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Assessment of model-based results on the effects of future climate change on the agricultural sector in Europe

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Executive Summary

Agriculture is a sector with substantial public budgets, great importance for human survival and wellbeing and high climate sensitivity. Therefore, besides the water sector it seems to be one of the most extensively studied sectors in terms of potential climate change impacts. At the same time, modelling these impacts is challenging as it encompasses multiple disciplines, sectors and scales, in particular, when not only the biophysical but also the economic consequences are being studied. This report aims to assess the current literature in the field and summarizes the expected agro-economic consequences of climate change in Europe. To this end, 16 relevant papers following the so-called structural approach (the impacts on agricultural yields are modeled with crop models, this input is fed into economic models) and published since 2005 were screened. The modeling setups in the studies are substantially different, therefore it was not possible to integrate their results into a single metric as a well-founded basis for the development of related adaptation and mitigation strategies.

Differences between studies include the following:

- Basic setups (time horizon, spatial resolution, regional setup, sectoral resolution for general equilibrium models).
- Different reported variables, different definitions of these variables (e.g. prices).
- Different baselines.
- Choice and implementation of future socio-economic scenarios.
- Derivation of biophysical crop yield changes (climate models, emission scenarios, crop models, CO_2 fertilization effect).
- Incorporation of crop yield changes (how, which crops, treatment of non-modeled crops, treatment of other regions in regional studies).
- Inclusion of global trade relations and inter-regionally consistent climate change effects on crop yields.
- Adaptation assumptions.

Important results collected from the papers in the assessment include the following:

- Aggregate effects are relatively small, both on the positive and the negative side.
- Aggregation masks large regional differences, in particular more positive effects in Northern and rather negative effects in Southern Europe are found
- Effects in the agricultural sector are large compared to other sectors for Northern and Southern Europe, medium to small in other regions
- Inclusion of international trade effects as well as explicitly excluding or including adaptation is decisive for results and can potentially reverse signs.

Recently, the focus of the impact modeling community has shifted on increased systematic efforts towards model validation and model intercomparison, both of which could lead to a consolidation of the research area helping with the comparability of results as well as to address some areas of uncertainty, which can be tackled through intensified interdisciplinary research or harmonized study frameworks.

Finally, we derive some recommendations for reaching and communicating a consolidated and comprehensive picture of climate change effects on agriculture in Europe:

- Transparent and efficient communication between scientists and stakeholders on uncertainties is a key requirement.

- A structured assessment of agro-economic impacts of climate change in Europe based on a suit of climate, crop and economic models would be a big step towards a more comprehensive picture. Including related sectors like water and energy would be an additional benefit in particular for policy planning.

- The list of agricultural products (crop types, grasslands, livestock) included in these studies needs to be extended.

- The occurrence of weeds, pests and diseases under climate change needs to be studied and included in the models.

- All studies need to include global trade effects and consistent climate change effects in all regions.

- Adaptation modeling needs to be improved and handled more transparently.

- The policy relevance of the studies needs to be ensured, also through a closer interaction with stakeholders, e.g. in the design phase of studies and projects.

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1 Introduction

Assessing the economic effects of climate change in the agricultural sector is a challenging endeavor on multiple levels. First it is an interdisciplinary task, as it needs physical input about changes in the global climate system from General Circulation Models (GCMs), biophysical information about resulting changes in cropping systems and finally a study of the economic responses to these changes. Second it is a cross-sectoral task, as agriculture is closely linked to the water sector through irrigation, to the health sector through questions of nutrition or the industry as agriculture competes for the same resources (water, land). Third, it is a cross-scale task – agricultural production happens on small scales for which high resolution climate projections and crop modeling is necessary. In fact, in its purest form crop modeling is site-based and crop specific, in order to be able to take into account the most detailed information. However, on the economic side one needs to take into account large-scale interactions, in particular through global trade, price effects and the impact of national and European agricultural policies. This is a large challenge and studies often focus on one end of the scale spectrum without taking into account the other. The final level of difficulty stems from the treatment of adaptation. In the agricultural sector, due to its inherent vulnerability to weather and climate, adaptation has historically happened autonomously and rather efficiently (Iglesias, Garrote, Quiroga, & Moneo, 2012), but all of its aspects are difficult to model. At the same time, economic models often contain automatic adaptive processes as e.g. trade, production reallocation, changes to more suitable crops or shift in management systems. Therefore it is hard to make adaptation explicit.

