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Integration of Biophysical and Agro-economic Models to Assess the Economic Effects of Climate Change on Agriculture: A Review of Global and EU Regional Approaches

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Abstract
The economic effects of climate change on agriculture have been widely assessed in the last two decades. Many of these assessments are based on the integration of biophysical and agro-economic models, allowing to understand the physical and socio-economic responses of the agricultural sector to future climate change scenarios. The evolution of the bio-economic approach has gone through different stages.This review analyses its evolution: firstly, framing the bio-economic approach into the context of the assessments of climate change impacts, and secondly, by reviewing empirical studies at the global and European level. Based on this review, common findings emerge in both global and regional assessments. Among them, we show that overall results tend to hide significant disparities on smaller spatial scales. Furthermore, due to the effects of crop prices over yield changes, several authors highlight the need to consider endogenous price models to assess production impacts of climate change. Further, major developments are discussed: the progress made since the last two decades and the recent methods used to provide insights into modeling uncertainties. However, there are still challenges to be met. On this matter, we take these unresolved challenges as guidelines for future research.

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Keywords Climate change, bio-economic modelling, agricultural markets, food security, food prices

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1 Introduction

Assessing the economic effects of climate change on agriculture imply the identification and analysis of biophysical and socio-economic aspects (Blanco et al., 2014a). As a way to deal with this challenge, an important share of climate change impact assessments has based their methodology on the integration of biophysical and economic models. This integration has evolved over the years thanks to several improvements in various aspects underlying this methodology. Amongst them, the increased knowledge of socio-economic and environmental dynamics, improvements in computer capacities, greater data availability, higher spatial resolution and the recent wider scope of biophysical and economic models.

The objective of this paper is to review the evolution and use of this methodology for the study of climate change impacts on agricultural markets, focusing primarily on global and EU-regional assessments. We have carried out a thorough analysis of peer-reviewed papers and selected reports whose methodologies have been based on the integration of biophysical and economic models. This paper identifies common findings through the evolution of this approach; reveals how advancement of this methodology has stimulated further studies; and provides relevant information that could be a guidepost for future researches.

This article builds on the Intergovernmental Panel on Climate Change (IPCC) assessment reports with special attention to those chapters focused on the review of the economic impact of climate change on global and EU agriculture. Several other studies have also been included in our analysis, mainly from peer-reviewed journals and some selected scientific reports, all of which are available online.

This review is organized as follows: in section 2 we provide a brief overview of the different approaches used to evaluate the economic effects of climate change on agriculture, providing a simple scheme to identify the different methods and their variants. Section 3 reviews both global and European economic assessments of the impact of climate change on agriculture, highlighting their main differences and similarities. Section 4 reviews recent assessments based on the new Fifth Assessment Report of the IPCC (AR5) Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs). Finally, section 5 summarizes the main findings from the literature surveyed, commenting on the main lessons learned and proposing future research directions for both global and European assessments.

A summary of global and European papers reviewed their modelling approaches, data, regional scope and time horizon is presented in table 1 and 2 of the appendices as additional material. All these studies are framed within the development/updating process of IPCCs' assessment and special reports.

2 Economic assessment methods, overview and focus of the study

There is a vast literature regarding the assessment of the effects of climate change on agriculture. From a general perspective, the different methodologies used to estimate these effects can be divided into two categories: 1) agriculturally oriented, focused on the biophysical response of crops to climatic variations; and 2) economically oriented, which considers market and socio-economic responses to crop yield changes induced by climate change (Bosello and Zhang, 2005; Iglesias et al., 2011). In terms of the agriculturally oriented studies, three main approaches within the literature have been distinguished: biophysical process-based models (Jones et al. 2011; Challinor et al. 2004; van Ittersum and Donatelli, 2003); agro-ecosystem models (Fischer et al., 2002); and statistical analysis of historical data (Lobell and Burke, 2010b). Within the economically oriented category, a common taxonomy of these approaches has been proposed by Schimmelpfennig et al. (1996) and Adams et al. (1998) which classified these methods, dividing them into "spatial-analogue approaches" or "structural approaches".

The spatial analogue approach is mainly based on econometric techniques to analyse changes in spatial patterns of production. Information collected from farmers operating across a range of conditions, allows inferring and then predicts how future changes may affect profits. The main difference with the structural approach lies in how the possible adaptations are estimated since they are embedded in the information collected on farmer's behaviour. This approach is categorized depending on how these adaptations are estimated. Amongst them, we found methods which estimate adaptations through cross-sectional statistics and econometric techniques (Mendelsohn et al., 1994, 1996) also known as Ricardian approach; and those which used geographic information systems combined with an economic model, also known as duality-based models (Darwin et al., 1995; Darwin, 1999). Regardless the method used, both approaches assume that variation in land values reflects the welfare implication of the impact of climate change on agriculture. The spatial analogue approach is a powerful tool capturing the effects included in the data used for the analysis; however, two major drawbacks are commonly mentioned in literature: 1) the assumption of no feedback of changes in land prices on agricultural prices, ignoring future impact of price changes over domestic and foreign supply and demand (Bosello and Zhang, 2005); and 2) the fact that this approach can only capture the effects observed in the data, which puts into question its plausibility for long-term projections (Nelson et al., 2014).

The structural approach, on the contrary, includes changes in land values within the economic models so that the responses of all economic agents are explicitly considered, including also the direct effects of specific farm-level adaptations. This interdisciplinary approach interlinks models from several disciplines. The most common method within this approach consists of using biophysical models to predict crop yield effects of climate change scenarios which are then used as an input into the economic model to predict future socio-economic effects. These methods have been applied at different geographical scales and also with a different treatment of the economic dimension. According to their geographical coverage a common distinction is between global and regional assessments. This last, with different levels of disaggregation such as at country (Adams et al., 1995; Yates and Strzepek, 1998; Reilly et al., 2003; Dube et al., 2013) state (Kaiser et al., 1993), or another sub-regional level. In terms of the economic dimension, the main distinction is based on the economic model used to quantify the behavioural responses of economic agents and markets, identifying here the studies that use: 1) farm economic models; 2) partial equilibrium (PE) models; 3) computable general equilibrium (CGE) models; or 4) the Basic Linked System (BLS) trade model.

