IAJ The Integrated Assessment Journal
Bridging Sciences & Policy
Vol. 8, Iss. 1 (2008), Pp. 165–184

Developing climate change impact metrics for agriculture

Francesco N. Tubiello
Center for Climate Systems Research, Columbia University, 2880 Broadway, New York, NY 1025 USA
and
Climate Impacts Group, NASA-GISS *

Cynthia Rosenzweig
Center for Climate Systems Research, Columbia University
and
Climate Impacts Group, NASA-GISS

Abstract

We propose a framework for the analysis of the benefits of climate change policies on the agricultural sector, identifying biophysical factors, agricultural system characteristics, socio-economic data, and climate policy as key categories for analysis, and relating 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 such a framework, a set of metrics is developed, comprised of variables that can be easily extracted from current impact assessment models and used to obtain consistent and comparable information on climate change impacts and benefits, in both monetary and non-monetary terms. Specifically, this work focuses on 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. The metrics, which include crop yield and variability, water stress indicators, production and land value, as well as a nutrition index for the number of people at risk of hunger, can help to identify risk thresholds and to evaluate policies related to adaptation. Finally, a number of improvements needed within current agronomic and economic models to address key uncertainties in assessing benefits of climate policies are discussed, with attention to the representation of the effects of climate extremes (heat waves, droughts, and floods), pest and disease interactions, and elevated CO_2 on crops.

*Corresponding Author. E-mail: franci@giss.nasa.gov

1 Introduction

Climate change impacts on agriculture have local, regional, and global dimensions (Intergovernmental Panel on Climate Change, 2001). The nature of those impacts will depend upon how much and how rapidly climate changes over time and on how natural and human systems respond. In particular, responses 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 impacts, so that the benefits of climate change policies on agriculture can be assessed within coherent frameworks—providing for both non-monetary and monetary estimations (Corfee-Morlot & 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 for agro-ecosystems, reflecting a level of change beyond which adaptation can no longer be an effective response.

The objective of this work is to develop the general framework, 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 that critical information for their construction can be readily quantified 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); we likewise 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 work focuses mainly at national to regional (here intended as supra-national) and global scales—while bearing in mind decision-makers may require information at more local scale as well. Inputs from an international workshop and a survey questionnaire were used to consider which metrics may be relevant to different regions and players, and to discuss methods for their development and application (Rosenzweig & Tubiello, 2007). Section 2 below provides a review of recent studies of climate impacts and adaptation in agriculture; Section 3 discusses criteria for metric development; Section 4 proposes a generalized framework for analysis and applications, providing an explicit example for application at the regional and global scale.

2 Impacts and Adaptation in Agriculture: A Review

Under climate change the impacts of high temperatures, altered patterns of precipitation, increased water demand, and increased frequency of extreme events such as drought and floods—including positive effects of elevated CO_2 on crops (e.g., Ainsworth & Long, 2005; Kimball et al., 2002)—will combine to progressively depress crop yields and increase production risks in many regions in coming decades (e.g., Intergovernmental Panel on Climate Change, 2007, 2001).

At the plot level, moderate warming in the first part of this century may benefit crop and pasture yields in temperate regions (up to 1–3°C), while it would decrease yields in semi-arid and tropical regions (1–2°C). Further warming—projected for the second part of the 21^{st} century—would reduce crop yields in all regions. Farm-level adaptation may allow to cope with up to 1–2°C warming, an effect that can be seen as "buying time" (Howden et al., 2007).

Realistic projections of food supply however need to include not only climate change factors at the field level, but importantly the entire production chain and market mechanisms, including how these are affected by trends in key socio-economic factors (e.g., Reilly et al., 2007; Schmidhuber & Tubiello, 2007; Tubiello et al., 2007*a*). Once socio-economic considerations are taken into account, global climate impacts on food production are currently thought to be small, albeit with significant regional variation (Intergovernmental Panel on Climate Change, 2007). Specifically, developing countries are more vulnerable to climate change than developed countries, because of often-warmer baseline climates and thus already stressed marginal production environments, heightened exposure to extreme events, and the scarcity of capital for development and dissemination of adaptation measures. Climate change may thus result in 5–170 million people additionally at risk of hunger by 2100, depending on assumed socio-economic scenario (Schmidhuber & Tubiello, 2007). Among developing countries, sub-Saharan Africa may be the most negatively affected, due to and decreased quality of land and water resources and an increasing share of people at risk of hunger. Mediterranean countries are expected to experience severe droughts, leading to abandonment of agricultural land and desertification.