While there has been an increasing amount of literature on agro-economic effects of future climate change in the past years, globally and with detailed focus on Europe, it is almost impossible to compare the results and draw conclusions due to the large spread in methodologies, scales and assumptions. This becomes clear in a few recent review papers in this area (Fernández & Blanco, 2015; Salvo, 2013; van Wijk et al., 2014). Van Wijk et al. focus on the farm household level, the other two on global and regional models. All attempt to systematically classify the existing modeling approaches, which turns out to be very difficult. Fernández & Blanco also summarize results and have a particular focus on EU regional studies, however a concise picture of the state-of-the-art results does not emerge. The IPCC 5th Assessment Report in Chapter 7 of the Working Group 2 contribution (Porter et al., 2014) presents the state of the knowledge on food security under climate change, but does not provide much information on economic effects beyond global food prices.

In this report we build on the two global/regional review papers mentioned above and extend the list of reviewed papers. We extract and highlight the quantitative results of the major recent studies on economic effects of climate change on agriculture in Europe and we discuss the challenges in comparing them. We also highlight a recent study by Stevanovic et al. undertaken in the framework of the ECONADAPT project as a methodological improvement, developing a monetary damage indicator and studying in detail effects for consumers and producers separately with a focus on several levels of uncertainty. For the sake of clarity and in line with the focus of the work package this report will focus on economy-wide results on the European level, leaving the farm and household level out of its scope.

This deliverable deviates both in title and in scope from the deliverable outlined in the DoW. The title of the deliverable listed in the DoW is “Review paper on model-based assessments of climate change impacts on agriculture, forestry, water systems and biomes”. As the focus of the work package is the Common Agricultural Policy (CAP) reform, we concentrated here on agriculture. Our assessment extends the review paper on climate change impacts on agriculture by Fernández and Blanco (2015) substantially and major outcomes have been published in Serdeczny et al. (2015) demonstrating the challenges related to developing a common picture of impacts even within one discipline. In addition, the paper by Stevanovic et al. (2015), assessing the impact of CC on agricultural welfare is directly related to ECONADAPT and highlighted in Section 7.

The deliverable is structured as follows. It will first discuss the pathways through which economic impacts in the agricultural sector can arise, including an overview of the indicators typically used to quantify these as well as the level of relevant biophysical knowledge. It will then briefly summarize existing modeling approaches, followed by an overview of the current state-of-the art results and a short introduction to the study by Stevanovic et al. (2015). Finally it will discuss open questions, problems and gaps and conclude.

2 How does climate change influence agriculture? Pathways & indicators

Figure 1 summarizes the relevant levels and indicators through which climate change on global level affects agricultural systems and finally economics. Looking at Europe the large differences between different parts of Europe under climate change should be highlighted. Northern Europe will face stronger warming in winter than in summer and an increase in precipitation, while southern Europe will see strong warming in summer (up to 7°C by 2100 in the highest emission scenario RCP8.5) as well as losses in precipitation (van Oldenborgh et al., 2013). There will also be an increase in extreme events, in particular of heat waves and extreme precipitation (especially Northern and Continental Europe) (Kovats et al., 2014), and longer and more intensive droughts in Southern Europe.

Crop yields will be directly influenced by these climatic changes, as well as by the increased CO_2 concentration (to which some crops are more sensitive than others, see e.g. (McGrath & Lobell, 2013)). The CO_2 fertilization effect is always positive (or neutral), however the net climate change effect can be positive or negative, depending on region and crop. In addition, there will be indirect effects from regional shifts in suitability, through changes in crop nutrition content and the movement of weeds, pests and diseases towards Northern latitudes. These latter effects as well as the aspect of extreme events are typically not studied with crop models (Olesen et al., 2011). In general, crop yields are expected to increase in Northern Europe, while potentially large losses are expected for Southern Europe. Results for central Europe are mixed and can be initially positive (until middle of the century) while declining later in the century (Kovats et al., 2014). Signs of these trends can already be seen today (Moore & Lobell, 2015). While there is also impact on livestock production, this is, with the exception of crop production for feed, not part of most agro-economic models and therefore outside of the scope of this report.

Finally, on the economic level, crop production amounts as well as production costs and crop prices are affected, not only directly by local or regional climatic changes, but also indirectly by changes elsewhere through international trade. This can affect GDP as well as welfare, where different measures of welfare are used in different studies (e.g. Ciscar et al.(2011) use household-level welfare while Stevanovic et al. (2015) investigate combined producer and consumer surpluses). Indirect effects include effects on food-producing industries, shifts in the labor force (either because agriculture becomes more labor demanding or less so in a country), and the reallocation of national/business funds (e.g. investment to increase productivity and/or to adapt, or increased spending on food imports) as well as private consumption (when food prices increase). Economic effects depend strongly on how much the agricultural sector contributes to the GDP of a country, or if a country is strongly dependent on food exports (for income, e.g. in the case of cash crops) or on food imports (to provide for its population).