Is important to highlight the distinction we have made between CGE and the BLS trade model. Although the literature classified this last as a general equilibrium approach (Fischer, 1988), there are important features that make it different from other CGE models used for the analysis of the economic effects of climate change on agriculture. The first important feature is its coarse aggregation, which correspond to one-simplified non-agricultural sector, and ten agricultural commodities. This simple description of non-agricultural side fails to identify some key linkages between agriculture and other industries (Burniaux and van der Mensbrugghe, 1991). On the other hand, the agricultural sector's aggregation may affect qualitative findings, creating, for instance, false competition between countries producing different products (Hertel, 2002). A second critical limitation of the BLS model is its way on how individual economies are modelled within the global economic system. Although its linked country model approach can capture more country/regional economic details, it also could difficult the data handling and the final interpretation of results, compared with those approaches that use the same modelling structure for all individual economies (Tongeren et al., 2001).

Considering the above, we go further in the common taxonomy presented in most literature, which in most cases only presents the differences between structural and spatial approaches, without a clear identification of the different methodologies within them. Based on the geographical coverage and the treatment of the economic dimension the next scheme proposes a classification of the different methodologies used within the structural approaches. We divide them into those with: 1) worldwide coverage, using CGE models (Hertel et al., 2010; Calzadilla et al., 2013); 2) worldwide coverage using PE models (Tobey et al., 1992; Kane et al., 1992; Nelson et al., 2010; Witzke et al., 2014); 3) worldwide coverage, using the BLS model (Rosenzweig and Parry, 1994; Parry et al., 2004; Fischer et al., 2005); 4) regional assessments using CGE models (Ciscar et al., 2009; Arndt et al., 2011); 5) regional assessments using PE models, (Shrestha et al., 2013; Blanco et al., 2014a; Kiselev et al., 2013); and 6) regional studies using farm level economic model (Kaiser et al., 1993). Although this scheme is far from cover all the methods found within the literature (Reilly et al., 2003; Butt et al., 2005), it is a useful classification to encompass the different assessments reviewed in the next sections.

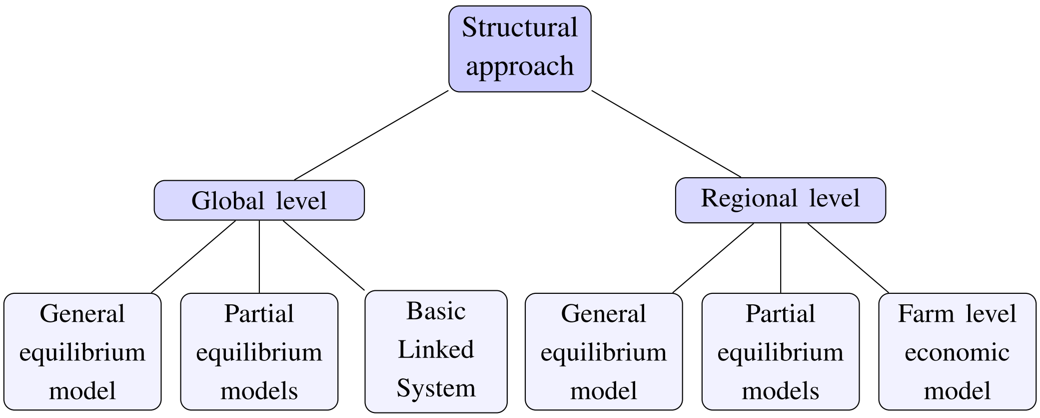

Figure 1: Proposed scheme of the different methodologies within the structural approach.

Within this framework, in the next sections we will focus explicitly on the development of those studies that meet the following: 1) those approaches from the 1990s until present; 2) global assessments and studies at EU-regional level; and 3) methods that include market feedbacks through endogenous price models excluding those studies based on farm models (Kaiser et al., 1993). We review the studies selected into two stages: firstly, we focus on those studies which are within the period from 1990 to the recent release of the new Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs), subdividing these into global and regional studies. Secondly, we concentrate on those assessments based on the new RCPs and SSPs scenarios at global and EU level.

3 Climate change impacts, global and European economic assessments.

3.1 Assessments of Global economic impacts of climate change on agriculture

In the early 1990s, just a few global assessments integrated crop responses with economic models. Amongst them, the seminal works by Tobey et al. (1992) and Kane et al. (1992) introduced crop effects suggested by previous studies into the PE model SWOPSIM. The former presents 15 different scenarios based on three simulation experiments, which in turn were divided in 5 concurrent yield reductions in the U.S., Canada and the European Community. Kane et al. (1992), meanwhile, present two different scenarios that reflect "moderate impacts" and "very adverse impacts". Despite their differences, a common consensus with respect to the role of trade and markets on economic impact assessments was established: "*global warming would not seriously disrupt the global agricultural market, mainly because the consequences would be diffused throughout the world through trade and inter-regional adjustments"*. Both studies compared their results with the work of Adams et al. (1988), which considers the climate change effects on the U.S. only. They found smaller net welfare effects than Adams et al. (1988), interpreting this as the offsetting of the impact of climate change by international price changes. Both works, led the way in establishing that an assessment of climate change cannot be made on the basis of domestic yield effects alone.

Few years later, the study of Rosenzweig and Parry (1994) was one of the first that considered both, climate change along with CO_2 fertilization effects, examining also the potential impact of adaptation measures. In this study two main components were considered: 1) estimating potential changes in crop yield, through the use of crop models and a decision support system; and 2) assessment of the world food trade's responses through the use of the BLS trade model developed at the International Institute for Applied System Analysis (IIASA). Climate change scenarios were created by changing the observed data according to doubled CO_2 simulations of three GCMs (GISS, GFDL and UKMO). Agricultural scientist in 18 countries estimated potential changes in crop yields through compatible crop models and the GCM scenarios at 112 sites. These estimations were then used to assume national level production changes for all cereals in all countries based on similarities among crops and countries. The results were then aggregated into regional yield changes according to the regions defined in the BLS model. Their main results show that world cereal production decreases between 11 and 20% in climate change scenarios without direct CO_2 effects. The inclusion of CO_2 effects leads to small global production decreases in the range of 1 and 8%, increasing cereal prices between 24-145%. The scenarios that include different

Table 1: Percentage range of changes on global cereal production and prices. (Source: Rosenzweig and Parry (1994))

Scenario	Production (% changes)	Price (% changes)
With CO_2 fertilization	∼ -1 to -8	∼ 24 to 150
With CO_2 and Ad. Level 1	∼ 0 to -5	∼ 10 to 100
With CO_2 and Ad. Level 2	∼ 1 to -2	∼ -5 to 35

∼ approximately equal to

adaptation options indicate even fewer effects on production and prices, compared with the above mentioned scenarios (Table 1). The main results presented by Rosenzweig and Parry (1994) exhibit some of the main features of global impact assessments: reduced impacts on high latitude countries compared with tropical countries; greater impacts on C4 crops due to their lower responses to an increase of CO_2 fertilization; a large degree of spatial variation in crop yields across the globe; and lower impacts of climate change when adaptation measures are considered.

