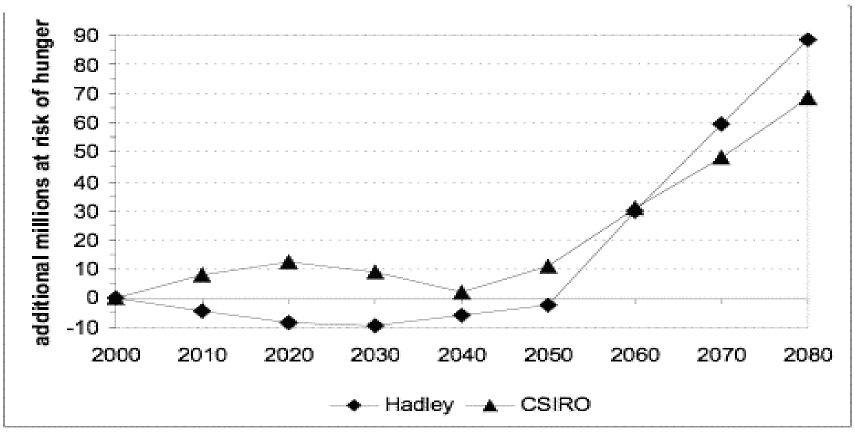
	2020		**2050**		**2080**	
	Hadley	CSIRO	Hadley	CSIRO	Hadley	CSIRO
WORLD	-0.2	0.1	1.9	0.1	33.7	22.9
IND	-0.3	-0.1	2.3	-3.1	0.9	-12.2
DC	0.0	0.1	-0.3	3.7	33.6	36.1
North America	-0.2	-0.2	2.3	-5.2	-3.6	-4.3
EU	0.0	0.3	1.1	3.1	3.8	-4.9
Pacific	0.0	0.0	-1.4	-0.4	0.0	-1.5
Eastern Europe	-0.2	-0.2	0.4	-0.6	0.8	-1.6
Africa	-0.1	0.1	2.1	2.7	9.1	24.8
Latin America	-0.2	-0.3	-1.9	-0.8	-4.2	-14.3
Middle East	0.1	-0.3	-1.0	0.6	4.4	11.8
China	0.0	0.3	-1.4	0.7	11.1	7.5
India	0.3	0.1	3.3	1.3	11.6	5.0
South East Asia	-0.2	0.1	-1.4	-0.8	1.7	1.3

Aggregate Regional data output from BLS and MESSAGE models (Grubler et al., 2006; Tubiello and Fischer, 2006). Among the regional groups, “Africa” represents sub-Saharan Africa; North African countries are grouped into the “Middle East” regional group.

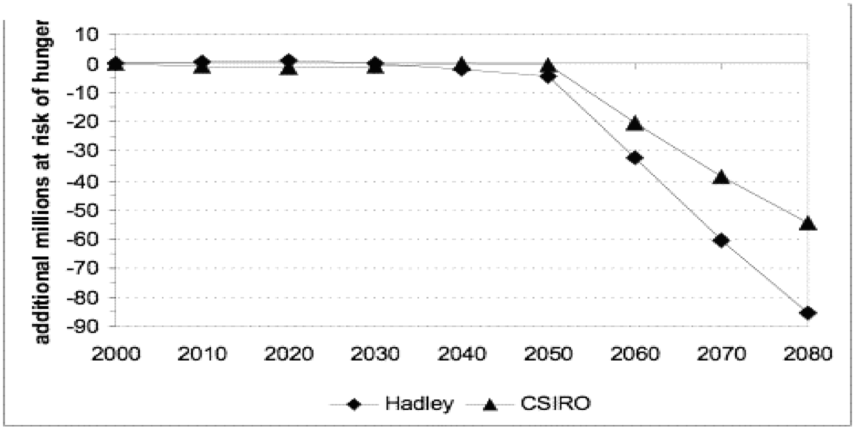
Details on climate projections from the coupled ocean-atmospheric HadCM3 GCM of the UK Hadley Center, and the GCM at CSIRO, are given in Fischer et al., (2005).

Figure 7. **Impacts of climate change and effects of mitigation policies on the number of people at risk of hunger, as computed by the BLS model over time, for selected decades into the future. Data is aggregated globally, representing contributions mainly from Sub-Saharan Africa, Asia, and Latin America. The graphs show: a) Impacts of climate change without mitigation policies; b) Effects of mitigation, defined as the difference in impacts between scenarios with and without atmospheric CO_2 stabilization. Negative values indicate *benefits*, i.e., a reduction of negative impacts with respect to the unmitigated scenario (Tubiello and Fischer, 2006).**

a) Impacts of climate change on risk of hunger –unmitigated



b) Effects of mitigation (550 ppm CO_2)



This study quantified the potential benefits of mitigation to the agricultural sector as a whole, for future decades up to 2080, focusing on climatic impacts on crop yields and their implications for regional production and trade, within a specific socio-economic development path. The results of this simulation/example can be summarized as follows, with ranges indicating GCM differences (Tubiello and Fischer 2006):

1) *The annual global agricultural economic benefit of mitigation policies in 2080 is estimated to be US$ 23-34 billion*, measured as differences in agricultural GDP (at constant 1990 prices) between the mitigated and unmitigated scenarios. These figures represented only 0.8-1.2% of agricultural GDP in 2080; in relative terms, however, mitigation actions entirely eliminated the projected global costs of climate change to agriculture. The geographical redistribution of these changes

was found to be complex, in some cases, varying over time, heterogeneous across regions, and dependent on GCM scenario.

2) *Mitigation benefits developing regions*. Specifically developing countries were projected to gain with mitigation (US$ +20 to +36 billions annually in 2080), i.e., recovered nearly 75% of the losses computed in the non-mitigated scenario. Developed countries, however, lost about half of the gains computed due to climate change without mitigation.

3) *The humanitarian benefits of mitigation policies, in terms of the reduced number of people at risk of hunger, are 70-90 million less people undernourished in 2080.* In relative terms, humanitarian savings of mitigation represented a reduction by 80-95% of the additional numbers of people at risk of hunger due to non-mitigated climate change, nearly two-thirds of this reduction being realized in Africa.

4) *The time evolution of key variables is not constrained by the 2080 end results*. For instance, agricultural GDP gains from mitigation policies computed by BLS were small until 2050 under both GCM scenarios. They were rather globally insignificant for decades up to mid-century, and sometimes even negative up to 2030. In addition, mainly due to production benefits caused by CO_2 fertilization of plants, the number of people at risk of hunger *can at times be higher* (by small amounts) under the mitigated than under the non-mitigated climate change scenario. For instance, results for the early decades up to about 2030s showed more people at risk of hunger with mitigation for Hadley scenario than without.

Limitations of modeling and uncertainties

Simulation models provide a useful tool to investigate complex agro-climatic interactions and feedbacks. Many of the proposed metrics match and are linked to the inputs and outputs of simulation models used to project climate change impacts with and without mitigative policies. However, care is needed to interpret the results of models for several reasons.

First, there is uncertainty in the magnitude of climate change and its spatial and temporal distribution. For these reasons, GCMs results must be considered as representative of physically plausible future climates, rather than exact predictions. As a consequence, when estimating metrics for agriculture, and especially given the prominent role played by rainfed production worldwide, it is very important not to depend on one GCM alone, but to use several estimates based on different climate predictions (Tubiello and Ewert, 2002). Particularly in agriculture, the direction of predicted precipitation can largely shape regional results. At the same time, GCM simulations do not contain all information on potential changes in the frequency of extreme events, nor are the dynamic crop models and agro-ecological approaches designed to fully capture the impacts of increased climate variability. The few studies to date that have included such variables in their assessments show additional negative impacts (e.g., Rosenzweig et al., 2002).

Secondly, the crop model simulations have been validated in many places, but the regional to global nature of metrics means that in many places projections will be based on model results that are poorly tested against local data. In addition, for agro-ecological assessments, often the gap between current actual yields and potentially attainable yields in many developing countries is much larger than the impacts of climate changes on potential yields, leaving uncertainty as to what actual effects of climate change on yields will be.

Another key uncertainty in regard to crop modeling is that the simulated crop response to elevated CO_2, derived from experimental data may be larger than actually possible at farm levels, because of many factors that would limit further crop growth in the field, such as soil and water quality; pest and disease, competition with weeds. All these are not well represented in crop models. Also, response of crops to elevated CO_2 and how experimental data should be incorporated in crop models is a keenly debated topic (e.g., Tubiello and Ewert, 2002; Long et al., 2006; Tubiello et al., 2006). There is a consensus that the CO_2 saturation point of crops is unknown, i.e., the concentration beyond which crop response becomes marginal. This is an important point in relation to estimating the benefits to agriculture of climate mitigation policies, since benefits in early decades (i.e., before 2050) may critically depend on the strength of beneficial CO_2 effects compared to detrimental temperature stresses (e.g., Parry et al., 2005; Tubiello and Fischer, 2006).

Thirdly, simulation results depend strongly on the dynamics of the economic models used. Although these provide internally coherent pictures of socio-economic dynamics, representing plausible futures for scenario analysis, these models are hard to maintain and upgrade, they are poorly validated against current socio-economic data, and in addition must rely on rather uncertain assumptions needed to project food systems in future decades (e.g., technical progress in crop yields, regional irrigation development, changes in food preferences, etc.).

