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Adapting agriculture to climate change

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ABSTRACT: We evaluate the potential impacts and measure the potential limits of adaptation of agriculture to climate change. Pressures on land and water resources are expected to intensify existing risks in low latitude areas – e.g., South-East Asia deltas – and in regions with current water scarcity – e.g. Mediterranean, and create new opportunities in some northern temperate areas – e.g., Northern Russia, Northern Europe. The need to respond to these risks and opportunities is addressed by evaluating the costs and benefits of a number of technical and policy actions. The discussion aims to assist stakeholders facing the adaptation challenge and develop measures to reduce the vulnerability of the sector to climate change.

KEYWORDS: Adaptation, climatic change, global production, mitigation.

JEL classification: C51, C53, Q17, Q18.

Adaptando la agricultura al cambio climático

RESUMEN: Evaluamos impactos y medidas de adaptación potenciales de la agricultura frente al cambio climático. Se proyecta una gran intensificación de las presiones sobre los recursos hídricos y la capacidad productiva en regiones de latitudes bajas – por ejemplo los deltas del Sureste de Asia y en países Mediterráneos. Por otra parte se proyectan oportunidades en regiones de zonas templadas – por ejemplo el norte de Rusia y el norte de Europa. Analizamos un serie de medidas técnicas y de regulación como respuesta de adaptación a estos riesgos y oportunidades, que pueden ser útiles para que los grupos de interés desarrollen medidas para reducir la vulnerabilidad del sector agrario al cambio climático.

PALABRAS CLAVES: Adaptación, cambio climático, producción global, mitigación.

Clasificación JEL: C51, C53, Q17, Q18.

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1. Introduction

Global climate change raises a number of reasons for concern, not least because it is a major source of uncertainty for today's vulnerable societies. This uncertainty is especially relevant for the agriculture and food security given both sectors' links to ecosystems, water, cities, and culture. Societies have evolved adapting to mean climatic conditions and have developed mechanisms to face conflicts that may no longer be valid under climate change. Adaptation to uncertain conditions is a challenge as climate change comes in conjunction with high development pressure, increasing populations, water management that is already facing conflicts and agricultural systems that are often not adapted (any more) to local conditions. Prioritizing adaptation of agriculture to limited water or to more extreme floods and droughts is complex, and, at least, requires information on: a measure of the potential impacts and a measure of the potential limits (social and physical) to adaptation. Here we evaluate these two aspects across world regions to synthesise the reasons for concern for agriculture and water resources.

Global climate change will modify the optimal location for crops (Trnka *et al.*, 2011) and crop productivity levels (Lobell *et al.,* 2011; Iglesias *et al.,* 2011a). Additionally, it will drive increases in irrigation requirements (Döll and Siebert, 2002; Fischer *et al.*, 2007) as well as increases in soil salinity and erosion (Rosenzweig and Hillel, 2000). Agricultural production will also be affected by increased likelihood of extreme events as well as pests and diseases (Rosenzweig *et al.*, 2001; Christensen and Christensen, 2003).

To date the majority of studies on these reasons for concern have focused in individual aspects of climate change impacts. Given the global nature of trade patterns and future adaptation and mitigation policies, however, understanding the impacts of climate change on agriculture as a whole requires a multi-dimensional analysis at the global level.

In this paper we propose to undertake such an analysis through the application of the Climate Crop model which considers crop productivity and water demands in response to climate change. Additionally, we use the model to analyse the impact of adaptation policies on crop productivity, irrigation water demands and fertiliser use. We test the effects of climate change on agriculture under the latest generation of scenarios (Moss *et al.,* 2010).

2. Methods

2.1. *The modelling approach*

Expanding on a previous study (Císcar *et al.,* 2011) we develop global scenarios of agricultural change for the 2080s based on global scenarios of changes in environmental and social variables and the understanding of the sensitivity of each agricultural region to these changes. First, we identified changes in agroclimatic regions. Second, we developed statistical models of crop yield response based on process-based crop models, linking productivity, management and climate variables, as detailed below; livestock production is not considered, except for the possible inference of crop productivity. Third, we calculated the expected change in future crop productivity by applying the climate scenarios to the derived models worldwide.

Estimation of changes in 73 agro-climatic regions are defined based on K-mean cluster analysis of temperature and precipitation data from 1,141 meteorological stations, district crop yield data, and irrigation data. Shifts in agro-climatic zones are considered for the application of the climate change scenarios, so the crop types simulated in the future are consistent with the agro-climatic conditions of the future. The future zones are derived in the same way as the zones in the current climate, but modifying the climate of the station by the changes in the climate scenarios.