These three seminal works were one of the few studies cited by the Second Assessment Report (SAR) (Watson et al., 1996), which linked estimates of yield responses to climate change with economic models to estimate production changes and their economic consequences. Similar studies also mentioned in the report are Reilly and Hohmann (1993) and Reilly et al. (1994). Based on these studies, the report indicates that although the direction of change in global production resulting from climate change is still uncertain, changes in the aggregate level would be small to moderate. This report also enlarges and updates the information contained in the First Assessment Report (FAR), establishing a new generation of assessments examining the impact of climate change on agriculture. From this point forward, more accurate projections of climate change resulting from GHG forcing were available, based on updated emission scenarios (Leggett et al., 1992).

Parry et al. (1999) used the same method as Rosenzweig and Parry (1994) to examine the potential effects of climate change on crop yields, world food supply, and risk of hunger. This study differs from the previous ones mainly in the use of GCMs with better spatial resolution, and the use of updated emission scenarios (IS92). They ran crop models for three future climate conditions (2020s, 2050s, and 2080s) predicted by the GCMs HadCM2 and HadCM3, all based on an IS92 scenario. Contrary to other studies of the mid 1990s (Darwin et al., 1995; Adams et al., 1998), this predicts real price increases with modest amounts of climate change. Small detrimental effects on cereal production by 2080, estimated by the HadCM2 climate change scenario, presents cereal price increases by 17%. In contrast, the greater negative impacts on yields projected under HadCM3, derives on a price increase about 45% by the 2080, with severe effects on the risk of hunger, especially in developing countries. The authors highlight that these global results hide regional differences in climate change impacts. For instance, under the HadCEM2 scenarios, yield increases at high and high-mid latitudes lead to production increases in these regions (e.g. Europe and Canada). However, yield decreases at lower latitudes (tropics), lead to production decreases, effect that may be exacerbated where adaptive capacity is lower than the global average. The next table presents cereal production changes estimated by Parry et al. (1999) at global and regional level by 2080.

Table 2: Global and regional cereal production (% change) for different climate models and across GCM scenarios by 2080 considering CO_2 fertilization and adaptation measures (Sources: Parry et al. (1999); McCarthy (2001))

Climate scenario (GCM-forcing)	Region	Cereal production change
HadCM2-IS92a	Global	∼ -2.1%
HadCM3-IS92a	Global	∼ -4.0%
Range across GCM scenarios	Range across countries	
	North America	∼ -10 to 3%
	Latin America	∼ -10 to 10%
	Western Europe	∼ 0 to 3%
	Eastern Europe	∼ -10 to 3%
	Asia	∼ -10 to 5%
	Africa	∼ -10 to 3%

∼ approximately equal to

Of broader use than the IS92 scenarios, in 2000 the IPCC released the new set of emission scenarios called SRES scenarios (Special Report on Emission Scenarios) (Nakicenovic and Swart, 2000), which were used in the Third and the Fourth assessment reports (TAR and AR4). From this point on, the number of studies that have quantified the economic impacts of climate change on agriculture at the global level has increased. In the first half of the 2000s several assessments were published whose projections were based on the outputs of GCMs, agro-ecological zone or dynamic crop models, and socioeconomic models, all considering socio-economic futures based on SRES scenarios (Parry et al., 2004; Fischer et al., 2002, 2005).

Parry et al. (2004), maintaining the same methodology as previous works (Rosenzweig and Parry, 1994; Parry et al., 1999), based their estimations on SRES scenarios. They used the GCM HadCM3 to run different emission scenarios (A1, A2, B1 and B2)[1], generating 7 different climate change scenarios. Each one of

[1] used ensemble members A1FI, A2a-c, B1a and B2a-b

these scenarios, forced different paths for global crop yields, however these paths did not diverge until the mid-century. The next table presents the impact of climate change on global cereal production and prices under the range of "Bs" (B1a - B2a-b) and "As" (A1FI - A2a-c) scenarios by 2080. Omitting CO_2, there are greater reductions in cereal production and larger increases in their prices than scenarios where CO_2 fertilization is included. When CO_2 effects are assumed, the differences in cereal production and prices between climate scenarios are less clear than no-CO_2 scenarios. This study confirms the negative impacts of climate change in developing regions and the less significant changes in developed regions, along with quite moderated globally aggregated effects on world food production and prices when CO_2 fertilization is assumed.

Table 3: Global cereal production and prices (% change) for a different averages of As (A1Fl; A2a-c) and Bs (B1a; B2a-b) scenarios, with and without CO_2 fertilization by 2080 (from Parry et al. (2004))

Climate scenario (GCM-forcing)	Production (% change)	Price (% changes)
HadCM3-B1-B2		
Without CO_2	$\sim -5\%$	$\sim 9.8\%$
With CO_2	$\sim -1.7\%$	$\sim 14.6\%$
HadCM3-A1-A2		
Without CO_2	$\sim -10\%$	$\sim 320\%$
With CO_2	$\sim -1\%$	$\sim 15.2\%$

$\sim$ approximately equal to

Fischer et al. (2002, 2005), assessed the global impact of climate change on agro-ecosystems up to 2080. Their approach was mainly differentiated by the use of the agro-ecological zones (AEZ) model (see Fischer et al. (2002) for a detail description), maintaining previous modelling frameworks, which encompassed climate scenarios based on different SRES scenarios and the BLS economic model. Fischer et al. (2005), used 14 combinations of socio-economic and climate scenarios between the SRES scenarios A1FI, A1B, A2, B2 and B1 and 5 GCMs (HadCM3, ECHAM, CSIROC, GCM2 and NCAR-PCM). Overall, they present moderate crop price changes under climate change mainly due to small net global climate change impacts on crop production (global cereal production changes fall by 2%). However, as with previous studies, aggregated results hide regional differences. Developing countries experience a decrease in cereal production of 5 - 6% based on the CSIRO climate projections, while developed countries such as the U.S. increase their production by 6 - 9%. The cereal prices present their major increases under the HadCM3 climate projections (2-20%) and for the CSIRO scenarios (4-10%), while remaining GCMs present even fewer climate change impacts. Their conclusions are consistent with previous studies, especially in the heterogeneity of climate change impacts at regional level but not so much globally.