Fourthly, it should be noted that the BLS simulations we considered herein do not consider the issue of the links between food security (and independence), international security and conflicts. In other words, the assumption underlying our simulations, i.e., that countries may accept to depend to a very large extent to world markets for their food security, may not be true in reality.

The SRES scenarios considered herein have been criticized for their regional economic growth patterns, some of which are regarded as too strong when compared to historical data (e.g., see Navicekovic et al., 2003), and may need re-evaluation. Importantly, it should be noted that current studies indicate that the impacts of climate change tend to be relatively small when compared to changes due to socio-economic scenarios alone (e.g., Parry et al., 2005; Fischer et al., 2005; Tubiello et al., 2006). The benefits of climate change policies estimated using metrics from integrated models therefore depend on the choice of socio-economic scenario considered. Changes in socio-economic assumptions, e.g., lower economic growth or alternative demographic development from those specified in SRES, could alter the computed dynamics of climate change impacts and benefits significantly. Finally, models do not address possible extreme and non-linear events and the non-market benefits of agricultural systems on society.

6. Conclusions

Impact metrics can help decision-makers to evaluate, quantify and communicate, the benefits of climate change policies on agricultural systems. Such metrics need to be based on a theoretical framework and tested by stakeholders, policy makers and agricultural experts having local, regional and global experience.

Metrics can represent monetary and non-monetary variables and can be designed for the short-term (20-30 years) and long-term (80-100 years). They can include biophysical factors, socio-economic data, and agricultural system characteristics.

Examples of the key metrics of climate change policy benefits for the agriculture sector include crop yield and variability, water stress indicators, production and land value, as well as a nutrition index for number of people at risk of hunger.

Metrics can be used to facilitate the evaluation of policy options, assess the long-term risks of climate change, and to identify potential thresholds beyond which significant adaptation of management techniques may no longer be sufficient to maintain system productivity and income. As a preliminary example, analyses of metrics used in conjunction with a combination dynamic crop model and an integrated global economic-trade model have shown that aggressive climate mitigation policies may reduce negative impacts of climate change on agriculture, with reductions measurable in both economic and humanitarian terms. However, limiting climate change can result in new sets of regional winners and losers relative to an unmitigated climate scenario.

Additional work is necessary to evaluate the proposed metrics and to test the framework across a range of agricultural systems, socio-economic pathways, and climate change regimes, since the spatial and temporal distributions of climate benefits is uncertain due to the inherent limitations in regional GCM predictions and knowledge of the elevated effects of CO_2 on crops.

Analysis of integrated model scenarios with the metrics proposed has helped to assess usefulness of current models and indicates the need for a range of research development. With respect to the comprehensive analysis of input-output variables performed, we found that dynamic crop models, coupled to economic models that include agricultural trade dynamics, are more useful than Ricardian approaches when developing estimates of climate policy benefits that involve non-equilibrium temporal and spatial dynamics. These dynamics are of key importance to understanding temporal and spatial distribution of benefits arising form given policy targets. On the other hand, while dynamic-crop/economic coupled tools allow for quantification of many metrics of importance to agricultural systems, they cannot include the full range of possible adaptation responses, and thus may overestimate negative impacts. Ricardian approaches, by including implicitly all adaptation, thus remain valuable tools for developing first-order estimates, i.e., focused on large scales and static long-term horizons, of the potential magnitude of climate change impacts and related policy benefits.

Analysis of metrics also suggests a number of key improvements needed in integrated models. *First*, there is a need to include predictions of changes in the frequency of extreme events, most importantly drought and floods, and their impacts on agricultural system vulnerability. If this were done, it would likely have important implications for estimates of the benefits of climate change policies, that is it would increase the benefits of mitigation policies. *Second*, although crop models already allow for simulation of CO_2 effects on crop yields, there is a need for continuing research on, and inclusion in models of, several key limiting factors that characterize real crops in the field, such as dynamics of pests and disease, competition with weeds, air pollution. The effects of elevated CO_2 on crops may critically control the time evolution of the benefits of climate change mitigation policies. *Third*, there is a need to refine and extend predictions of water resources needs as a function not only of climate, but of agricultural land use and sector competition as well. The ability of farmers to irrigate may largely shape system vulnerability and the ability to adapt to increased heat stress. The relevant metrics to this end could be only partially computed within the examples in this report for lack of coupling to hydrologic and sector-demand models. Finally, while soil carbon dynamics and other greenhouse gas agricultural emissions can be simulated within a number of farm-level models and a few agro-ecological frameworks, it cannot be computed within the example framework employed in the simulation presented in this report. Such capabilities need to be better integrated within coupled crop-dynamic and economic agricultural models, to better explain the trade-offs between land use for food, fibre, bio-energy and C-sequestration, as well as the implications of adaptation responses, can be better explored.

In conclusion, the proposed metric set represents a useful tool for consistent and comparable analysis across integrated assessment results, providing for improved estimates of climate policy benefits at both regional and global scales, and allowing for analysis of both short-term and long-term horizons. At the same time, the proposed metrics allow for agricultural system analyses of vulnerability, and are thus useful to evaluate benefits of the regional and sector specific adaptation responses that may be necessary to complement and enhance climate mitigation strategies.

APPENDIX A. WORKSHOP REPORT

Climate Change Impacts and Adaptation Metrics Workshop

NASA Goddard Institute of Space Studies

5th and 6th June 2006

1. Attendees

Walter Baethgen	IRI, Columbia University/ IFDC, USA and Uruguay
Livia Bizik	Slovak Academy of Sciences/ University of British Columbia, Slovakia and Canada
Vittorio Canuto	NASA-GISS
Marcello Donatelli	ISCI Bologna, Italy
PierPaolo Duce	University of Sassari, Italy
Bill Easterling	Pennsylvania State University
Richie Goldberg	Columbia University, USA
Daniel Hillel	Columbia University, USA
Alexander Lotsch	Community Risk Management Group, the World Bank
Cynthia Rosenzweig	NASA-GISS, USA
Wolfram Schlenker	Columbia University, USA
Richard Snyder	UC Davis, USA
Donatella Spano	University of Sassari, Italy
Andrea Taramelli	Columbia University/ University of Perugia, USA and Italy
Francesco Tubiello	Columbia University, USA
Gary Yohe	Wesleyan University, USA
Francesco Zecca	Ministry of Agriculture and Forestry, Italy

The purpose of the workshop was three-fold: (1) Discuss presentations related to key topics and case study regions; (2) Develop breakout sessions to elicit inputs for metrics development; and (3) Analyse feedback on a questionnaire to be sent to experts and stakeholders.

Day One - Monday 5th June

Cynthia Rosenzweig and Francesco Tubiello introduced the overall goals of the project and the purpose of the workshop.

Session 1. Draft Metrics - Suggestions from Case Studies

Livia Bizik identified the socio-economic transformations that need to be taken into account in climate change metric development in transition countries. In Slovakia, Poland and the Ukraine, socio-economic factors have been drivers of negative changes in the agricultural sector. Major changes have occurred in terms of private land ownership that have led to increased fragmentation of land in these countries since 1990. Land abandonment is identified as another threat to the agricultural system. There are significant changes occurring now in the level of institutional development in the region that can play positive role in climate change adaptation.

Donatella Spano reported on relevant results from studies conducted in Sardegna and Emilia-Romagna, regarding the use of bioclimatic indicators as metrics for climate change and agriculture. The main objectives were to develop a methodology for assessing climatic risk based on bioclimatic indexes, to evaluate the potential effects of climatic variations on agriculture, and to obtain maps of climatic risk for agriculture based on past and future climatic variability. Lessons from this study include: Due to climate variability in the Mediterranean region, metrics based on observed trends are not very useful since several decades of data are needed to determine the climate change impacts on agricultural production. The impacts of climate variability are heterogeneous. In Sardegna, precipitation was the main factor and in Emilia Romagna, both temperature and precipitation were important in determining the effect of climate on land capability for agriculture. Thus both temperature and precipitation are needed for metrics related to the impacts of climate change on Italian agriculture.

Walter Baethgen utilized climate, crop yield, and prices as metrics important for characterizing the current state of agriculture. The studies were conducted as part of the AIACC program – a GEF-funded program – in the pampas of Argentina, Brazil and Uruguay. Using data from 1930-2000, these studies show increased precipitation, decreased maximum temperature, increased minimum temperature, and shorter and milder frost seasons. These trends have had a positive effect on land-use changes, but incidences of diseases have been higher.

Bill Easterling recommended that bioclimatic metrics include thermal time indicators such as degree days and heat stress days. He used the Kendall-Thiel regression to calculate thermal time and heat stress days in the U.S. Midwest, and found that there was an upward trend.