Process-based crop models provide the means to derive information of crop responses to climate and management when experimental data is not available. Nevertheless, process-based crop models are data intensive, including daily climate data, soil characteristics and definition of crop management; usually data constraints limit the use of models to sites where the information necessary for calibration is available. In this study, we select sites to represent the major agro-climatic regions. At each site, process-based crop responses to climate and management are simulated by using the DSSAT crop models for wheat, maize, and soybeans. The DSSAT simulate daily phenological development and growth in response to environmental factors (soil and climate) and management (crop variety, planting conditions, nitrogen fertilisation, and irrigation). The DSSAT models can simulate the current understanding of the effect of CO2 on crops. Daily climate data for the 1961 to 1990 time period was obtained from NOAA; soil characteristics and management data were obtained from agricultural research stations.

For each of the sites, three crops and thirty years of daily climate, we conducted a sensitivity analysis to environmental variables (temperature, precipitation and CO2 levels) and management variables (planting date, nitrogen and irrigation applications) (3.600 simulations per site). The resulting output was then used to define statistical models of yield response for each site. This approach has been proven useful for analysis in China, Spain (Iglesias *et al.,* 2000) and globally (Lobell and Burke, 2010). Variables explaining a significant proportion of simulated yield variance are crop water (sum of precipitation and irrigation) and temperature over the growing season. The functional forms for each region represent; the realistic water limitations and potential conditions for the mixture of crops, management alternatives, and an opportunity to analyse potential endogenous adaptation in relation to the climate assumed in each area.

Our methodology expands process-based crop model results over large areas and therefore overcomes the limitation of data requirements for process based crop models; includes conditions that are outside the range of historical observations of crop yield data; and includes simulation of optimal management and therefore estimates agricultural responses to changes in regional climate. Because of the nature of our assumptions, we consider that the results represent an agricultural policy scenario that does not impose major additional environmental restrictions beyond the ones currently implemented, nor does it include pollution taxes (for example for nitrogen emissions to mitigate climate change).

Here we have developed three policy scenarios to evaluate three levels of adaptation to climate change. In a first level we analyze land crop productivity in a context in which the productivity is optimised by actions taken at the farm level with no policy intervention. The second level of adaptation we consider is based on management with policy that emphasises water resources protection in the countries with water scarcity problems and mitigation policies in the developed countries. The third level of adaptation considers management with policy that emphasises protection of agricultural production and rural development.

For estimating the agricultural productivity changes and the water and nitrogen requirements we have applied the Climate Crop model (Iglesias *et al.,* 2011a) to a range of climate and policy scenarios. In general, models have to address the trade-off between uncertainty and complexity. The more the complexity of the model the more realistic assumptions can be made. However, this requires one to increase the number of parameters that have to be estimated and makes the calibration issue more complicated and less robustness of results can be expected. So an acceptable level of uncertainty can be found when a number of reasonable assumptions are made and considering a geographical scale according the available information for initial conditions. The Climate Crop model is a crop productivity model combining process-based models and statistical functions of yield response developed for a global world database at the site level (Iglesias *et al.,* 2011a).

The approach of computing land productivity changes is based on the development of land productivity functions for the agro-climatic areas. The model links biophysical and statistical models in a rigorous and testable methodology, based on current understanding of processes of crop growth and development, to quantify crop responses to changing climate conditions. Dynamic process-based crop growth models are specified and validated for sites in the major agro-climatic regions. The validated site crop models are useful for simulating the range of conditions under which crops are grown, and provide the means to estimate production functions when experimental field data are not available. Variables explaining a significant proportion of simulated yield variance are crop water (sum of precipitation and irrigation) and temperature over the growing season. Crop production functions are derived from the process based model results.

2.2. *The climate change scenarios*

We have used a number of climate scenarios based on the updated socio-economic assumptions described in Moss *et al*. (2010). These authors evaluated the next generation of scenarios for climate change research by analysing the advances in the science and observation of climate change that are providing a clearer understanding of the Earth's climate system and its likely response to human and natural influences.