At this point, despite the differences among the studies reviewed (especially in the magnitude of their results), a general consensus is observed in several issues. Firstly, developing regions maybe more negatively affected by climate change than other regions, mainly due to the fact that most developing countries are within warmer baseline climates and most of them rely more on C4 crops that present little CO_2 fertilization; a further factor is the predominance of the agriculture in their economies and the scarcity of capital for adaptation measures. Secondly, the studies agree that including the effects of trade in their assessments tends to offset the overall projected impacts of climate change. Thirdly, production in the developed countries generally benefits from climate change, compensating for the decline projected for developing regions. These three common findings explain the small globally aggregated impacts on food production observed in previous studies. Despite this relatively broad consensus amongst researchers, new questions arose regarding the uncertainty of these global impact assessments and the limitations of the economic modelling tools used at that moment. For instance, crop yield projections were mainly based on a limited number of crop models (DSSAT and AEZ), while for economic assessments, the same economic model (BLS) was used so that uncertainties associated with the structure of it could not be explored (See Annex 1).Furthermore, specific limitations of the BLS model caused a searching for new economic modelling tools that could be used to fill some gaps observed on this method. For instance, in the analysis of BLS results, most of the studies focus only on major cereal food crops. In turn, as we mentioned in previous section, the non-agriculture sector was poorly modelled in the BLS model, which led to simplifications in the simulation of responses to climatic change.

Since the mid-2000s, with the release of the IPCCs Fourth Assessment Report (AR4), several improvements in all the components of the bio-economic approaches were observed. Amongst them: 1) a large number of simulations were available from a broader range of more sophisticated climate models (Parry, 2007); 2) better downscaling techniques, which improve the climate input into biophysical models; 3) there are updated versions of crop models; and 4) a combination of biophysical-socioeconomic modelling at high level of detail and extent. Moreover there has been an expansion of trade models used, a greater diversity of yield projections to consider, and there has been a disaggregation of prices by commodity. Moreover, from this time on, the first attempts to identify the underlying uncertainty of these approaches appeared. This issue was addressed mainly through 2 different ways: using a range of plausible biophysical outcomes (Hertel et al., 2010), or by a wider range of plausible climate scenarios (Nelson et al., 2009, 2010).

As a way to deal with the coarse aggregate at sectoral and regional level of earlier economic assessments, and to face the underlying uncertainty of these approaches; Hertel et al. (2010), based their results on a synthesis of values from impact assessments for the Global Trade Analysis Project (GTAP) model. They bracket a range of plausible outcomes estimating the central and the tails of potential yield impacts in 2030, used then as exogenous supply shocks in the GTAP model to look at the economic impacts of climate change on agriculture. They found that there is potential for much greater changes in food price than reported in other studies, with major average world food price rises in the low productivity scenario (32% for cereals and 63% for coarse grains). They emphasise the importance of looking beyond central case climate shocks as well as the importance of considering the full range of possibilities in designing policy responses.

Using a new version of GTAP, Calzadilla et al. (2013) assess the potential impact of climate change and CO_2 fertilization on global agriculture and food prices. This assessment was based on external predictions (Falloon and Betts, 2010; Stott et al., 2006) of changes in precipitation, temperature and river flow for the SRES A1B and A2 scenarios. Based on these changes they assess the impact of climate change on agriculture according to 6 scenarios (see annex 1), each one applied to two time periods (2020, 2050). Crop responses were also based on external studies: 1) Rosenzweig and Parry (1994) for responses to changes in precipitation and temperature; 2)Tubiello et al. (2007) for CO_2 fertilization effects on crop yields; and 3) Darwin et al. (1995) for runoff elasticities of water supply. Like previous studies, they estimate production decreases and price increases under both emission scenarios and time periods for most of the crops assessed (all-factors scenario). Higher prices were estimated by 2050 for cereal grains, sugar cane, sugar beet and wheat, between a range of 39 and 43%.

Nelson et al. (2009, 2010), provide two widely cited works. Nelson et al. (2010) follow the same methodology as the food policy report of 2009 and use a wider range of plausible economic, demographic and climatic scenarios. At this time, this was one of the first assessments to combine biophysical and socio-economic models with such a high level of detail and extent. They used the latest updated version of the DSSAT suite of crop models; combining a very detailed process-based climate change productivity effects into a detail partial equilibrium model of world agriculture (IMPACT model). This study utilises three combinations of income and population growth from 2010 to 2050. For each, a series of 4 climate scenarios[2] where the baseline is perfect mitigation were examined. In all, there are fifteen perspectives on the future that encompass a wide range of plausible outcomes. Several conclusions can be drawn from these studies. Focusing on the price effects of climate change on agriculture they found that: 1) for three main staple grains (maize, rice, wheat), averaging the four climate change scenarios, prices would rise between 31.2% for the rice in optimistic scenario to 106.3% for

[2] The CSIRO A1B and B1 and the MIROC A1B and B1

maize in the pessimistic scenario; 2) even with perfect mitigation scenarios, prices still increase, although in a lesser extent (18.4% for rice in the optimistic scenario to 34.1% for maize in the pessimistic scenario). Moreover, they confirm earlier findings (Parry et al., 2004) that international trade offsets various climate change effects (where benefited regions supply those with more negative effects).

The next table compares the effects of climate change on food prices obtained by different studies after the AR4 of the IPCC. As a common finding, most of the studies estimate an increase of prices for 2050 compared with the baseline. Focusing on the magnitude of results, price effects of climate change are smaller (or less pessimistic) in general equilibrium simulations than partial equilibrium simulations. This is consistent with other studies, which explain that this is mainly due to the use of more flexible economic functional forms by CGE models (Ciscar et al., 2009; Nelson et al., 2014; von Lampe et al., 2014).