Session 2. Economic Perspectives

Alexander Lotsch explained how and why index-based insurance model works. The Community Risk Management Group (CRMG) model uses the change in cropland patterns as a function of climate change. Cropland density models for Africa projects that most of the cropland will be lost over the next 30 years. The CRMG has developed a new business model for risk management that includes the following goals: (1) insure weather and disaster risks for developing countries; (2) target most vulnerable populations; (3) develop mechanisms for risk sharing and transfer; (4) partner with major re-insurers to ensure sustainability; and (5) enable the poor and supporting institutions to adapt. The pilot program began with ~200 insurers in India, which then extended insurance ~2000 farmers. The CRMG of the World Bank develops the product and then sells it to the insurance agency, which evaluates the data. These kinds of product can be traded as derivatives.

Wolfram Schlenker described a hedonic study that captures the effects of farmer adaptations to climate. Using corn, soybeans, and cotton yield data, he showed that there is a large negative effect of heat waves, although the relationship between weather and crop yield is non-linear. The eastern US shows losses in the aggregate, no technological progress in heat resistance in last 55 years, and limited potential for climate adaptation. In the western U.S. water rights are very important. In the study, losses are lower with adaptation, and results are comparable between models.

Session 3. Breakout Group Discussion Sessions: Metrics Development and Use

Eight questions regarding metrics development were posed to the participants, who were divided into two groups for discussions. The results were as follows:

Who are the stakeholders for climate change and agriculture metrics? What is the key spectrum of scales?

In relation to metrics that provide a general guide about the capacities and needs to address climate change and agriculture with regard to both biophysical and socio-economic determinants, the primary stakeholders should be national governments. These should utilize the generic information from the metrics to evaluate potential risks, assess likely costs of impacts, and evaluate the benefits of mitigation and adaptation policies, strengthening their capacity to respond to climate stressors. Importantly, evaluation with metrics can help governments to mainstream climate change issues into their development policies for future sustainable agricultural practices. Local and regional agricultural planners and stakeholders should provide key inputs to national government officials, in the form of local data on production, environmental quality and rural welfare.

What are the stakeholders’ needs at the different scales? Do needs differ among groups?

At the local to regional scale, stakeholders need to have information on what specific climatic changes are likely in their area, an associated timeline, and a measure of the potential impacts on their agricultural systems. At the same time, they need information of the adaptation strategies that could be implemented to reduce negative impacts or even ameliorate the current situation. Locally, information on changes in production indexes as well as on rural welfare would be necessary. Regional and national planners would need metrics for the overall vulnerability of agricultural systems, as well as for evaluation of response strategies, including costs and benefits of climate policy. In general, the metrics need to include not only hazard assessment, but also socio-economic data for quantifying the resiliency of the system. Needs for metrics differ among different groups.

What overall framework is needed?

While group discussions did not converge to defining a specific overall framework for the metric set to be developed, a number of important characteristics were identified as important for the development process. Specifically:

- Risk management and risk analysis approaches are fundamental for metrics development, with adaptation and mitigation strategies needed to provide focus on climate change issues;

- Metrics should include a concept of vulnerability as a function of exposure, sensibility to exposures, and adaptive capacity.

- Existing indicators of agricultural production systems could be used to help develop key metrics;
- The financial component of climate change impacts and response actions should be considered. Costs and benefits need to be quantified;
- Long-term policy perspectives are needed to guide the development process.
- At the same time, workshop participants discussed potential frameworks for application of metrics. Specifically, the metrics should help in the following tasks:
- Provide guidance for adaptation planning, for instance by quantifying adaptation benefits over the next a 20-30 years;
- Identify specific actions needed for reducing impacts in developing countries and help elucidate potential support mechanism by developed countries;
- Facilitate analysis of vulnerability to food systems and food supply under climate change at global, regional and national levels;
- Help quantify issues of social, regional and intergenerational equality, as well as of environmental sustainability, within agricultural development, and their interactions with climate change impacts and adaptation actions.

What specific metrics are needed for the different groups? (Global/regional climate and agro-climate indices for climate change risk and thresholds)

The main conclusion of this discussion session was the importance of identifying the affected sectors, crops and specific stresses under a number of climate change scenarios. Thresholds should be specific to the sectors, crops and stresses and should include prices.

Temperature and precipitation are universally important across different groups. Food-sufficiency and trade-related indexes would be useful for developed regions, while number of people at risk of starvation is more appropriate for developing countries. Rain fed crop production is important because it directly depends upon availability of water resources. Level of irrigation and health could be considered as vulnerability indices. For all of these variables, increased spatial data coverage than currently available is needed to improve estimates.

What timeframes should be considered? Past/Present/Future (time-slices?)

It was generally recognized that management of agricultural systems and related policy planning is typically operational on the short-term, so that increasing resources should be applied towards improving system knowledge for planning on short-term timeframes, say at least 5-10 years, but possibly 20-30 years for climate change issues. In addition, historical data should be used for calibration, and current conditions employed to establish a baseline against which to monitor changes and impacts of agricultural systems. Long-term projections could be used to estimate climate change impacts and to identify and invest in structural changes that reduced long-term risk, for instance by 2050. It was observed that different timeframes, i.e., more frequently spaced and towards earlier decades, could be necessary for monitoring of sensitive, marginal areas such as the semi-arid tropics and the Mediterranean. Historical land use information would be important for transition countries, where rapid changes of land property rights as well as management techniques are occurring, and for tropical regions with respect to rapid, non-sustainable deforestation. In order to define baselines, metrics should be standardized to reference periods containing ideally 30 years of historical data.

Finally, it was observed that metrics must describe impact and adaptation responses alike. This requires setting up a baseline of socio-economic conditions, and monitor future changes in relation to a system's adaptive capacity. In this way metrics will provide dynamic information about ongoing changes, however they won't necessarily highlight the underlying processes. Therefore, it was proposed that case studies may be used to improve the interpretation of country-level data and to address important regional and local synergies, and trade-offs, linking agricultural change with other sectors and with local livelihood.

1. How should thresholds be handled?

There was no clear suggestion to this end emerging from this discussion session. First, it was noted that it is difficult to extrapolate agro-climatic thresholds from local to regional or national levels, given the heterogeneity of climate, landscape and agricultural management characteristics. Provided regional thresholds could be defined, however, frequencies of exceeding thresholds under a given climate and management scenario could be used as a key indicator of risk. Mitigation strategies could then be analysed in terms of thresholds.

2. How should adaptation levels be handled? How can we bring the biophysical and economic approaches together?

Although recognizing that climate impacts on agricultural systems, and the ability to respond, should be enumerated in economic terms in order to inform policy within a cost-benefit framework, it is difficult and in specific cases not possible to evaluate all natural resources in monetary terms. Different evaluations should be considered in response to the interests of different stakeholders. In order to develop sets of metrics that bridge monetary and non-monetary aspects of climate change, multi-criteria analysis was proposed as a useful tool, although associated with subjective criteria and thus leading to uncertainty. Climate impact scientists could help reduce ambiguity by identifying impact evaluation criteria that could be synthesized and easily communicated across regions, for instance distilled into a series of vulnerability indexes.

3. How should climate change metrics be communicated?

It was generally agreed among participants that communicating metrics effectively to stakeholders and policy makers is an important step towards identifying useful adaptation options. In general, while recognizing that different perceptions of risks exist among communities, communication could focus on response strategies under increased climate extremes. In general to increase awareness, the internet was identified as a very effective tool. Specifically, outreach to extension services was proposed as an effective way to gain access to farmers both in developed and developing countries. It was further recognized that communication of uncertainty elements in both climate projections and benefit estimation models should be communicated appropriately, so that policy makers would better understand the ranges of potential outcomes implicit in specific policies, as well as be aware of incomplete scientific knowledge in specific areas, such as future patterns of extreme events or effects of elevated CO_2 on crops. Finally, bio-physical indicators were identified as appropriate for the scientific community, while socio-economic indicators were seen as the key to communicate to policy makers and the public alike.

Session 4 Regional Views - Mediterranean Marginal Environments

Marcello Donatelli shared the findings of a paper that he co-authored with Cynthia Rosenzweig and Francesco Tubiello. The objectives of this work were to evaluate the impact of climate change scenarios on cropping systems and to develop adaptation strategies to alleviate the negative outcomes of such scenarios. Adaptation strategies for crop production were studied using the biophysical model CropSys, which simulates crop development and growth, water and nitrogen balances, salinity, residue fate, soil erosion by water and CO_2 effects on crop growth. Under scenarios of climate change, CropSys allows to simulate changes in agricultural management, such as irrigation type and schedule, planting dates, crop rotation, N fertilization regimes and genotype selection. For the study presented, crop rotations were simulated at six different locations. It was noted that a key uncertainty was the downscaling of GCM output to the local level. In addition, many untested assumptions about pests and diseases had been made for the purpose of the study. This study demonstrated that several metrics could be defined at the local level, describing variables of interest to local and regional stakeholders, such as crop yield and its variability across agricultural systems and locations, while a dynamic crop model could be used to both provide a unifying framework across the landscape, as well as to identify a number of generic adaptation strategies aimed at minimizing impacts of climate change, as well as to quantify their efficacy at specific locations.