Importantly, increases in the frequency of extreme events, such as drought or flooding, could have significant negative consequences on food supply over and above the impacts projected from changes in mean climate variables alone (Tubiello et al., 2007*b*); the magnitude of projected impacts could be significantly larger, and be realized much earlier—i.e., within few decades as opposed to the second half of this century—than indicated by current projections. Impacts of climate change on irrigation requirements may likewise be larger than assumed in current models, leading to additional negative impacts, especially in North Africa and southest Asia (Fischer et al., 2005).

In terms of policy analysis of agricultural impacts, Hitz & Smith (2004) defined a first set of impact metrics that included crop yield by crop, cultivated land area, and number of people at risk of hunger. They mapped these impact

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

metrics against global mean temperature (GMT) change, used 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 (Intergovernmental Panel on Climate Change, 2001), suggest 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 global 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 key climate change proxy, we refine their analysis by adding both regional and temporal depth to the impacts analysed, by means of a larger set of metrics.

2.1 Adaptation

Adaptation strategies optimize climate responses, by reducing risk or by taking advantage of potential benefits 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 *autonomous adaptation*, i.e., actions taken by individual actors such as single farmers or agricultural organizations, as well as *planned adaptation*, 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 responses by farmers and organizations (Table 2).

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

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.

with decreased rainfall (Howden et al., 2007). Warming beyond these ranges would exceed autonomous adaptive capacity in all regions. Additional measures, planned ahead of time at local, regional, national and international levels may then be needed to facilitate responses. Options involve activities such as developing infrastructure, capacity building in the broader user community and institutions, and in general modifying the decision-making environment. The process of 'mainstreaming' adaptation into policy planning in the face of risk and vulnerability is well recognized (Howden et al., 2007).

Adaptive 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.

Recent studies have also emphasized the concept of vulnerability of an agricultural system (e.g., Kates, 2001) 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.

2.2 Mitigation

Mitigation actions to reduce greenhouse gas emissions will be implemented at the same time as adaptation responses. Yet the two may be at odds with each other, for example due to competition for land between food crops and biofuel or land expansion. By contrast, specific mitigation strategies for enhanced soil carbon sequestration may have strong synergies with adaptation—helping to reduce system vulnerability by improving soil-water status (Rosenzweig & Tubiello, 2007).

Both adaptation and mitigation solutions will deliver benefits in terms of avoided negative impacts in the agricultural sector. While many studies have compared impacts with and without adaptation, however, little has been done in quantifying impacts under scenarios with and without mitigation. Initial results from recent 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; concerted efforts are likely to be needed to redistribute risk and benefits globally (Parry et al., 2005; Tubiello & Fischer, 2007).

We focus our analysis on studies that assess both regional and temporal dynamics of agricultural impacts over the 21st century (e.g., Tubiello & Fischer, 2007; Parry et al., 2005; Fischer et al., 2005; Parry et al., 2004; FAO, 2003; Fischer et al., 2002); we also review another important category of models, so-called Ricardian (e.g., Mendelsohn & Nordhaus, 1999). We argue however that despite representing an interesting alternative approach with a powerful treatment of adaptation, the latter are less useful for metrics, as they are regionally limited, do not consider explicitly the effects of regional and global trade, and lack transition dynamics—being based on equilibrium criteria.

3 Methodological Issues

While the literature on climate change impacts on agriculture is extensive, there is nonetheless a need to develop an analytic framework—i.e., a system of metrics beyond a simple, global mean temperature proxy—for comprehensive comparisons of projections across scales, regions and models (Corfee-Morlot & Agrawala, 2004; Jacoby, 2004).