Table 4: Price changes comparison between different studies after AR4.

Source	Price (% changes)
Nelson et al. (2010)	Range among optimistic and pessimistic scenarios[a] Maize (87.3 - 106.3) Rice (31.2 - 78.1) Wheat (43.5 - 58)
Hertel et al. (2010)	Low productivity scenario: Cereals (32) Coarse grains (64)
Calzadilla et al. (2013)	All-factors scenario Wheat (∼ 40) Cereal grains (∼ 45) Rice (∼ 20) Oilseed (∼ 30)

[a] Mean across climate scenarios CSIRO and MIROC with the SRES A1B and B1;∼ approximately equal to

3.2 Regional economic impact assessments of climate change on EU agriculture.

As one of the world's biggest cereal producers and traders, Europe is an important region to assess in terms of the economic effects of climate change on agriculture and how these effects will affect global agricultural markets. Many regional impact assessment of climate change on EU agriculture has been developed in recent years. An important share of these have focused on the biophysical consequences of climate change, evaluating its impacts through literature surveys (Olesen and Bindi, 2002; Lavalle et al., 2009; Olesen et al., 2011); through yield response functions, focused on selected regions of Europe (Quiroga and Iglesias, 2009); or through the link of biophysical and statistical models for different agro-climatic regions (Iglesias et al., 2009). Other works have assessed the economic impacts of climate change on EU agriculture, basing their methodology on spatial-analogue approaches (Reidsma et al., 2007, 2009). Furthermore, economic indicators for Europe, through the integration of biophysical and economic models, have primarily come from global-scale analysis (Parry et al., 2004; Nelson et al., 2010), delivering only aggregated results. Evidence from peer reviewed literature of structural economic assessments at EU regional level is sparse before the mid 2000s. Wide economic impacts assessments, following the approach of linking biophysical and economic models, became more common from 2009 onwards.

Under the PESETA[3] project, Ciscar et al. (2009) assessed the potential economic effects of climate change on the EU agricultural sector. Climate data was based on two SRES emission scenarios (A2 and B2) which were used as input in two combinations of GCMs and Regional Climate models (RCMs) for 2020 and 2080. The biophysical impact was calculated trough the DSSAT crop growth models, whose result were used to derived crop production functions for nine agro-climatic regions of Europe. These yield functions were then used with a spatial agro-climatic database to conduct a Europe-wide spatial analysis of crop production vulnerability to climate change. Finally productivity shocks were introduced in GTAP as land-productivity-augmenting technical change over crop sector in each region, resulting in changes in GDP. Their results show significant regional differences between northern and southern European countries, Mediterranean countries being the most affected.

The PESETA project not only assessed potential effects of climate change on agriculture, it also covered other market impact categories such as river flood, coastal system and tourism. In one of the latter stages of this project, the impact of these four sectors was integrated in the CGE model GEM-E3 in order to have a comparable vision of effects across sector. Ciscar et al. (2011) present a detailed description of this last stage of the project, assessing the potential impact of climate change in Europe in the four market impact categories. Results related with the agricultural sector show important regional disparities. Southern regions present high yield losses under warming scenarios; Central Europe present moderate yield changes in all scenarios; northern regions were the only ones with positive effects

[3] Projection of Economic impacts of climate change in Sectors of the European Union base on boTtom-up.

of climate change in all scenarios and the only region with net economic benefits, due mainly to agriculture.

Both above mentioned works marked an important step in the regional assessment of economic climate change impact on EU agriculture. These studies are the first regionally-focused, quantitative, integrated assessment of the effects of climate change on vulnerable aspects of the European economy and its overall welfare. These arise as an alternative for further detail, with a methodology that integrated a set of high-resolution climate change projections, detail impact modelling tools and a regional focus, integrated all into an economic framework. Both works prepare the ground for further studies in European regional assessments of the economic impact of climate change on agriculture.

Shrestha et al. (2013) took the next step in the improvement of economic regional impact assessments of EU agriculture. They analyse the economic impact of climate change by linking climate data, biophysical and economic models at a high disaggregated regional level. Yield change data are taken from the BIOMA (Biophysical models application) platform, which is then used in the partial equilibrium CAPRI model to predict the economic impacts. As a further advancement Shrestha et al. (2013) simulate results for the EU at sub-member state (NUTS-2[4]) level, whilst at the same time model global world agricultural trade. They used two climate scenarios (warm and mild), both based on the A1B emission scenario used as input for two combinations of GCMs and Regional Climate models (RCMs) for 2020. Their results were consistent with previous studies, where minor effects were projected at EU level, with stronger effects being projected at regional level. This is reflected in the estimated regional effects, which vary by a factor of up to 10 relative to the aggregate EU impacts. Furthermore, the simulation results show how price adjustments reduce the response of agricultural sector to climate change. This study, like the previous one, marked another landmark in European regional assessments, showing high EU regional disaggregated results. These results allowed for a better understanding of the regional disparities that climate change can cause on agriculture depending on the location or sector. The results in this research were subject, however, to some limitations; amongst them the assumption that crop yields will remain unchanged in the non-EU countries.

Blanco et al. (2014a) filled this gap and introduced several improvements in European regional impact assessment. They used the same methodological approach as Shrestha et al. (2013), (analyzing climate impact at regional level within the EU accounting for feedback effects from the world agrifood market) but this time considering climate induced changes on crop yields for non-EU countries. They used the WOFOST (World Food Studies) crop model (through the BIOMA

[4] Nomenclature of Territorial Units for Statistics with 272 NUTS 2 regions in EU27 (EUROSTAT, 2013)

platform) to simulate yield effects of climate change at high grid resolution all over the EU up to 2030. As particular features, simulations were performed both with and without effects of CO_2 fertilization and they increase the crops covered compared with previous studies. Simulations for non-EU regions were based on the work done for the 2010 World Development Report (Müller et al., 2010). Their main results are consistent with previous works (Ciscar et al., 2009; Shrestha et al., 2013), in that they show that climate change impacts on crop yields vary widely across EU regions and crops, highlighting that EU aggregate results hide these significant disparities. According to global impact assessments (e.g. Parry et al. (2004)) their simulations were strongly influenced by carbon fertilization, which under a full carbon fertilization scenario shows greater production increases. As a main conclusion the authors highlight the need of using price endogenous models to assess the impact of climate change on production, mainly due to the counterbalanced effects of crop prices on final yield effects.