Francesco Zecca analyzed a number of socio-economic contrasts across countries in the Mediterranean region, of importance to identifying potential future risks to agricultural systems in coming decades. For instance, while populations in the coastal EU countries are largely decreasing and urban, populations in North African countries are increasing and largely rural. In economic terms, Mediterranean countries in Africa and the Middle East have higher shares of Agricultural to total GDP than the EU costal countries. In the former countries, agricultural activity is very labour intensive and low input, while agricultural production in the EU is characterized by low labour and is input intensive. In his conclusions Mr. Zecca proposesd strategies to develop climate change indexes and the creation of a health risk index as potential metrics of importance to the Mediterranean situation.

Andrea Taramelli discussed the effectiveness of time series analysis using remote sensing in the agricultural sector, both in terms of potential applications for climate monitoring (i.e., compilation of drought indexes; estimation of the length of growing seasons; extent of flooding), as well as in terms of monitoring for adaptation, for instance by determining patterns of land use and associated changes through time.

Day Two - Tuesday 6th June

Additional reports were presented and discussed on the second day of the workshop. In particular, there were further discussions regarding agricultural metrics development and use. The participants also shared their initial response to the appropriateness of the draft questionnaire for stakeholders.

Reports from Group Discussions: Metrics Development and Use (Continued from day one)

Additional comments were added to the group discussion as follows:

- Indexes should be developed first, and then additional inputs from stakeholders can be requested to improve them.
- Good quality spatial data should be available for computing indexes;
- Uncertainty related to error bars of climate observations and projections should be included in metrics. Remote sensing data may be useful to complement land-based observation systems and reduce uncertainty;
- Information from traditional and climate index-based crop insurance schemes should be incorporated in metrics;
- Crop simulation models should be used in computing metrics and to integrate information on soil and water resources;
- Stakeholders from developed and developing countries need to be involved in the process of developing region-specific metrics: to this end, simple metrics would be best.

- There is a mismatch in the developing countries between the probabilistic climate forecast and stakeholders' ability to respond.
- In order to meet the needs of policy makers, metrics should allow for evaluation of adaptation strategies.

Feedback for the Draft Questionnaire

Workshop participants made a number of suggestions regarding a draft questionnaire to be sent to agricultural experts and stakeholders in the US and internationally. The final questionnaire is given in Appendix B. The following are a few of the suggestions made by the participants:

- Include the concept of system thresholds and extreme climate events;
- Uncertainty elements should be mentioned;
- Ensure that timeframes are clear to the recipients.

The participants recommended that a possible modification to question 6 in the draft document could be to ask policy makers/farmers at what point they would intervene. One way to determine threshold levels would be to work along a continuum and identify a cut-off point. An additional stakeholders' workshop could provide information on what stakeholders think is a critical threshold and their response to risk management. Other possible questions to the stakeholders could be "what could you do in the anticipation of approaching certain thresholds, and in case you have not prepared, what would you do to cope with the consequences?"

According to the workshop participants, targeted interviews with few important stakeholders would be helpful as a first-order approach to the survey. Lists of bio-physical indicators to describe the problem, and a set of socio-economic indicators to communicate the setbacks, need to be mentioned, as well as scenarios for planning adaptation. Finally, monitoring and evaluation criteria should be developed at the outset of the metrics design process.

Main Outcomes

During the final session, Cynthia Rosenzweig and Francesco Tubiello wrapped up the workshop reiterating the final take-away points and requested each participant to share their final thoughts. Key summarizing ideas for metrics development included the following:

Importance of the process:

- Engage stakeholders from the beginning and plan an evaluation process;
- Keep it realistic and manage expectations. Emphasize the development process;
- Understand critical thresholds;
- Keep metrics simple enough to be manageable, but not too simple to be useless;
- Manage data appropriately—identify processes from simple to complex;

- Understand criticality of exposure, sensitivity and vulnerability to climate change. Mitigation and adaptation strategies are also important.

Metrics development:

- Include uncertainty;
- Include observed changes as well as projections of system evolution;
- Facilitate differential approaches for different location;
- Integrate dynamic crop and economic model approaches;
- Include CO_2 fertilization effects;
- Include economic impacts and indicators.

APPENDIX B. SURVEY DESIGN, DISTRIBUTION, AND RESPONSE

1. Background

A draft questionnaire with seven questions was formulated in order to assess the views of experts in the agricultural sector in terms of climate change impact metrics. At the preliminary stage, the draft questionnaire "Improving Methodologies to Assess the Benefits of Policies to Address Climate Change Impacts on Agriculture," was reviewed by the workshop attendees. The questionnaire was composed of questions regarding issues and challenges, timeframe for strategic planning, metrics for assessment and communication of climate change impacts, usefulness of scenarios and relevance of sensitive thresholds.

For the purpose of the survey, eleven top ranking agricultural states[1], based on the 1995 census by the US Department of Commerce, were selected. These states were North Dakota, Kansas, Iowa, Indiana, Nebraska, Illinois, Minnesota, Missouri, Texas, California and Mississippi. Two hundred sixty eight agricultural experts were selected from random counties within these states. Their contacts were found on the USDA webpage, Cooperative Extension System Offices[2]. The questionnaire then was directly sent to the experts via email. They were also contacted by phone. Some states have few crop specialists representing multiple counties, thus, are difficult to randomize. For example, Mississippi State has 12 area extension agents in agronomic crops in total. Because of that, the questionnaire was sent to all of these experts. Likewise, in California, each agricultural advisor from the Central Valley Region was selected for the agricultural value of the area. Additional questionnaires were sent to few experts in Florida and North Carolina as well.

Within a two-week timeframe, fifty-three agricultural experts responded to this survey. Microsoft Excel software was used for the analysis of the responses. In the following sections, the references in the parenthesis refer to Respondent IDs, a numerical value was assigned to each respondent.

2. Respondents

The highest number of responses was received from Iowa and Missouri. The number of respondents from each state is listed in Figure B1.

Section 1 of the survey provides the professional details of the respondents. Most of the respondents identified themselves either as belonging to university-based research organizations or university extension agencies. Only three responses were received from government agencies. Figure B2 summarizes these result. Most of the respondents operated in local scale of decision-making. Figure B3 summarizes the scale of decision-making by the corresponding organizations.

The feedback from the agencies provided invaluable insight regarding how the issue of climate change is perceived in the agricultural states of the US. Few responses suggested that agricultural experts are not well informed regarding climate change impacts on agriculture. Some experts politely turned down the invitation to participate in the survey, saying climate change is not their area of expertise.

3. Long-term Climate Change Impact on Agriculture

Section 2 of the questionnaire attempts to identify the following issues:

1. The issues and challenges raised by climate change impact on agriculture for the organization in question,

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[1] United States Department of Commerce News. February, 1995. http://www.census.gov/Press-Release/cb95-33.html

[2] USDA. Cooperative Extension System Offices. http://www.csrees.usda.gov/Extension/index.html

2. The timeframe for strategic planning keeping long term climate change scenarios and resulting socio-economic changes in mind,
3. Metrics for assessing and communicating the impact of climate change on agriculture.
4. Benefits of scenarios and threshold(s).

3.1 Issues and Challenges

Question 1 in Section 2 aims to find out the issues and challenges might be raised by the impacts of climate change on agriculture for the corresponding organizations. The issues and challenges raised by the respondents in (Question 1) include but not limited to new research challenges and educational needs, farm profitability, alternative crops production and management strategy, crop maturity and crop stress times, changes in crop production and yields and crop insects and diseases. Some identified droughts as one of their major concerns. Nine percent of the respondents found no challenges posed by climate change on agriculture. A few mentioned the possibility of crop gain in the place of crop loss in the corresponding states and expressed the need for further studies. A sample of the responses is provided in Box 1.

3.2 Current Strategic Planning

Answering (Question 2), almost half of the respondents (46%) preferred incorporating climate change scenarios and socio-economic implications in their short term (0-25 years) strategic planning (see Figure B4). Surprisingly, 25% of the experts were not sure about the relevance of this question in agricultural planning. Twenty three percent did not answer this question. Some experts defined short term as 1-5 years or various numbers of years below 10 years. Examples of responses in regard to the current planning time scales are provided in Box 2.

3.3 Impact Metrics for Agriculture

Question 3 in this section aims to find our local expert opinions regarding useful metrics to assess climate change impact and adaptation in agriculture and to communicate the risk to the farmers, colleagues and wider public. About 50% of the respondents identified the risk of increased frequency of extreme events as their preferred indicator for assessing the climate change impacts on agriculture (see Figure B5). Nineteen percent responded that the number of tons of crop lost per hectare was the most important metrics for communication and 27% suggested other metrics (see Figure B3-3). Some of the sample responses are highlighted in Box 3 and Box 4.

Fifteen and thirty one percent did not state their preferred metrics for assessment and communication respectively. It seems that multiple choice with a choice of "Other (please explain) __" would work better for this question regarding impact metrics. Some of the experts expressed their preference for bushels per acre as the unit of reference over tons per hectare. In response to this question, some experts provided additional list of assessment and communication indicators that they found important. They are listed in Table 1.

3.4 Benefits of scenarios and thresholds

Local opinions were assessed in Question 4 regarding the usefulness of climate change and socio-economic scenarios. The majority (62%) found the scenarios to be beneficial for their organizations. Twenty percent of all the experts found the scenarios not useful at all. Another 12% was ambivalent regarding the benefits of using scenarios. Figure B7 illustrates these results.