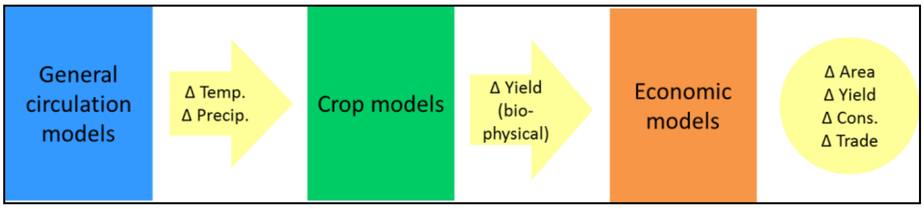

Figure 1: Overview of pathways and indicators through which climate change affects agricultural economics. Figure from Nelson et al. (2014a). Abbreviations: Temp. = temperature, Precip. = precipitation, Cons. = consumption.

3 A general overview of modeling approaches

This overview only highlights the most important categories of models. For more details, please see the recent reviews by Salvo et al. and Fernández & Blanco (Fernández & Blanco, 2015; Salvo, 2013). In particular Salvo et al. provide a classification of models and a tool allowing the selection of the appropriate model approach for a given problem.

Crop modeling

The biophysical response of crops to climate and other environmental changes can be modeled in two ways. The first, so-called bottom-up approach (Bosello & Zhang, 2005), models the growth of the plants, taking into account characteristics of the plant itself and of the environment, using process-based crop models. These can be crop and/or site specific (e.g. APSIM, CERES-Maize (Bassu et al., 2014)) or spatially explicit on global level including a larger number of crops (e.g. LPJmL (Cynthia Rosenzweig et al., 2014)). The second is the top-down (Bosello & Zhang, 2005) or production-function (Salvo, 2013) approach. It employs a spatial analog technique and is based on observations of the same crops in different environments (e.g. different locations or seasons). From that, through statistical analysis, behavior under climate change is inferred.

Economic modeling

Also on this level, two main approaches exist. The first is an extension of the spatial analog approach above, the so-called Ricardian model approach developed by Mendelsohn et al. (Mendelsohn, Nordhaus, & Shaw, 1994, 1996). Here, observations of farmers' behavior and strategies in different locations and therefore different climatic conditions are used to infer a likely response of farmers to climate changes. The different values of land are then taken as reflecting welfare effects of climate change. This has the major weaknesses that (i) it does not take into account feedback effects from changes in land values to changing agricultural prices as well as effects with the rest of the economy, both domestic and international (Bosello & Zhang, 2005); (ii) it relies on observations and therefore is of limited value to studies of climate change, where conditions may change beyond present-day experience (Nelson, van der Mensbrugghe, et al., 2014).

The second, more widely used approach is the so-called structural approach. It feeds the output of process-based crop models, like changes in yield level, yield variability and sometimes water availability into economic models which calculate changes in production and prices endogenously and treat the behavior of economic agents including adaptation in more detail. A number of different model types, in particular partial and general equilibrium models (PE, CGE) are distinguished. Partial refers to the coverage of only one sector, in our case agriculture, while general equilibrium models model the whole economic system. A specific type of partial modeling is the Basic Linked System (BLS), which is a general equilibrium approach considering a detailed agricultural sector and a highly aggregated and simplified non-agricultural sector, with a focus on world food production as an output (Fischer, Shah, Tubiello, & van Velhuizen, 2005; e.g. Cynthia Rosenzweig & Parry, 1994).

The use of biophysical crop model outcomes in economic models comes with a number of challenges (Müller & Robertson, 2014). The yield changes have to be translated into an economic variable, typically productivity changes. Individual crops have to be combined into crop classes like cereals and, very often, assumptions have to be made for crops not covered by the crop models. Finally, crop modelling results have to be aggregated spatially and temporally, as economic models typically operate on much coarser scales. While both types of models include certain adaptive responses, there is no feedback of potential economically driven adaptation from the economic to the crop model.