The metrics to be developed, to be referred herein as climate change impact and adaptation metrics, should 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. Appropriate and relevant metrics communicate in a simple and concise manner the importance of the observed and projected impacts, 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 (World Bank, 2005)—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.

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

3.1 Tools for Impact and Policy Assessment

Models are necessary, in addition to observed data, to project impacts of future climate change and socio-economic development on agricultural systems, and to derive associated metrics for estimation of climate benefits. 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, 1995), AEZ (Fischer et al., 2002), are biophysical representations of crop growth and production that include explicit representation of land and crop management techniques. These models 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., Tubiello & Ewert, 2002). They have been coupled to agricultural-economic models, such as BLS (Fischer et al., 2002) and FARMer (Darwin, 1998), to estimate regional and global food demand, production and trade as a function of agro-climatic and socio-economic factors (i.e., Fischer et al., 2005; Parry et al., 2005).

Ricardian approaches (Mendelsohn & Nordhaus, 1994; Schlenker et al., 2005) primarily provide assessments of monetary impacts on agricultural systems, such as land value at risk under climate change. The many proposed statistical approaches underlying this methodology assume in essence efficient geographic distribution of agricultural activity as a function of climate regime. When applied to climate change scenarios, model results implicitly include full adaptation under the new situation—based on information from current statistics and assuming an equilibrium response.

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 climate policy. They provide quantifiable 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, they link regional agricultural production to issues of trade, food supply, and nutrition levels. Such models cannot cover all possible adaptation solutions, however, and thus may tend to overestimate climate change impacts and their costs.

Ricardian models by contrast 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. They are however of little dynamic value: they cannot provide any further insight regarding which specific adaptations would work in practice, their spatial distribution and 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, detection and attribution of climate change; culture and habits; lack of know-how in some regions; and investment. For these reasons, they may provide overestimates of adaptation efficiency and thus underestimates of climate change impacts.

3.2 Agricultural Production Metrics

Developing a set of metrics that would apply to all scales (local, regional, national, and global) would be extremely complex in practice. An expert and stakeholder workshop was organized to help evaluate users' needs for practical application (Rosenzweig & Tubiello, 2007). First, metrics of interest may help characterize the status of agricultural production systems currently, over short-term (20–30 years) and long-term (80–100 years) horizons. Second, they need to be assessed against the backdrop of socio-economic development. Third, they should quantify benefits of adaptation and mitigation strategies.

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, 2001, 2003).

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., FAO, 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 (FAO, 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.

4 Proposed Framework and Application

Following the criteria identified in the previous sections, 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. This general framework is useful for planning and evaluating the costs and benefits of adaptation and mitigation 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 3). 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 Figure 1. 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. Figure 2 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