Forty three percent of the respondents affirmed the usefulness of thresholds approach based on system sensitivity in Question 5. Twenty three percent left this question unanswered. A similar percentage of respondents either did not understand the question or were not sure. This reflects the lack or minimal understanding of climate change among the local experts in the leading agricultural states. Fifteen percent was against setting a threshold. The results are provided in Figure 3-5. Sample responses for this question is provided in Box 3

4. Conclusions

These 53 responses provide some important insights. It seems that the majority thinks climate change poses problems for the agricultural sector and would consider 0-25 years of strategic planning, although some put more emphasis on the prospect of initial crop gains due to warming climate. Survey results are biased toward the responses by the agronomists from Iowa and Missouri. Most respondents represent either university-based research or extension agencies. In terms of assessment metrics, the priority lies in the risk of increased frequency of extreme events. For communication purposes, most agronomists prefer tons of crops produced per hectare. Main points from this survey are summarized below:

- Local experts are interested more in the short term strategic planning rather than longer term.
- Majority finds the risk of increased frequency of extreme events be the most important assessment metrics.
- Crop loss metric is the most preferred among the three examples in the questionnaire.
- The climate change and the socio-economic scenarios are favoured by most of the respondents
- About half of the respondents found setting thresholds based on system sensitivity useful.

These survey results will be shared with the respondents, who will also receive a summary of this report. Based on lessons learned from this exercise, future surveys that may be organized as a follow-up would include:

- Simple graphs or tables summarizing potential changes to climate and their impacts on agriculture, extracted from the scientific literature.
- Simpler language, and perhaps a glossary, to clearly define specific technical terms that may be clear in academic circles but not among stakeholders, in particular those related to the current vulnerability literature.

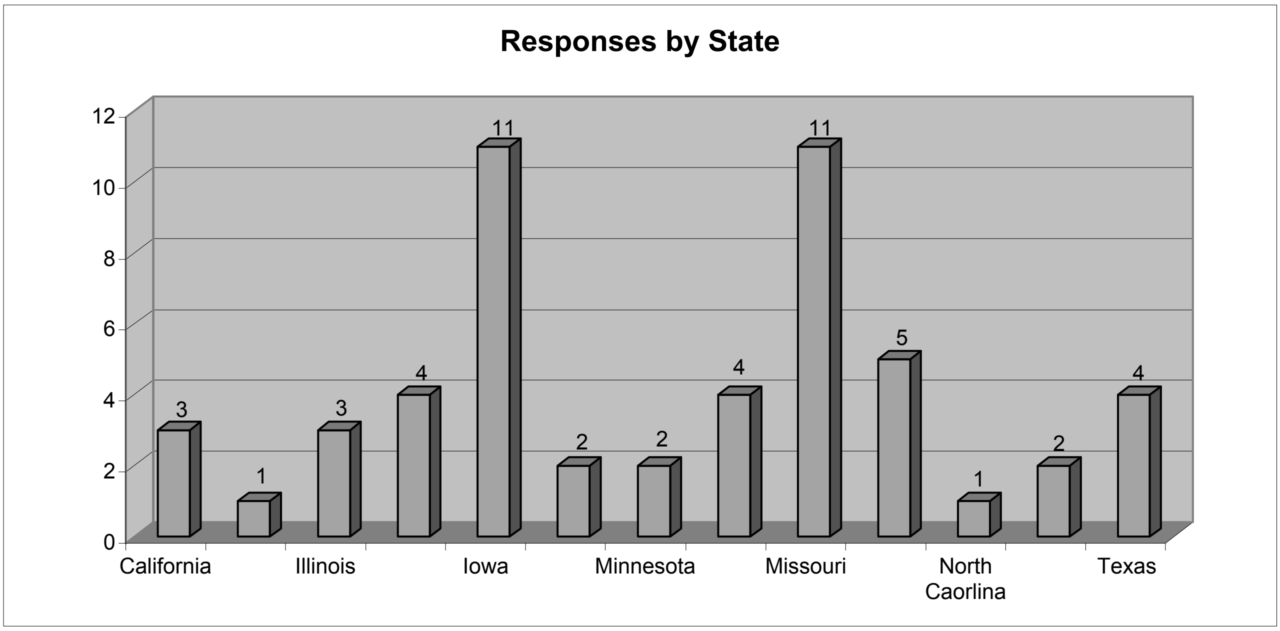

Figure B1 Number of respondents from each state.

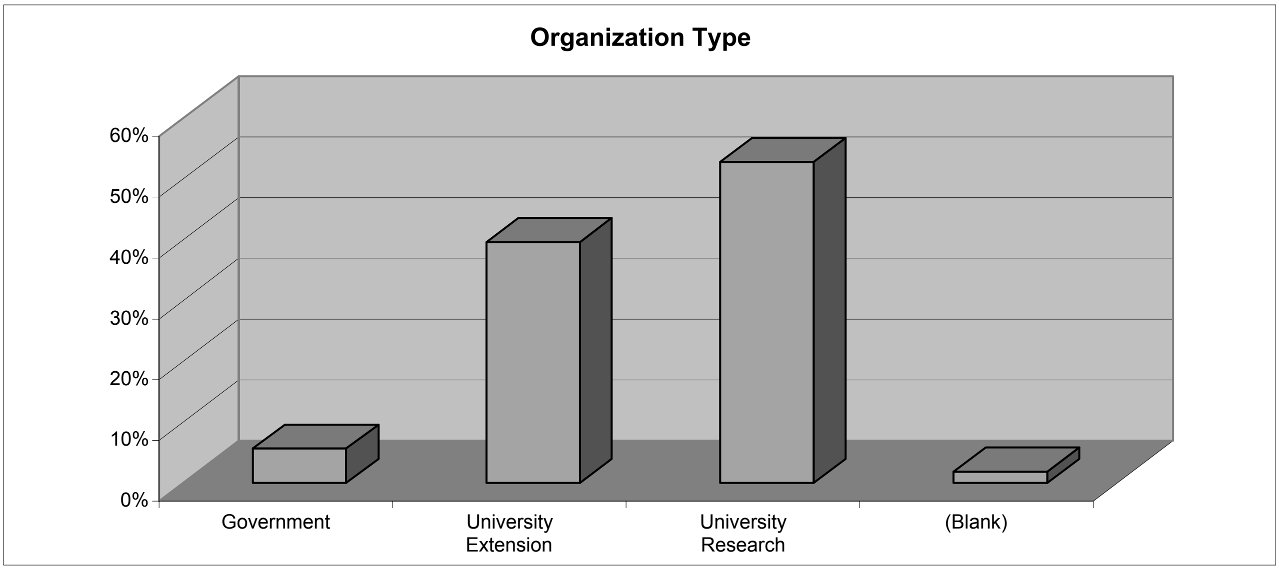

Figure B2 Percentage distribution of respondents by organization type.

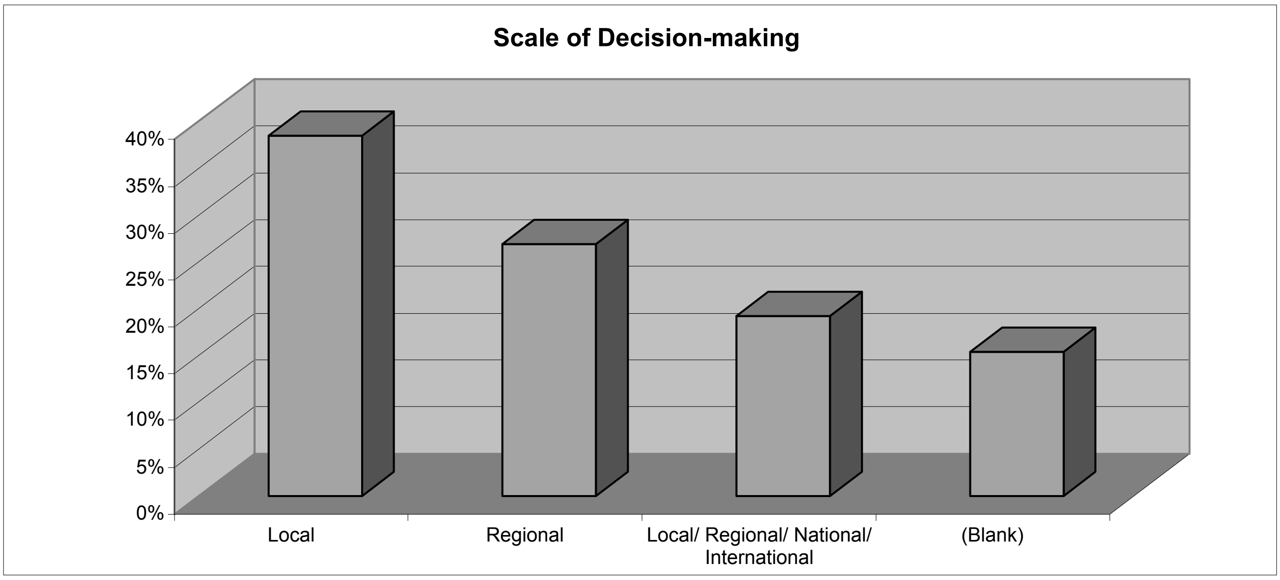

Figure B3 Decision-making scales covered by questionnaire respondents.