The next table shows some economic indicators presented by two of the above mentioned studies. Although they used similar methodologies, the comparison of results is quite difficult mainly due to the differences in the time horizon of the studies. However, an interesting result to highlight is the difference between climate scenarios and the changes in agricultural income. Although both studies use the same economic model to estimate the socio-economic responses to climate change, contrary to Shrestha et al. (2013), Blanco et al. (2014a) present more negative results and higher differences between climate scenarios. A possible reason for this could be the effects of the simulations of climate change in non-EU countries considered by Blanco et al. (2014a).

4 Bio-economic impact assessments under new scenarios

Since AR4 (Parry, 2007), new global socio-economic and environmental scenarios for climate change research have emerged. These are richer, more diverse and offer a higher level of regional detail compared with previous SRES scenarios (Field et al., 2014). The AR5 of the IPCC distinguishes between two kinds of scenarios. The Representative Concentration Pathways (RCPs), named according to their radiative forcing level in the year 2100 and the Shared Socioeconomic Pathways (SSPs), which represent the assumptions about the state of global and regional society as it evolve over the course of the 21st century. The RCPs include one scenario leading to a very low forcing level (RCP2.6), two stabilisation scenarios (RCP4.5 and RCP6), and a high scenario, RCP8.5, which corresponds to a high greenhouse gas emission pathway (Stocker et al., 2013). On the other hand the SSPs include five different pathways, each one assembled along the axes of challenges to mitigation and adaptation to climate change. Additionally, they contain population

Table 5: Economic results comparison between EU-regional assessments.

Source	Climate scenario (GCM-forcing)	Production changes in EU (% change)	Price changes in EU (% change)	Agr. income changes in EU (% change)
Shrestha et al. (2013)[a]	Mid-Global HIRHAM5-ECHAM5 (A1B)	Cereals (+2.8) Oilseeds (-4.8)	Cereals (-2.4) Oilseeds (+2.9)	-0.02
	Warm-Global HadRM3Q0 HadCM3 (A1B)	Cereals (+9.6) Oilseeds (-1.2)	Cereals (-10.2) Oilseeds (-6.7)	-0.02
Blanco et al. (2014a)[b]	ECHAM-CO_2 HIRHAM5-ECHAM5 (A1B)	Range across crops Cereals (∼ 1 to -8) Oilseeds (∼ 0 to -12)	↓	-4.5
	Hadley-CO_2 HadRM3-HadCM3 (A1B)	Cereals (∼ 0 to -14) Oilseeds (∼ 1 to -12)	↓	-0.2

[a] Time horizon 2020; [b] Time horizon 2030; ↓ world price effects drive down EU crop prices; ∼ approximately equal to

and gross domestic product (GDP) developments and semi-quantitative elements (Kriegler et al., 2012).

Over the last two years, most of the impact assessments that based their results on the new scenarios have been focused towards the quantification of the uncertainty that underlie their approaches. Amongst the methodologies used to provide insights into modelling uncertainties, the comparison of results among different modelling approaches has had an important development. Focusing on agricultural oriented studies, Rosenzweig et al. (2013) used all the four RCPs scenarios, 5 global climate models (HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2M and NorESM1-M) and 7 Global grid crop models (GGCMs) (EPIC, GEPIC, IMAGE, LPJmL, LPJ-GUESS, pDSSAT and PEGASUS) to quantify the global effects of climate change on major crops. This research has meant an important development providing insights into crop modelling uncertainties.

If we turn our attention to economically oriented studies, just a few have quantified the economic impact of climate change derived from the RCPs and SSPs scenarios. At global level, Nelson et al. (2014, 2013), present results from a global economic model inter-comparison exercise, with harmonised data for future yield changes. The main aim of these exercises was to provide estimates of uncertainties at the economic phase of the impact assessment process. Nelson et al. (2013) analysed the endogenous responses of nine global economic models to standardized climate change scenarios produced by two GCM and five crop models under the RCP8.5 and the SSP2 (population of 9.3 billion by 2050 and global GDP triples). They show a global mean yield decrease of 17% by 2050, without CO_2 fertilization. This result was the mean between four crop groups (coarse grains, oil seed, wheat and rice) and 13 regions of the globe, with a standard deviation of $\pm$ 13% coming from differences on the impacts across crops and regions and the diversity of GCM and crop models. Several endogenous economic responses were analysed: yield loss was reduced to 11% and the area of major crops increased by 11%. Both effects resulted in a mean decline of production of 2% with a final price increase of 20%. An important finding extracted from this work is the fact that all economic models transfer the shock effects to the response of economic variables, which imply that analyses focusing only on the biophysical effects of climate change, underestimate our capacity to respond.

With a similar approach, Nelson et al. (2014) supplied yield projections from two global crop growth models (DSSAT and LPJmL) for two implementations of the RCP8.5 emission scenario in two GCMs (HadGEM-ES and IPSL-CM5A-LR), all under the SSP2. These scenarios were designed to assess the upper end of climate change impacts (omitting considering CO2 fertilization and adaptation mechanisms). Ten global agricultural models used these productivity shocks as inputs to generate different economic responses. They analysed the effects of individual endogenous responses such as prices, yield and area changes. Then, they broke down the effects of climate change shock, to identify the importance of the adjustment of three components in the model response (consumption, area and yield). Focusing on the individual responses, they present results for five commodities/commodity groups, collectively called CR5 (coarse grains, rice, oilseeds, sugar and wheat). They show a price increase relative to the reference scenario across all models, with a high variation between economic models and crop models and a small variation across climate models. For the CR5 aggregate, all models present higher prices in 2050 with a range between 3.0 to 78.9%, and a range of 1.9 to 118.1% for coarse grains (see table 6).

Witzke et al. (2014), under the same scenarios used by Nelson et al. (2014), simulated long-term economic responses using the PE model CAPRI. As with previous studies, they showed moderate impacts on the global agricultural markets at aggregated level, with a strong variation across regions. At global level they present agricultural price increases of between 6% and 13% relative to the reference scenario. Like Nelson et al. (2014), they show stronger price increases in the HadGEM2-ES scenario. Major variations of price changes were observed across regions and also across commodity aggregates. For instance wheat, coarse grains and rice increase their prices by 2050 in the range between 28% and 56%, while sugar prices do not increase more than 4% in all four climate scenarios.