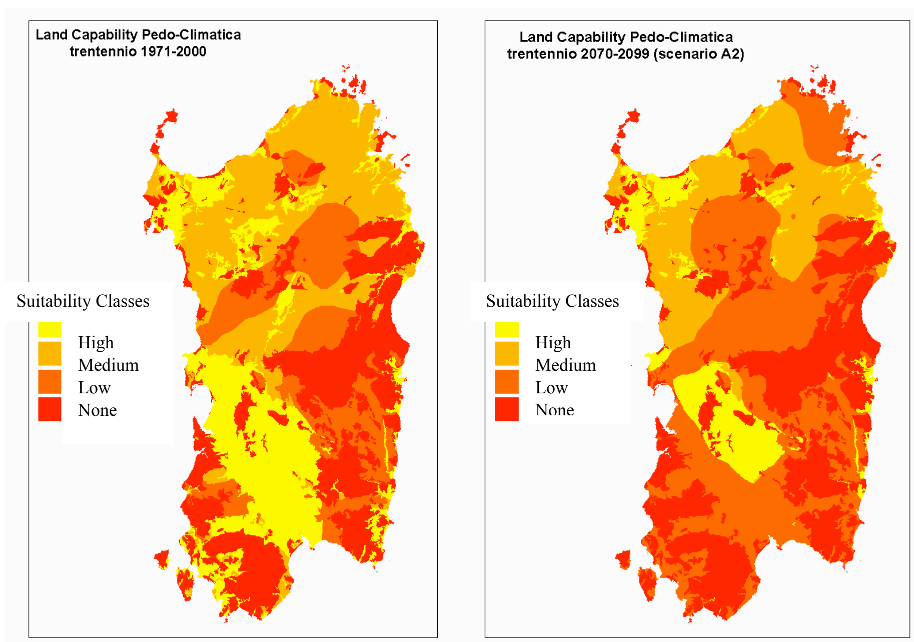

Figure 1: Applications of a crop suitability index for Sardenia, Italy, under current and future climate. The figures show suitability for cereals under current (right) and future (left) climate conditions (Example provided by D. Spano, University of Sassari, Sardegna, Italy).

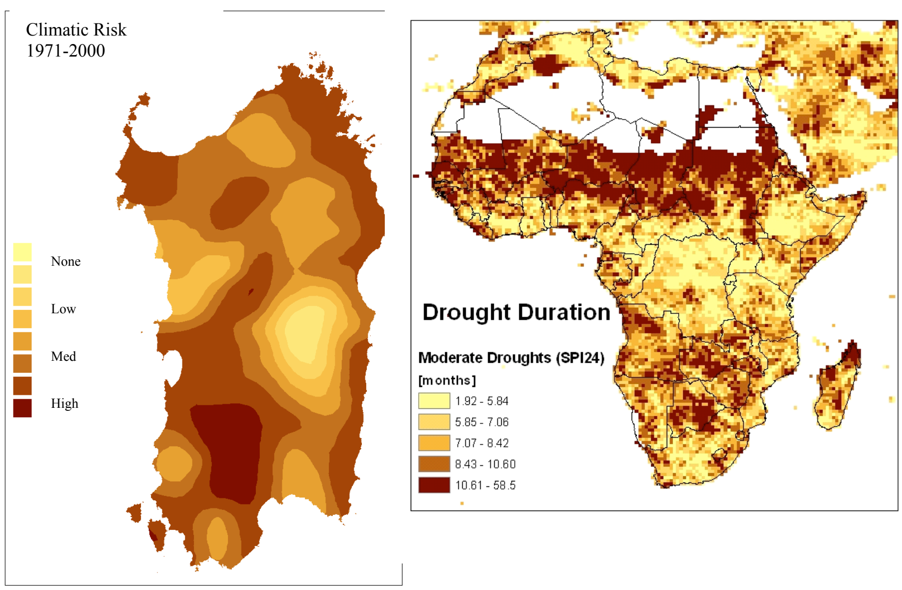

Figure 2: Applications of a water stress/drought duration index for semi-arid and arid environments in two different regions. Computations of water stress in Sardenia (left) provided by D. Spano (University of Sassari, Italy); computations of drought duration in Africa (right) provided by A. Loetsch (World Bank).

Table 3: 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

Table 4: 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})

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.

Based on the framework provided in Table 3 above, many potential metrics are available for system characterization. Here we propose a first set of specific metrics for policy applications, as shown in Table 4. 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.

4.1 Application: Estimating benefits of climate mitigation

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 4. This example refers to a simulation exercise developed at 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 (for more details see: Tubiello & Fischer, 2007).

In order to estimate benefits of climate change policies, two distinct sets of climate simulations were analyzed within a SRES A2 storyline, a business-as-usual case with atmospheric CO_2 over 800 ppm by 2100; and the other being a climate mitigation policy scenario, with atmospheric CO_2 stabilizing at 550 ppm by 2100.

Results suggested that mitigation policies could have significant positive effects on agriculture, compared to unmitigated climate change (Figure 3). Specifically, in monetary terms, the impacts of unmitigated climate change were reduced by roughly 75–100% by mitigation. In non-monetary but key humanitarian terms, the number of additional people at risk of malnutrition due to climate change was reduced by 80–95% by mitigation, with most of the gains projected in sub-Saharan Africa.