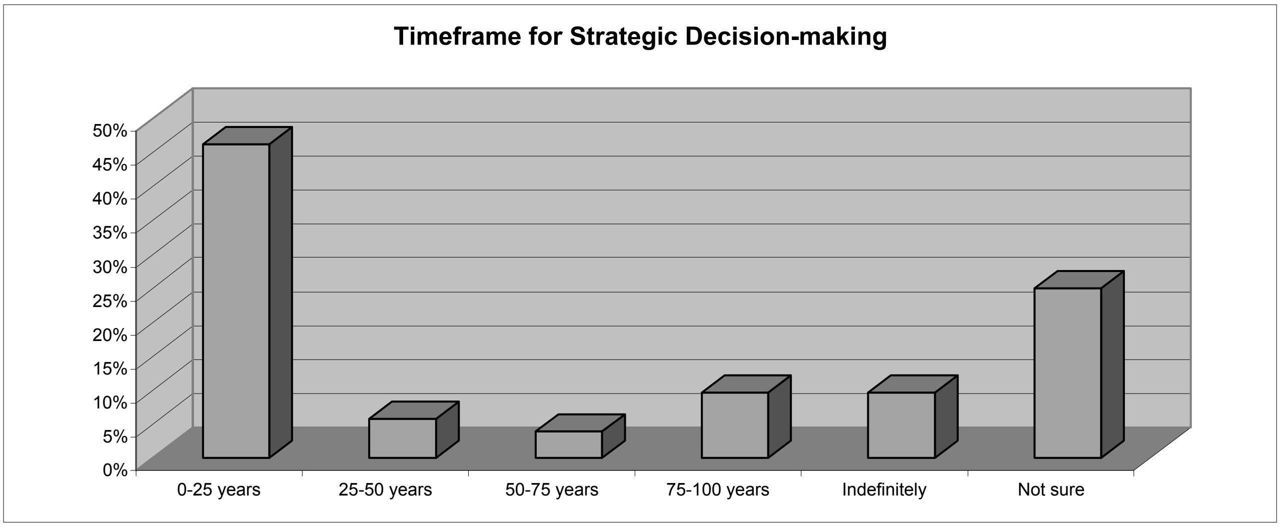

Figure B4 Suggested timeframe for strategic planning.

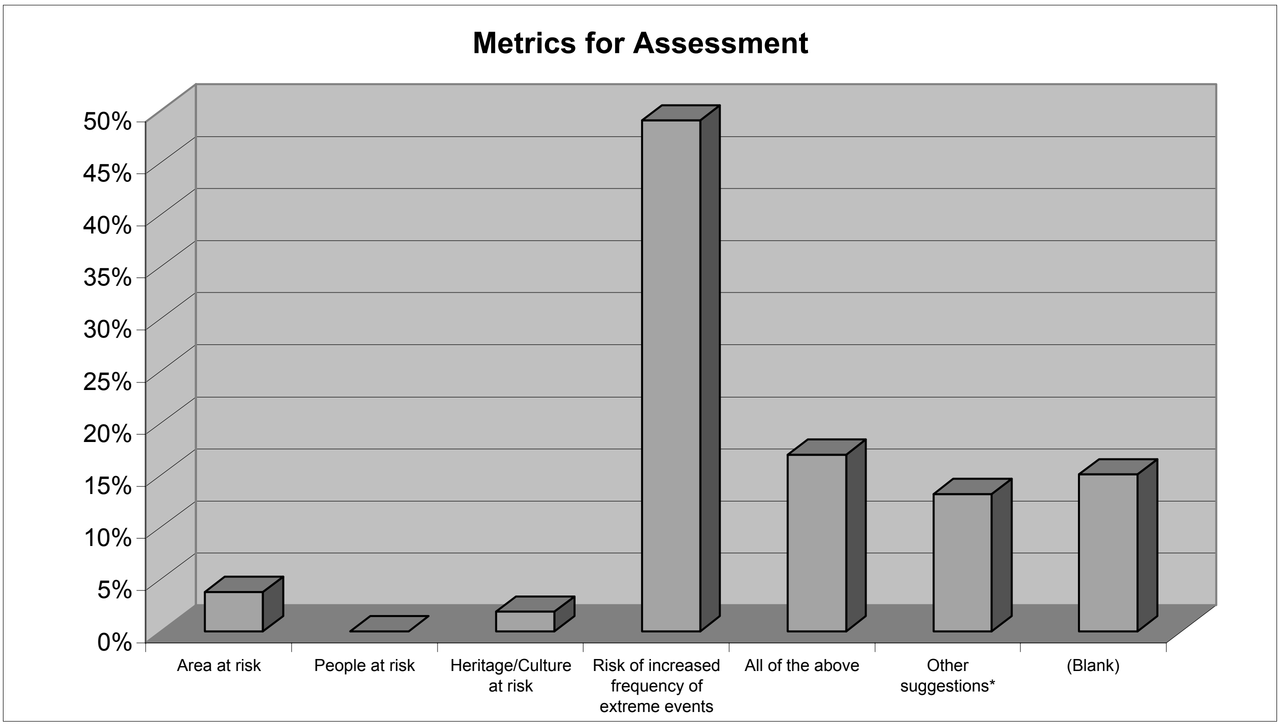

Figure B5 Metrics for assessing climate change impacts and adaptation on agriculture.

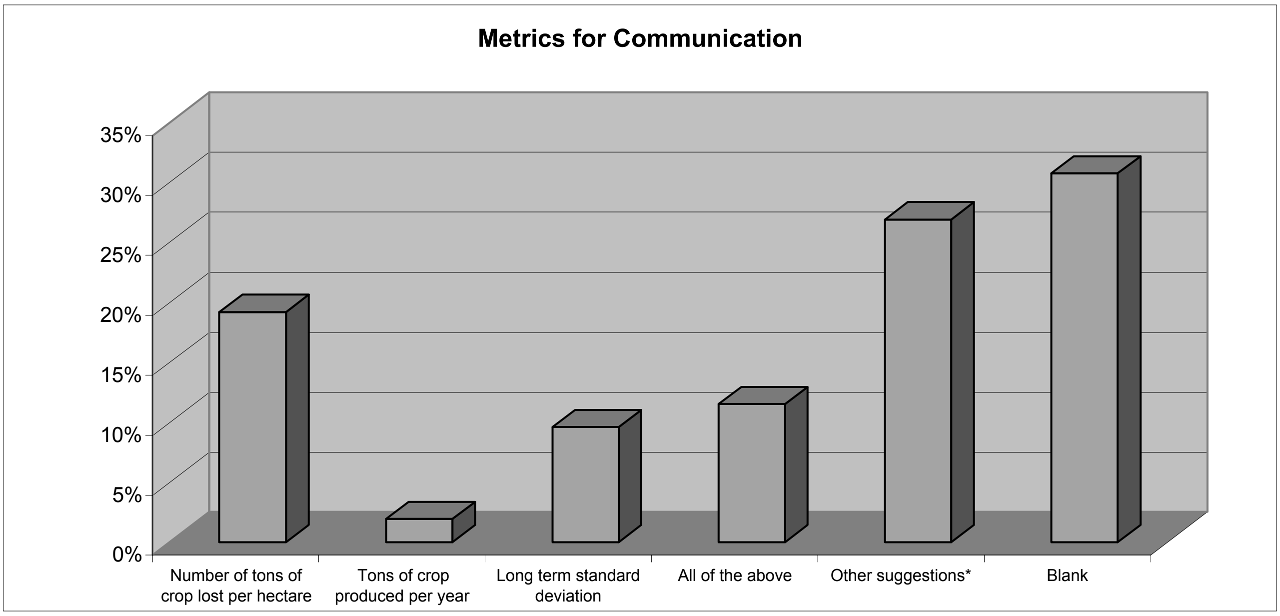

Figure B6 Metrics for communicating climate change impacts and adaptation on agriculture.