The next table presents a comparison of some of the economic results presented by the three studies mentioned before for a selected commodity group. Focusing on price changes, we divide the results presented by Nelson et al. (2014)Nelson et al (2014) into those released by PE and CGE models. There is a greater variation amongst PE models than amongst CGE models, with also a higher median in the final price increase for coarse grains. This is consistent with what other authors have mentioned before regarding the magnitude of price changes, which are smaller in CGE models than in PE models.

Table 6: Range of price percent change between climate scenarios by 2050 for coarse grains.

Source	**Price (range of % changes)**	**Endogenous yields (range of % changes)**
Nelson et al. (2009)	Average producer price 20	Average yield mean 11 (mean in production: -2)
Nelson et al. (2014)	GCE models range 2.1 to 43.2 (mean: 12.25)	GCE models range -28.8 to -1.9 (mean: -12.3)
	PE models range 2.5 to 118.1 (mean: 37.9)	PE models range -26.4 to -1.5 (mean: -12.8)
Witzke et al. (2014)	28 to 49	-12 to -5[a]

[a] Impact on global production by commodity aggregate (CGR).

At regional level, particularly at the European level, a recent scientific report of Blanco et al. (2014b) assesses the impacts of climate change at a regionalised level within the EU, under the new RCPs and SSPs scenarios. They used a similar approach to that used by Blanco et al. (2014a), however they developed important advances compared than previous works: 1) this study and their simulations are based on the new RCPs and SSPs scenarios; 2) climate changes on crop yields for non-EU regions are based on a highly detailed database; 3) there are more crops covered by the biophysical simulations; and 4) there is a wider range of plausible climate scenarios. They considered six simulation scenarios which focus on the RCP8.5 and the "middle of the road" socio-economic scenario (SSP2). Moreover, they used three GCMs (HadGEM2-ES, IPSL-CM5A-LR and MIROC), considering the effects with and without CO_2 fertilization. Their general results are not different from those of previous studies. They showed moderate global changes in production driven mainly by interregional adjustments in production, consumption and trade (both with and without the effects of CO_2 taken into account). Additionally, the direction of the effects is clearly influenced by the magnitude of carbon fertilization. Similar patterns of production and price changes variations were observed comparing with global impact assessment. The variation increases as the geographical resolution of the results increases. For instance, wheat production at global level increases by the range of 0.9 to 2.3% under climate scenarios considering CO_2 fertilization. As for effects on EU production, in the same context as above, the effects are in the range of -0.9 to 2.2%. Important variations also were observed across commodities. Within the EU, in the same scenario HadGEM2-CO_2, the results show a decrease in production of 0.1% for rapeseed, while maize presented decreases of 12.4%.

In line with the current global comparison exercises, Frank et al. (2014) present a recent analysis of climate change impacts on the agricultural sector from a European perspective using two European focused global PE models. They quantify the economic impacts of climate change up to 2050, applying and linking the partial equilibrium models CAPRI and GLOBIOM-EU. As a comparison exercise, they contrast their results under the same set of scenarios which are based on the RCP8.5 and SSP2 scenarios. They considered a Baseline scenario, and two climate change scenarios (S3 and S6) picked from the full set of AgMIP scenarios (von Lampe et al., 2014). The climate change scenarios were differed on the GCM model and the crop model used; the S3 scenario was based on the GCM IPSL-CM5A-LR and the crop model LPJmL, while the S6 scenario was based on the GCM HadGEM2-ES and the crop model DSSAT. They present similar findings than global assessments, regarding how endogenous responses buffer exogenous yield shocks due to climate change. For instance, at global level the exogenous yield shock was in the range of -11% (S3) to -21% (S6), compared to global demand and production decreases by 4-6% in S3 and 7-10% in S6. A similar pattern is observed at European level, where exogenous shocks of -11% (S3) and -16% (S6), were translated in production declines only by 3-4% in S3 and 4-7% in S6. Within the comparison of the economic results, and consistently with global studies, prices are the most sensitive parameter affected by climate change. Although CAPRI predicts stronger price effects and smaller impacts on the demand side, their differences in a context of a larger model comparison exercise become negligible.

5 Common findings, sum of developments and future research directions

The integration of biophysical and economic models to assess the future economic impacts of climate change on agriculture has developed under different geographical coverage and with different treatment of the economy. With this in mind, we have identified six major methods within the structural approach in order to facilitate the analysis of the different studies in this review: 1) worldwide coverage studies, using PE models to assess the economic effects of climate change on agriculture; 2) worldwide coverage assessments, using CGE models; 3) global assessments using the BLS trade model; 4) regional coverage studies assessing the economic effects through a PE model; 5) regional coverage works using CGE models to assess the economic effects of climate change; and 6) regional coverage studies assessing the economic effects of climate change through a farm-level economic model.

This review synthesises these assessments and focuses primarily on studies at global and EU level, since the 1990s until present, which also include market feedbacks through endogenous price models. Within this review some general consensus on several issues can be extracted:

- Aggregated results at global and regional level hide the effects at more disaggregated scales. This means that overall results show smaller impacts of climate change than results that we can find in a finer disaggregation. From the global studies here reviewed, most of them present moderate globally aggregated impacts on world food production and their prices, but with important negative impacts in developing regions. The same pattern was observed on EU studies, where most of them present small effects at the EU aggregate, but greater effects at regional level (Shrestha et al., 2013).

- All the studies, independently of their geographical coverage or economic treatment, confirm the important role of trade and inter-regional adjustments as buffers of projected climate change impact. Most of the economic models used in the studies reviewed here, transferred part of the climate change shock to the trade responses and international price changes. This resulted in lower and most reliable results than assessments based only on domestic yield effects (Tobey et al., 1992).

- Economic models also transfer the climate change shock to the production side of the economic model. This contributes to offsetting the primarily exogenous yield impact through a final lower endogenous yield response. This economic adjustment, added to the above-mentioned issue, implies that analyses focusing only on the biophysical effects of climate change significantly underestimate our capacity to respond (Nelson et al., 2013).

- Of the global assessments reviewed, there is common agreement that climate change impact will be more negative in developing countries than in developed countries. Several authors attributed this to: 1) the warmer baseline climate of developing countries and the effects on them due to an increase of temperatures; and 2) an important share of developing countries, located in tropical regions, tend to rely more on C4 crops, which have less significant responses to a higher increase of CO_2 (Lobell and Burke, 2010a). This particular issue is commonly highlighted by the economic researchers, which warn that the impacts could be higher considering the scarcity of capital for adaptation measures.