Moss *et al*. (2010) discussed the 'representative concentration pathways' (RCPs) that will provide a framework for modelling in the next stages of scenario-based research. The two sets of climate projections used in this study may be said to represent two RCPs: one focusing on the near term (the stabilisation scenario) and the other extending to 2080s. Here we use the A1B and E1 as proxy to the RCP scenario assumptions. Although the A1B and E1 scenarios are based on the ENSEMBLES project and were concluded before the RCPs scenarios have been developed, they are used here as corresponding specific radiactive forcing RCP6.5 and RCP2.5, respectively.

We explore the future by looking at the response of crop productivity to climate scenarios derived from representative concentrations pathways of global emissions for the 2080s: the A1B a scenarios with a balanced emphasis on all energy sources (574 ppm of CO2) and the E1 scenarios representing stabilisation (458 ppm of CO2). To address uncertainty we use several climate models driven by these representative concentration pathways: A1B: DMIEH5-4; A1B: HADGEM-1 and the E1: DMICM3-1; E1: DMICM3-2; E1: HADGEM2-1. The source of climate data is the University of East Anglia (Climate Cost project, publication in press). A1B represents a balanced emphasis on all energy sources with CO2 level in 2080 of 712 ppm. E1 is the so-called global "2 °C-stabilization" scenario that is characterised by atmospheric concentrations of 498 ppm CO2 in the 2080s.

This last generation socio-economic scenarios were not developed in the PRUDENCE project but new climate projections are now available from the Climate Cost project (Iglesias *et al.,* 2011b). Table 1 shows the climate scenarios considered in this paper.

TABLE 1

Climate change scenarios considered

Climate Scenarios for A1B RCP	Name	Climate Scenarios for E1 RCP	Name
A1B.BCM2_1_M.2080	A1B_1	E1.CNCM33_2_M.2080	E1_1
A1B.CNCM3_1_M.2080	A1B_2	E1.DMICM3_1_M.2080	E1_2
A1B.DMIEH5_4_M.2080	A1B_3	E1.DMICM3_2_M.2080	E1_3
A1B.EGMAM_1_M.2080	A1B_4	E1.EGMAM2_2_M.2080	E1_4
A1B.EGMAM_2_M.2080	A1B_5	E1.EGMAM2_3_M.2080	E1_5
A1B.EGMAM_3_M.2080	A1B_6	E1.HADCM3C_1_M.2080	E1_6
A1B.HADGEM_1_M.2080	A1B_7	E1.HADGEM2_1_M.2080	E1_7
A1B.INGVSX_1_M.2080	A1B_8	E1.INGVCE_1_M.2080	E1_8
A1B.IPCM4_1_M.2080	A1B_9	E1.IPCM4v2_1_M.2080	E1_9
A1B.MPEH5_1_M.2080	A1B_10	E1.IPCM4v2_2_M.2080	E1_10
A1B.MPEH5_2_M.2080	A1B_11	E1.IPCM4v2_3_M.2080	E1_11
A1B.MPEH5_3_M.2080	A1B_12	E1.MPEH5C_1_M.2080	E1_12
		E1.MPEH5C_2_M.2080	E1_13
		E1.MPEH5C_3_M.2080	E1_14

3. Results

The results in Figure 1 representing an average of all the scenarios considered, show that crop production without adaptation policies (summarised in Table 2) is likely to decrease in most parts of Africa, the southern Mediterranean, the Middle East South America and South East Asia under the two climate scenarios. Compared to the no-policy scenario, adaptation policy 1 (optimisation of environmental water requirements) seems to make a difference in North and South America and large parts of South East Asia and the Mediterranean, while alleviating the drops in production in Africa and the Middle East. The policy 2 scenario (fertiliser optimisation) makes less of a difference with respect to the no-policy scenario, while the main changes seem to be an alleviation of the drop in productivity in Africa and South East Asia. Finally, under policy scenario 3 (fertiliser use and environmental water requirements are optimised) there is a noticeable upsurge in production with respect to the no-policy scenarios; trouble spots remain however in large parts of Africa and the Middle East. Under the E1 scenario, similar trends can be noted but in each case less pronounced both in a positive and negative sense. The crop productivity losses seen under the A1B scenario and adaptation policy 1 will be less severe but conversely, the gains seen in Canada will be less marked.