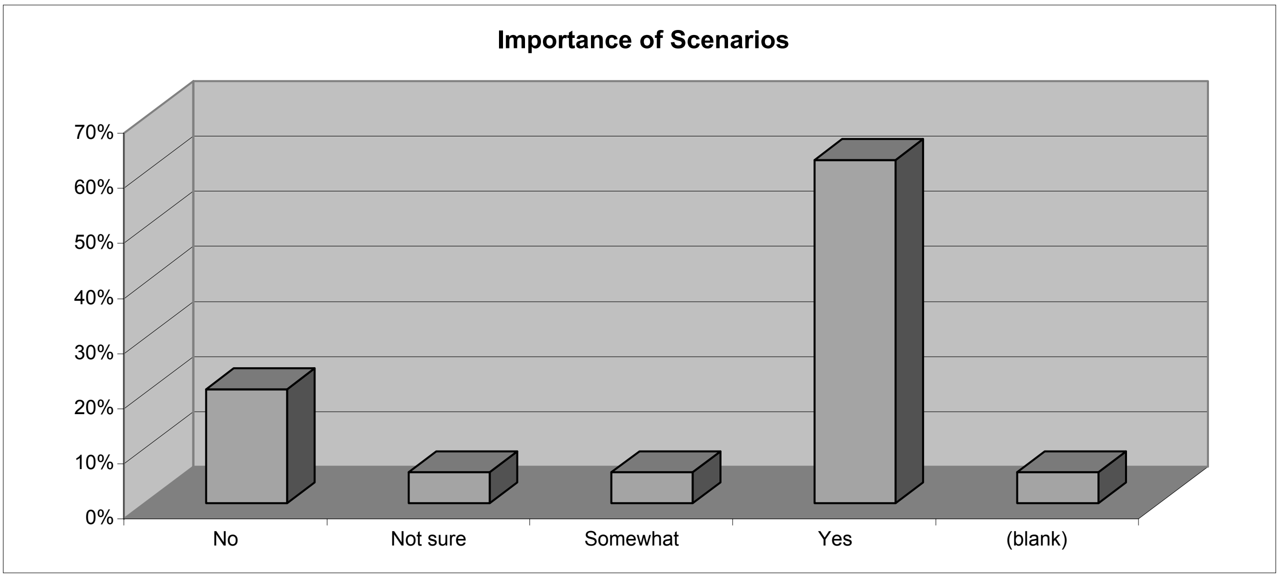

Figure B7 Benefits of climate change and socio-economic scenarios.

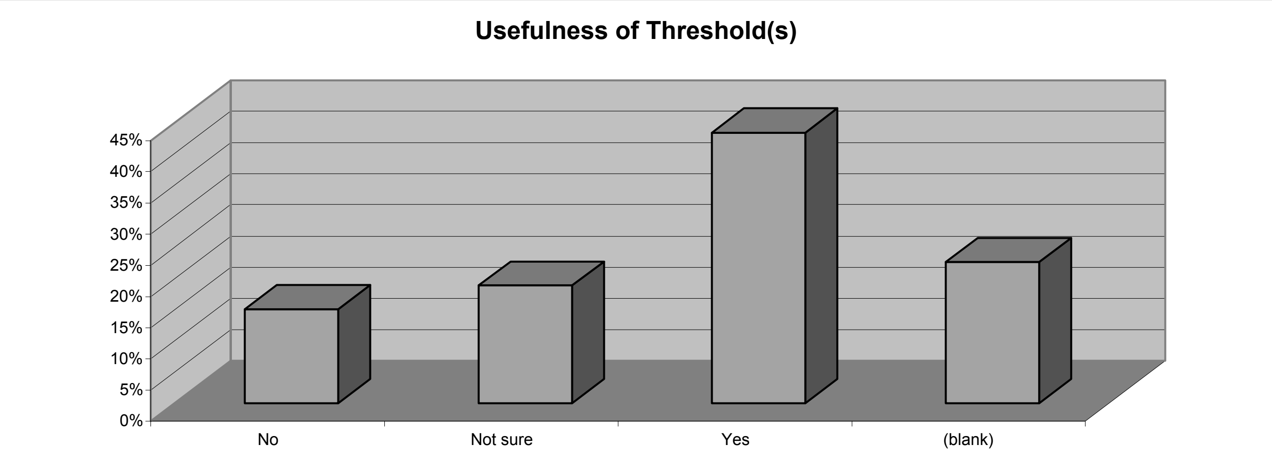

Figure B8 Significance of setting threshold(s) based on system sensitivity

Table B1 (metrics that match with the proposed metrics in the paper are bolded and italicized):

Suggested Metrics			
		Metric	*Units*
Risk Assessment Metrics	***Biophysical indicators***	***Crop Yields*** Crop Failure; Crop at risk	***Bushels/ acre*** ***Tons/ year***
		Yield Variability	
		Probability of different weather scenarios Temperature; Rainfall; Day length; Solar radiation Hail info; Evapotranspiration	
		Risk/benefit of later frost in the fall and earlier frost-free days in the spring	
	Socio-economic data	***Land value at risk*** Expected economic impacts of climate change Crop insurance premiums	
		Nutritional Index—*Food Security*	
	Agricultural system characteristics	***Water--*** *Decreased water supply*	
Communication Metrics for Wider Public	***Biophysical indicators***	***Percent irrigated*** Tons or bushels per hectare or acre compared to a long term mean Tons of crop lost in % of the total production of a given area Crop yield gain per acre or hectare Statewide crop acreage changes Changes in gross revenue/acre/crop Average changes in yields/ac/yr Percent of crop loss vs. expected crop production Change in crop reserves due to production; Crop shift Historical average yield of each crop by county and state Crop specific climate change correlation Other yield expectations in bushels per acre	
		Precipitation and snow pack Frequency of extreme events Abnormal weather related fluctuation Historic weather data compared with more current trends Long term correlation b/w temperature increase and decrease in regional yields	
	Socio-economic data	***Nutrition Index***—Scope of famine and mal-nourishment Change in crop insurance premium	
	Agricultural system characteristic	***Production level***—Decrease in feed and food production Expected forage production over the long term	
		Water—Water quality, water for irrigation	

Box 1 Examples of issues and challenges that concern local agronomists

"Irrigation water shortages and higher costs for fuel, fertilizers, agricultural chemicals, equipment. More severe rain, wind and hail storms will cause crop and infrastructure damage. These will be unpredictable but ever more threatening." (1)

"No measurable impact. No real evidence that significant climate change is occurring." (53)

"Change of focus from traditional corn / soybean production to possibly using irrigation. Better genetics for drought / heat tolerance." (38)

"... Changes in climate could dramatically alter accepted practices which would require assistance be provided to clients on adapting how crops are grown, what crops are grown and when crops are grown. The economic ramifications would need to be studied and presented to our clients." (46)

"This entire question is in my opinion based on an incorrect assumption that man is the primary reason for climate change. ... As an agronomist, a slowly rising level of atmospheric carbon dioxide does not alarm me since it will actually stimulate crop production."(16)

Box 2 Examples of proposed timescale for strategic planning

"Planning for farm management should include short-term (10-year), mid-term (40-year), and long-term (+100-year) scenarios as well as an overall perspective on potential trends well into the future." (4)
"That is an impossible question to answer. Unless mandated, it would be difficult to have government and private entities follow strict guidelines to prevent a possible climate change, unless evidence was very, very strong." (9)
"We need to look at the long term, which to me is 50 years, but we also need to be concerned about addressing current conditions as well." (16)
"We work off of a 5 year program planning process that is reviewed and updated annually. Our budget is on a fiscal year basis (July 1 – June 30) with the budget planning developed in the previous December and open for public debate thru January." (17)

"Producer planning would be based on the length of their operational loan. So as short term as possible." (22)
"not even on my radar screen, we will see what happens. I still remember when we were worried about global cooling in the 80's." (41)

Box 3 Risk of increased frequency of extreme events is the most important assessment metric

"Knowing about extreme weather conditions such as heat or cold and drought would be important to me to help farmers and ranchers make decisions." (3)
"Following Hurricane Katrina, producers see events such as hurricanes and droughts as our most devastating scenarios." (8)
"The extreme weather conditions would be the main gauge for production risks as crop production is dependant upon the weather conditions for frost, extreme hear, extreme cold, excess water, excess snow, etc." (14)
"…the possibility of increased frequency of extreme weather events and the resulting impact on food production are one of the indicators that I would be concerned about." (38)

Box 4 Crop loss is the most favoured communication metric

"For colleagues the standard deviation from mean crop yields. For the general public, the decline of crop yields per year." (24)

"Number of tons gained or lost per acre or hectare. Document shifts in what hybrids or varieties are planted in terms of maturity." (31)

"If responding to technical or professional colleagues the use of standard deviation may be useful but to convey the impact to the general public, I would suggest tons of crop lost per hectare (bushels per acre) or % of the total production of the given area." (38)

"Percent of crop loss vs. expected crop production" (46)

Box 5 Sample responses on importance of scenarios

"Yes if it can be put in a $/acre terminology with relatively clear assumptions." (39)

"Such information could be useful as somewhat of an early warning so people can start thinking about new ideas and partial solutions." (4)

"If I had information on climate change I may be able to help area producers make better cropping decisions." (7)

"Very limited usefulness at this time. We look for weather forecast of the next rainfall event." (8)

"I believe we would utilize them once they were provided to us." (10)

No. There are more immediate issues that need to be addressed on the local and state level. (23)

"It is difficult to tell. On the short term some climate change scenarios may be helpful for controlling crop pest. Others may be too far to the future to be helpful." (25)

Box 6 Sample responses on the usefulness of setting threshold(s)

"Yes. Option (i) would be beneficial. It would help producers with long term risk management strategies they might put into practice." (4)

Yes, I suspect that number ii would have some usefulness. The other question that should be asked is when we reach that point where the ecosystem starts to significantly decline, what in the world are we going to do about it. Leave the earth. Lets not get to that point in the first place." (29)

"You are talking about research parameters and indicators that have value in academic circles but these would have to be interpreted and explained in laymans terms to be understood by the clientele I serve." (52)

"It is difficult to determine what, if any, impact or changes would or could be made based on that scenario." (48)

"Yes, if there was some way to develop a "risk assessment" methodology, it could have useful implications in not only local and regional farm management and ag suppliers, but also related businesses i.e. crop insurance, grain futures markets, farm equipment manufacturers, food and feed processors, etc." (47)

"An alternative approach similar to the Palmer Drought Severity Index might be useful, if it could take into effect all the variables mentioned in the previous queries." (42)

Questionnaire

"Improving Methodologies to Assess the Benefits of Policies to Address Climate Change Impacts on Agriculture"

SECTION 1 – Professional details

(Please note: use the tab key to navigate the questionnaire; boxes will expand as information is added)

1. Please give your profession.

2. Into which categories does your organisation belong?

Type		**Level**	
Governmental - management		Local	
Governmental - policy		Regional	
Charitable organisation		National	
Research – university based		International	
Research – other			
Private company			
Other: (Please define)			

SECTION 2 – Climate Change Impacts on Agriculture (Ex. reduction in crop yield, arable land, water effects, and people at risk)

1. Taking a professional perspective, what issues and challenges might these possible changes raise for your organisation?