Important geographic and temporal differences were identified. By the end of the century, regional effects of climate change and mitigation often diverged from global net results, with some regions worse off under the mitigation scenario, compared to the unmitigated case. Similarly, global and regional effects of mitigation in earlier decades, up to about 2050, were often insignificant, and

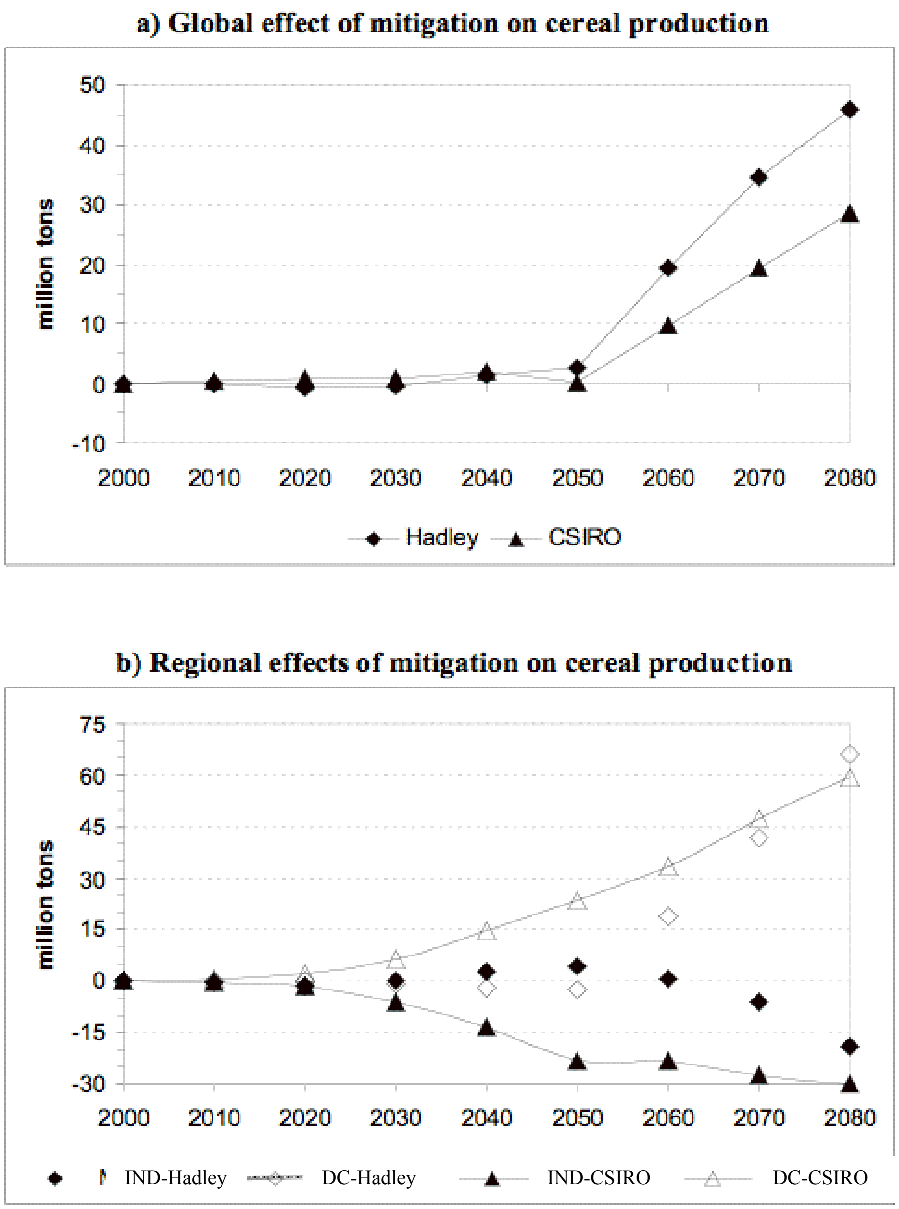

Figure 3: Effects of climate mitigation on aggregate regional cereal production, defined as the difference of impacts with and without stabilization, as computed by the BLS model over time, for selected decades into the future. Positive values correspond to benefits. a) Net global effect of mitigation; b) Data is aggregated into industrialized (IND) and developing (DC) regions (From Tubiello & Fischer, 2007).

in early decades sometimes even negative, i.e., worse than under unmitigated climate change.