TABLE 2

Summary of adaptation policies considered in this study

Adaptation policy	Irrigation water assumptions	Fertiliser input assumptions	Environmental implications
Adaptation 1	Demand satisfaction according to assumptions on technological capacity of the country	No optimisation of fertiliser input	Optimisation of environmental water requirements
Adaptation 2	No room for changes in irrigation	Optimised	Potential increase of diffuse pollution
Adaptation 3	Demand satisfaction according to assumptions on technological capacity of the country	Optimised	Optimisation of environmental water requirements Potential increase of diffuse pollution

FIGURE 1

Policy effects on crop production under climate change at a global scale represented by % change in 2080s

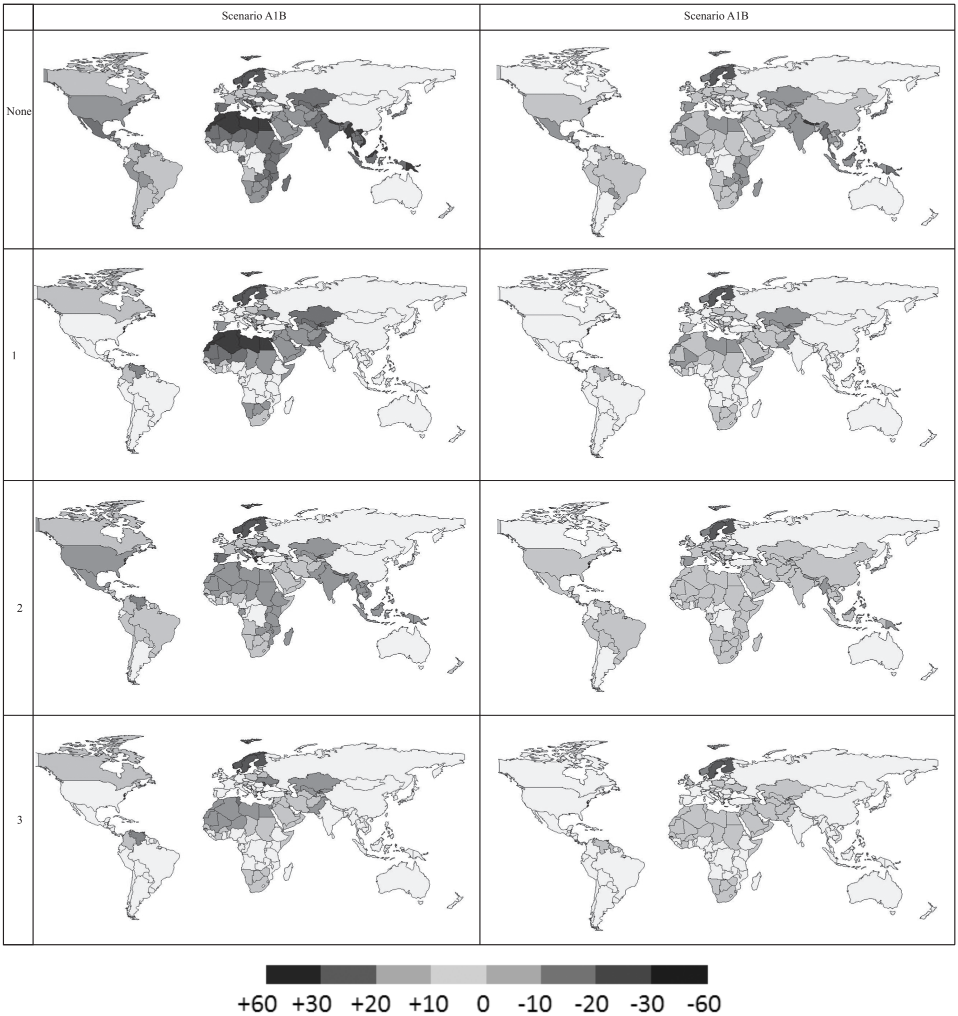
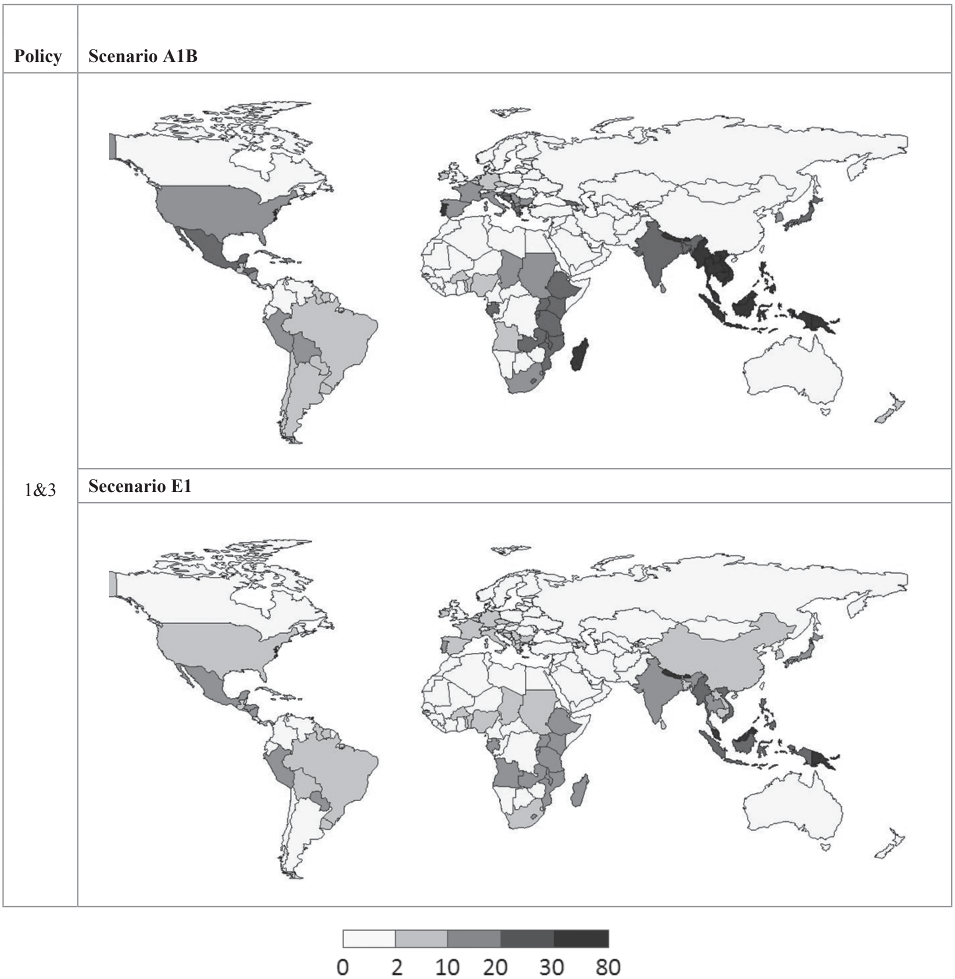