- In EU regional studies, regional disparities are also observed. Most of the studies reviewed, agree about the significant regional differences within Europe. Although deciding who are the winners or losers as a consequence of climate change depends on several factors (e.g. climate scenario, crop model used, adaptation measures, geographical features), most studies here reviewed, show more negative impacts on southern countries than in northern countries.

In addition to the foregoing, this review gives a summary of the development of the integration of biophysical and economic models used as a tool to estimate future economic effects of climate change on agriculture. From early assessments onward, we have witnessed an important evolution of the entire impact modelling chain. Better resolution, major data availability, and the use of more biophysical models and economic models, are just a few of the major advances that were mentioned in this literature survey.

Global economic impact assessments in the early 1990s usually obtained their information regarding crop yield responses to climate change from external studies and were distinguished by their low resolution. Similarly, economic models, although with a worldwide coverage, were characterized by highly aggregated results. Despite these limitations, from these studies onwards, trade and inter-regional adjustments become essential issues to consider in future economic assessments. A few years later, one of the first assessments considering CO_2 fertilization and adaptation measures in the impact analysis appeared (Rosenzweig and Parry, 1994), showing their important role in the final direction and magnitude of results. From the mid-1990s to year 2000, updating the process of new emission scenarios allowed more accurate projections of climate change, which led to the emergence of new studies based on GCMs with better spatial resolution. Since the mid-2000s, new impact assessments with new features such as new biophysical models (Fischer et al., 2005) appeared. Additionally, with the release of the AR4 a major number of improvements in modelling at all levels were observed. Amongst them: 1) a large number of simulations available from a broader range of more sophisticated climate models (Parry, 2007); 2) better downscaling techniques, improving the climate input into the biophysical models; 3) updated versions of crop models; and 4) more detail and extensive bio-economic modelling.

At EU-regional level, the first economic impact assessments based on structural approaches appeared at the end of 2000s. From this study until the present, most of studies have based their results on the SRES scenarios, high resolution GCMs, and regional climate models. The first EU regional impact assessment here reviewed were characterized by their high-resolution climate projections, detail impact modelling tools and their regional focus integrated into an economic framework (Ciscar et al., 2009). From this study until today, new regional impact assessments have appeared, differentiating from earlier ones by their higher level of disaggregation and the use of new modelling tools. The latest EU assessments here reviewed, have shown major improvements in the representation of climate change at regional level within the EU, the consideration of the effects of CO2 fertilization, and the representation of more variety of agricultural commodities.

Recently, the release of the new Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) has opened a new window for a new generation of economic impact assessments. Compared with previous SRES scenarios, these are richer, more diverse and offer a higher level of regional detail. Most of the global studies based on these scenarios have focused their objectives on providing insights into the modelling uncertainties, comparing results from different modelling approaches. Within this framework, these exercises have presented new biophysical and economic models to assess the economic impact of climate change on agriculture. Furthermore, thanks to the harmonization of data from the above studies, an important base for future simulations has been provided, making it easier to compare economic results amongst different models. At European level, the economic impact assessment under the new scenarios has just begun. Recently, two new scientific papers have been developed, providing several important issues: 1) new assessments under the new RCPs and SSPs scenarios; 2) Global and highly detailed results within the EU; and 3) initials insights regard the modelling uncertainties of European focused global models (Frank et al., 2014).

Although important advances have been observed in the integration of biophysical and economic modelling for the assessment of climate change, currently, there are still remain several unresolved challenges. These challenges must be taken as clues about how future research directions should be oriented. For global assessments, most of the studies here reviewed, have been focused mainly on the effects of climate change on crops (mainly wheat, maize, soybean and rice). The number of crops covered by these approaches has increased since the mid-2000s, however, still most of the global studies ignore the impacts over important commodities. For instance the responsiveness of grassland and animal productivity to climate change is rarely considered. A major number of commodities within the economic impact assessment could generate more plausible results (considering the cross-sectoral relations in agricultural markets). On the other hand, aspects such as those related with the responses of other drivers of crop yield changes, such as weeds, pest and diseases have been excluded from these economic assessments. Furthermore, there is a lack of studies that consider different adaptation options within this kind of assessments. Most of these studies assess minor agronomic management changes (e.g. sowing dates), leaving behind several other options that could have important effects over final results. In the same line, a harmonization of adaptation options in a comparison exercise could be a great help understanding uncertainty from management practices. Lastly, in the same line of the identification of modelling uncertainties, more work is needed to harmonize models' parameters, such as, price elasticities and/or income elasticities

Finally, at European level, there is still a long way to go regarding the research of the economic effects of climate change in agriculture. Similar challenges, such as those observed with global assessments, are unsolved. For instance, there is also a need to understand the consequences of adaptation options, especially to understand what the economic impacts of different adaptation measures under different climate change scenarios could be. On the other hand, there is lack of studies of the bio-economic effects of climate change on agriculture considering its effects on crop weeds, plant nutrient management choices, ozone damage, or biotic stresses. Furthermore, although there have been important advances, there is still a need for add more agricultural products on the biophysical estimations, which would allow improvements in future analysis. Regarding to narrowing the underlying uncertainties of these approaches, although a first attempt have been recently released, there is a need to include more biophysical and economic models to assess the economic effects of climate change on agriculture. Currently, the EU account on a strong set of biophysical modelling tools (BIOMA platform) and economic modelling tools (iMAP platform) that could be used to back up the findings and to reveal the range of uncertainties of the modelling process of climate change impact. At last, there are two major unresolved challenges extracted from the EU studies here reviewed: First, considering that climate change is a global issue, and agriculture is a complex system which involves interactions between different economic sectors; there is a lack of bio-economic modelling approaches that consider the impact of climate change on agriculture, together with closely related sectors. For instance, the impact of global warming on water and energy economic sectors will directly affect the final endogenous response of economic models, which probably understate final negative effects. On the other hand, there is a need to further consider the direct effects of climate change over grassland yields and animal productivity. Most of the EU studies show adjustments of these sectors as a consequence of changes on crop prices, without considering that these activities could be just as vulnerable to climate impacts as other crops.

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