Metrics computed form this study thus help quantify the potential benefits of climate mitigation to the agricultural sector as a whole, focusing on climatic impacts on crop yields and their implications for regional production and trade, within specific socio-economic scenarios.

5 Conclusions

Impact metrics can help policy and decision-makers to evaluate, quantify and communicate the benefits of climate change policies on agricultural systems. Such metrics need to be developed with 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.

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 be required to maintain system productivity and income. 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, including the need to include the effects of increased climate variability, 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. In particular, including the impacts of increased frequency of extreme events on agricultural production would likely have important implications for estimates of the benefits of climate change policies. Additionally, there is a need to refine and extend predictions of water resources 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 analysis, for lack of coupling to hydrologic and sector-demand models. Finally, the trade-offs between land use for food, fibre, bio-energy and C-sequestration, as well as the implications of adaptation responses, need to be increasingly considered within impact analyses.

In conclusion, while considering the needs for continued development work mentioned above, 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.

6 Acknowledgements

We thank D. Tirpak, G. Yohe, J. Corfee-Morlot and S. Hallegatte for many useful comments that helped improve this manuscript. L. Bizik; W. Easterling; W. Baethgen; F. Zecca, M. Donatelli, and D. Spano provided specific ideas on case studies applications. This work was funded by OECD and the Italian Ministry of the Environment.

7 Bibliography

Ainsworth, E. A. & Long, S. P. (2005), 'What have we learned from 15 years of free-air co_2 enrichment(FACE)? a meta-analysis of the responses of photosynthesis, canopy properties and plant production to rising co_2.', *New Phytologist* **165**, 351–372. 167

Corfee-Morlot, J. & Agrawala, S. (2004), An overview, *in* J. Corfee-Morlot & S. Agrawala, eds, 'The benefits of climate change policies', OECD, Paris, pp. 9–30. 166, 171

Darwin, R. (1998), *FARMer: A global framework for integrated land use/cover modeling*, Vol. 9802 of *Working papers in Ecological Economics*, Australian National University, Canberra. 172

FAO (2003), *World Agriculture: Towards 2015/2030. A FAO perspective*, Food and Agricultural Organization of the United Nations, Rome. 171, 173

Fischer, G., Shah, M. & van Velthuizen, H. (2002), Climate change and agricultural vulnerability, Special report to the un world summit on sustainable development, johannesburg 2002, IIASA. 171, 172

Fischer, G., Shah, M., Tubiello, F. N. & van Velthuizen, H. (2005), 'Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990–2080', *Philosophical Transactions of the Royal Society B.* **360**(1463), 2067–2083. 167, 171, 172, 173

Hitz, S. & Smith, J. (2004), 'Estimating global impacts of climat change', *Global Environmental Change* **14**, 210–218. 167

Howden, M., Soussana, J. F., Tubiello, F. N., Chhetri, N., Dunlop, M. & Aggarwal, P. K. (2007), 'Adaptation strategies for climate change', *Proceedings of the National Academy of Sciences* **104**, 19691–19698. 167, 170

Intergovernmental Panel on Climate Change (2001), Climate change 2001: Impacts, adaptation and vulnerability, Contribution of working group II to the third assessment report of the intergovernmental panel on climate change, Cambridge University Press. 166, 167, 168

Intergovernmental Panel on Climate Change (2007), Climate change 2007: Impacts, adaptation, and vulnerability., Contribution of working group II to the third assessment report of the intergovernmental panel on climate change, Cambridge University Press. 167

Jacoby, H. D. (2004), Toward a framework for climate benefits estimation, *in* J. Corfee-Morlot & P. K. Aggarwala, eds, 'The benefits of climate change policies', OECD, Paris, pp. 299–320. 166, 171