2. How far into the future would the climate change and socio-economic scenario(s) be considered as part of any planning decision?

3. Which indicator(s) would be most beneficial?

(i) to gauge the implications of production risk for your organisation (e.g. area at risk; people at risk; heritage/culture at risk, risk of increased frequency of extreme events such flood, droughts, etc.)

(ii) for communication of these implications to colleagues and the wider public (e.g., number of tons of crop lost per hectare, tons of crop produced per year, long term standard deviation from mean crop yield over mean yield (%), etc.)

4. Do you find the climate change and the socio-economic scenarios useful for your organisation?

5. Would an alternative approach based on system sensitivity be useful? You might define a value at which the system(s) you are managing would be significantly affected by the magnitude or rate of change

in climate means and their variability. Would establishing such threshold(s) and their timing using the figure be a useful alternative methodology? For example,

(i) given a design specification of agricultural practice, identification of when the frequency of production failure would become unacceptable would indicate the time span over which alternative management regimes or investment programme would need to be prepared

(ii) having decided the point at which agricultural ecosystem starts to significantly decline, when this point is likely to be reached.

If yes, please expand on the issues that are raised.

6.

Any other comments?

Thank you for participating in this research. If you require further information or have any questions regarding this research, please do not hesitate to contact

Cynthia Rosenzweig at crosenzweig@giss.nasa.gov and

Francesco Tubiello at franci@giss.nasa.gov.

Please note: all of your answers will be treated in accordance with NASA-GISS's code of ethical research, which guarantees the confidentiality, anonymity and protection of all research participants. Thank you.

APPENDIX C. AEZ BLS METHODOLOGY

In order to assess agricultural development over this century, with or without climate change, it is necessary to first make some coherent assumptions about key socio-economic drivers of food systems over the same period, and project their impacts on agriculture, since these provide the true benchmark against which to assess climatic impacts. We used plausible socio-economic development paths, as specified by the IPCC Special Report on Emissions Scenarios (SRES) (Nakicenovic and Swart, 2000). The SRES scenarios have been constructed to explore socio-economic development and related pressures on the global environment in this century, resulting in specific paths of emissions of greenhouse gases into the atmosphere. Within this context, climate change is the consequence of social, economic, and environmental interactions, possibly modulated by the capacity to mitigate and adapt at regional and national levels.

Emissions of greenhouse gases connected to specific SRES scenarios can be translated into projections of climate change by using general circulation models (GCM). The use of GCMs in climate change impact assessments is widespread (e.g., IPCC, 2007, 2001b; Reilly et al., 2001). These models provide internally coherent climates by solving globally all climate-relevant physical equations. Uncertainties of projections remain, due in part to issues of scale resolution, leading to incomplete model representation of regional climate systems; and in part to imperfect understanding of key climate dynamics, such as water vapour-cloud feedbacks (IPCC, 2001a). For instance, the Earth climate sensitivity, defined as mean global planetary temperature response to a doubling of CO_2 levels (~550 ppm) in the atmosphere, is thought to be in the 2.0-4.5 °C range (IPCC, 2007); although GCMs simulations fall squarely within this range, future climate projections corresponding to lower and upper values may be different in terms of projected global warming. More importantly, GCMs with similar temperature change projections may differ significantly in predictions of regional precipitation, due in part to the intrinsic chaotic nature of climate, and in part to different parameterizations of local and regional atmospheric dynamics.

In order to run simulations of crop yields under climate change, we used the IIASA agro-ecological zone model, AEZ, using standard methods (see e.g., Fischer et al., 2005). For three 30-year periods up to 2100 (the 2020s: years 2010–2030, the 2050s: years 2040–2060, and the 2080s: years 2070–2090), climate change parameters were computed at each grid point by comparing GCM monthly-mean prediction for that decade, to those corresponding to the GCM "baseline" climate 1960-1990. Such changes (i.e., delta differences for temperature; ratios for precipitation, etc.) were then applied to the observed climate of 1960-1990, used in AEZ, to generate future climate data. AEZ was then run for each future period, and its results compared to its climatic baseline.

The economic model coupled to AEZ, for estimation of actual regional production and consumption was the IIASA Basic Linked System (BLS). BLS provides a framework for analyzing the world food system, viewing national agricultural components as embedded in national economies, which in turn interact with each other at the international trade level. It consists of 34 national and regional geographical components covering the globe, calibrated and validated over past time windows and successfully reproduces regional consumption, production and trade of major agricultural commodities in 2000 (see e.g., Fischer et al., 2005). Several applications of the BLS to climate-change impact analysis have been published in the last fifteen years (Schmidhuber and Tubiello, 2007).

In BLS, the individual national/regional models are linked together by means of a world market, where international clearing prices are computed to equalize global demand with supply. The BLS is formulated as a recursively dynamic system, working in successive annual steps. Each individual model component focuses primarily on the agricultural sector, but attempts to represent the whole economy as necessary to capture essential dynamics among capital, labour and land. For the purpose of subsequent international linkage, production, consumption and trade of goods and services are aggregated into nine main agricultural sectors, though individual regional models have more detail. The nine agricultural sectors include: wheat; rice; coarse grains; bovine and ovine meat; dairy products; other meat and fish; protein feeds; other food; non-food agriculture. The rest of the economy is coarsely aggregated into one simplified non-agricultural sector. Agricultural commodities may be used within BLS for human consumption, feed, intermediate consumption, and stock accumulation. The non-agricultural commodity may contribute as investment, and for processing and transporting agricultural goods. All physical and financial accounts are balanced and mutually consistent: the production, consumption, and financial ones at the national level, and the trade and financial flows at the global level

Within each regional unit, the supply modules allocate land, labour and capital as a function of the relative profitability of its different economic sectors. In particular, actual cultivated acreage is computed from agro-climatic land parameters (derived from AEZ) and profitability estimates. Once acreage, labour and capital are assigned to cropping and livestock activities, actual yields and livestock production is computed as a function of fertilizer applications, feed rates, and available technology.

Population growth and technology are key external inputs to BLS. Population numbers and projected incomes are used to determine demand for food for the period of study. Technology affects BLS yield estimates, by modifying the efficiency of production per given units of input (e.g., Fischer et al., 2005). For simulations of historical periods up to the present, population data are taken from official U.N. data at country-level, while the rate of technical progress can be estimated from past agricultural performance. For simulations into the future, scenarios of socio-economic development and population growth must be chosen in order to inform BLS computations. The following methodology was developed for application of GCM and SRES scenarios to the AEZ-BLS framework. For use in AEZ, projected GCM changes were interpolated to a grid of 0.5°X 0.5° latitude/longitude and applied to the baseline climate period of 1961-90 (see also following section). Application of SRES scenarios to BLS were realized via the following steps. First, UN-based SRES population growth rates were either incorporated for individual countries or aggregated to BLS regions. In order to maintain consistency with SRES structure, the BLS 34 regions were further aggregated to 11, following SRES. We then let BLS dynamically compute allocation of labour and capital between agriculture and non-agriculture as a function of specified economic conditions. Secondly, BLS runs were harmonized with SRES specifications. The approach chosen was to harmonize rates of economic growth generated in the BLS with those projected in the IPCC SRES scenarios, through adjustment of capital investment (saving rates) and of rates of technical progress in non-agricultural sectors. The harmonization of production factors and GDP, individually for each decade during the period 1990-2080, was carried out on a region-by-region basis.

Notes on SRES scenarios:
Scenario A1 represents a future world of very rapid economic growth, low population growth, and rapid introduction of new and more efficient technologies. Major underlying themes are economic and cultural convergence and capacity building, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system: fossil-intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B). Scenario A2 portrays a very heterogeneous world. The underlying theme is that of strengthening regional cultural identities; with high population growth rates, and less concern for rapid economic development. Scenario B1 represents a convergent world with rapid change in economic structures, “dematerialization,” and introduction of clean technologies. The emphasis is on global solutions to environmental and social sustainability, including concerted efforts for rapid technology development, dematerialization of the economy, and improving equity. Scenario B2 depicts a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is again a heterogeneous world with less rapid, and more diverse technological change.

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