Figure 2 shows the effects of optimised adaptation policies in terms of fertiliser use and environmental water demands show slightly less intense changes water demands under the E1 scenario. Again we represent an averege of all the scerarios considered.

FIGURE 2

Policy effects on irrigation water demand under climate change at a global scale represented by % change in 2080s



Finally, Figure 3 shows the effects of adaptation policy on the user of fertiliser under scenarios A1B and E1. Here, an average of all the scenarios considered is represented. The results show that an optimisation of environmental water requirements in conjunction with an optimisation of fertiliser use will lead to important decreases in fertiliser use in a number of regions, most noticeably in South America and South East Asia, while fertiliser use remains high in large parts of Africa and the Middle East. Overall, as remarked upon for the crop productivity results, the E1 scenario, the so called 2ºC stabilisation scenario, will report less pronounced changes though in general the trend mirrors that discussed above. A summary of the data is included in Table 3.

FIGURE 3

Policy effects nitrogen fertiliser change under climate change at a global scale represented by % change in 2080s

Policy	Scenario A1B
2	
3	

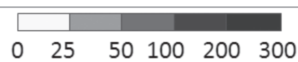


FIGURE 3 (cont.)

Policy effects nitrogen fertiliser change under climate change at a global scale represented by % change in 2080s

Policy	**Scenario E1**
2	
3	

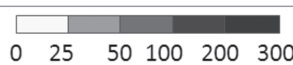


TABLE 3

Policy effects nitrogen fertiliser change under climate change at a global scale represented by % change in 2080s

Results 2080 averages	% Change
Crop Productivity A1B	-10,1
Crop Productivity E1	-4,1
Crop Productivity with Adaptation 1 A1B	-2,2
Crop Productivity with Adaptation 1 E1	0,2
Crop Productivity with Adaptation 2 A1B	-4,3
Crop Productivity with Adaptation 2 E1	-0,9
Crop Productivity with Adaptation 3 A1B	0,6
Crop Productivity with Adaptation 3 E1	1,6
Irrigation water demand A1B	9,6
Irrigation water demand E1	5,2
Nitrogen fertiliser change A1B	98,9
Nitrogen fertiliser change E1	54,1

4. Policy discussion

The results show the strong interactions between poverty and climate change impacts on crop production, irrigation water demands and fertiliser use. Although under the E1 scenario these impacts seem to be less forceful, it is important to note that Africa and the Middle East remain trouble spots in all scenarios and for the three impacts considered. In the case of the Middle East this can likely be explained through a consideration of the nature of the agricultural sector in the region – already faced by low levels of water availability and high water demands even minor temperature increases or precipitation decreases are likely to have serious consequences. Additionally, there is little room to cut down on fertiliser use due to the need to compensate for low levels of water availability.