Jones, R. N. (2001), 'An environmental risk assessment/management framework for climate change impact assessments', *Natural Hazards* **23**, 197–230. 173

Jones, R. N. (2003), Managing climate change risks, Oecd env/epoc/gsp, OECD. 173

Kates, R. W. (2001), 'Cautionary tales: Adaptation and the global poor', *Climatic Change* **45**(1), 5–17. 170

Kimball, B. A., Kobayashi, K. & Bindi, M. (2002), 'Responses of agricultural crops to free-air co_2 enrichment', *Advances in Agronomy* **77**, 293–368. 167

Mendelsohn, R. & Nordhaus, W. (1994), 'The impact of climate change on agriculture: A Ricardian approach', *American Economics Review* **84**, 753–771. 172

Mendelsohn, R. & Nordhaus, W. (1999), 'The impact of climate change on agriculture: A Ricardian approach: A reply', *American Economics Review* **89**(4), 1046–48. 171

Parry, M., Rosenzweig, C. & Livermore, M. (2005), 'Climate change, global food supply and risk of hunger', *Philosophical Transactions of the Royal Society B.* **360**, 2125–2138. 171, 172, 173

Parry, M., Rosenzweig, C., Iglesias, A., Livermore, M. & Fischer, G. (2004), 'Effects of climate change on global food production under SRES emissions and socio-econobic scenarios', *Global Environmental Change* **14**, 53–67. 171

Reilly, J., Paltsev, S., Felzer, B., Wang, X., Kicklighter, D., Melilo, J., Prinn, R., Sarofim, M., Sokolov, A. & Wang, C. (2007), 'Global economic effects of changes in crops, pasture, and forests due to changing climate, carbon dioxide, and ozone', *Energy Policy*. 167

Rosenzweig, C. & Tubiello, F. N. (2007), 'The interactions of adaptation and mitigation strategies in agriculture', *Mitigation and Adaptation Strategies for Global Change*. doi: 10.1007/s11027-007-9103-8. 166, 170, 173

Schlenker, W., Hanemann, W. M. & Fisher, A. C. (2005), 'Will U.S. agriculture really benefit from global warming? accounting for irrication in the hedonic approach.', *The American Economic Review* **March 2005**, 395–406. 172

Schmidhuber, J. & Tubiello, F. N. (2007), 'Food security under climate change', *Proceedings of the National Academy of Sciences* **104**, 19703–19708. 167

Smit, B., Burton, I., Klein, R. & et al (2000), 'An anatomy of adaptation to climate change and variability', *Climatic Change* **45**(1), 223–251. 168

Tsuji, G. Y., Uehara, G. & Balas, S., eds (1994), *DSSAT v3*, University of Hawaii, Honolulu, Hawaii. 172

Tubiello, F. N. & Ewert, F. (2002), 'Modeling the effects of elevated co_2 on crop growth and yield: A review', *European Journal of Agronomy* **18**(1), 57–74. 172

Tubiello, F. N. & Fischer, G. (2007), 'Reducing climate change impacts on agriculture: Global and regional effects of mitigation 1990–2080', *Tech. For. Soc. Ch.* **74**, 1030–1056. doi:10.1016/j.techfore. 171, 179, 180

Tubiello, F. N., Amthor, J. A., Boote, K., Donatelly, M., Easterling, W., Fischer, G., Gifford, R., Howden, M., Reilly, J. & Rosenzweig, C. (2007*a*), 'Crop response to elevated co_2 and world food supply', *European Journal of Agronomy* **26**(3), 215–223. 167

Tubiello, F. N., Soussana, J. F., Howden, M. & Easterling, W. (2007*b*), 'Crop and pasture responses to climate change: fundamental processes', *Proceedings of the National Academy of Sciences* **104**, 19686–19690. 167

Williams, J. R. (1995), The EPIC model., *in* V. P. Singh, ed., 'Computer models of watershed hydrology', Water Resources Publications, Highlands Ranch, CO. 172

World Bank (2005), Managing agricultural production risk, Report no. 32727-glb, The International Bank for Reconstruction and Devolopment/ The World Bank. 171