In the case of Africa, on the other hand, the prevalence of negative climate change impacts is likely to be due to the fact that agriculture in a number of countries is already functioning to full capacity given the technological and financial constraints under which the sector functions. Additionally, climate change projects typically indicate an increase in the variability of the climate further requiring improved adaptation techniques and technologies which are currently not in place or available.

A major factor that may contribute to decrease or intensify impacts of climate change on water resources in semiarid regions is management of the water resources system. Adequate rules for management of irrigation systems under drought conditions can significantly offset the reduction in natural inputs. The measures of demand management can also achieve a progressive reduction of the needs far greater than the reduction of available water supply which occurs naturally as a result of climate change. This requires a coordinated series of actions in terms of awareness and education, investment in conservation, maintenance and improvement of facilities, establishment of rules for exchanging water rights and increasing the flexibility of the operation of the water resource system.

5. Conclusions

This paper has presented a model used to estimate changes in future crop productivity under climate change and under different policy assumptions. The innovative aspects of the analysis lie in the multi-dimensional nature of the assessment and on its use of the latest generation of climate scenarios. The results demonstrate variability for the agricultural sector in most regions of the world but also demonstrate the clear linkages between poverty and agricultural capacity. Most clearly, the results show that large parts of Africa and the Middle East are under great risk from future climate changes, even under the less extreme E1 scenario. Of course, climate change is generally considered as a negative threat for agriculture – due, for instance, to changes in temperatures and precipitation or an increased likelihood of extreme events. But the heterogeneous nature of climate change impacts shown in the results suggests that not all regions will be equally affected.

Agricultural systems are also affected by underlying social, economic, and environmental conditions which determine the system's adaptive capacity. So the key issue is identifying the extent to which climate change impacts and their interactions with social systems will intensify levels of risk for agricultural systems. There is also a need to understand how adaptation planning can help strengthen and maintain agricultural production under a changing climate. To this is added the need for supplying food for a growing and diversifying population that may raise the demand for sustainable agricultural management.

The likelihood of climate change impacts will continue to increase as long as adaptation and mitigation strategies are not put in place and become the norm. Currently the countries with most adaptive capacity are also those which enjoy higher levels of socio-economic development. It is these countries which are in the best position for fostering and making use of technical innovations for the agricultural sector. However, a number of countries highly dependent on agriculture do not enjoy the same levels of adaptive capacity and their vulnerability to climate change is therefore intensified. This is mainly true of a number of poorer Central American, African and South-East Asian countries where large percentages of the population have strong links to agriculture for their livelihoods. These cases highlight the need for a strategic approach to adaptation.

It is difficult to predict climate change impacts because of the uncertainty produced by exogenous and interlinking factors which it is practically impossible to fully acknowledge or foresee. Additionally determining how farmers will adapt to climate change is a very complex dynamic process which is difficult to quantify. This study considers that farmers optimise management under climate change scenarios but cannot implement changes that require policy intervention. How agriculture policies might react to a changing climate is another critical factor which cannot be incorporated in the simulations.

The uncertainty of the climate scenario is characterized by selecting two emission scenarios (A1B, E1) and several global climate models, some of them downscaled using three time frames. In all regions, uncertainties with respect to the magnitude of the expected climate changes result in uncertainties of the agricultural evaluations. For example, in some regions projections of rainfall, a key variable for crop production may be positive or negative depending on the climate scenario used and variable in each season. In general, the assessment shows that the estimated yield changes vary more among different climate models, while the GDP projections show more discrepancy across socio-economic scenarios. Nevertheless, the time horizon is the main determinant of the physical and economic projections.

Adaptation planning is inherently challenging and often restricted by a number of factors, including limitations in the participatory processes with the stakeholders, the exhaustive data requirements for evaluating adaptive capacity, the problems related to selecting adequate evaluation methods and criteria; and the difficulties in forecasting crop response processes. This paper has not sought to simplify these matters; rather it demonstrates a way in which a global model can be used to test the effect of adaptive policy on agricultural production.

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