4 Studies and modelling approaches in this assessment

Starting with the work by Fernández & Blanco (2015) we have reviewed 16 papers reporting economic effects of climate change on agriculture for Europe. Table 1 (Annex) gives an overview of the studies. Some papers covered by Fernández & Blanco were left out as they do not report results specific for Europe (Fischer et al., 2005; Fischer, Shah, & van Velhuizen, 2002; M. . Parry, Rosenzweig, Iglesias, Livermore, & Fischer, 2004), are too old (Kane, Reilly, & Tobey, 1992; M. Parry, Rosenzweig, Iglesias, Fischer, & Livermore, 1999; Cynthia Rosenzweig & Parry, 1994; Tobey, Reilly, & Kane, 1992) or do not report actual economic variables (Nelson et al., 2009, 2010). Others were included newly (Bosello, de Cian, Eboli, & Parrado, 2009; Bosello, Eboli, & Pierfederici, 2012, 2013; Bosello & Zhang, 2005; Eboli, Parrado, & Roson, 2010; Roson & van der Mensbrugghe, 2012; Stevanovic et al., 2015). A large number of these studies arise from various EU FP6 and FP7 projects like GEMINA, CLIBIO, ClimateCost or ULYSSES.

The 16 studies use 7 different models: the global CGE models GTAP (Calzadilla et al., 2013; Hertel, Burke, & Lobell, 2010; Quiroga & Iglesias, 2008), ENVISAGE (Roson & van der Mensbrugghe, 2012) and ICES (Bosello et al., 2009, 2012; Eboli, Parrado, & Roson, 2012), the global PE models CAPRI (Blanco, Ramos, & Doorslaer, 2014; Frank, Witzke, Zimmermann, Havlík, & Ciaian, 2014; Shrestha, Ciaian, Himics, & Doorslaer, 2013), GLOBIOM (Frank et al., 2014) and MAgPIE (Stevanovic et al., 2015), and the regional CGE model GEM-E3 (Ciscar et al., 2011, 2014). The studies by Nelson et al. are model inter-comparison studies and apply a set of global CGE and PE models (Nelson, Valin, et al., 2014a; Nelson, van der Mensbrugghe, et al., 2014).

The studies using PE models with a focus on the agricultural sector (Blanco et al., 2014; Frank et al., 2014; Shrestha et al., 2013; Stevanovic et al., 2015) have the advantage that the detail of the mechanisms in agriculture, including the number of crops taken into account, is larger. However, important economic interaction effects like factor reallocation, e.g. of labor, as well as shifts of demand towards other sectors cannot be captured in such a setting. The studies by Blanco et al. (2014), Shrestha et al. (2013) and Ciscar et al. (2011, 2014) have a regional focus on Europe, despite using global models. Spatial resolution in Europe is higher than in other areas and processes are captured in more detail. However, this carries the problem of how to treat the rest of the world, in particular the effect of climate change on crops. Shrestha et al. (2013) do not consider climate impacts on crops outside of Europe at all. This is problematic as in particular the agricultural sector is strongly influenced by the global links through crop prices and trade, and climate change impacts can be alleviated or enhanced by these links, depending on how climate change affects other countries. Blanco et al. (2014) and Ciscar et al. (2011, 2014) do consider global climate effects, however use data from the literature instead of the same crop modeling approach as used for Europe. This can still lead to inconsistencies.

5 A summary of the current state-of-the art results for economic impacts of climate change from the agricultural sector in Europe

Table 1 (Annex) gives an overview of the most important components of the modeling setups of the different studies. It is immediately clear that a direct comparison of the results is difficult due to the large inherent differences. In the following we highlight some of the most important conclusions from the different studies, while the following section will discuss why it is so difficult to integrate results and how a way towards integration could look like.

Table 2 (Annex) provides an overview of the aggregate quantitative results. A comparison has to be undertaken with caution due to the different setups of the studies. The first challenge is the number of different indicators reported. They included production changes (not shown in Table 2), GDP changes stemming from the agricultural sector, welfare changes (where the definition of welfare is not always consistent between studies) and price effects. Table 2 collects results for Europe only, although some of the studies also cover other world regions and report global results.

The GDP effects are relatively small. The studies using the ICES model generally report positive results for the year 2050, in the range of 0.02 to 0.12% (Bosello et al., 2009, 2012; Eboli et al., 2010). Ciscar et al. (2011, 2014) and Roson & van der Mensbrugghe (2010) report for the end of the century results between -0.29 and 0.04%, depending on the climate scenario. Prices are generally projected to increase with the exception of the scenarios with CO_2 fertilization by Blanco et al. (2014) (who also see increases without CO_2 fertilization). Increasing prices can mean positive effects for producers while consumers would have to increase their spending on food (see also discussion by Stevanovic et al. (2015)).

However, aggregating results masks large regional differences. The studies showing regionally differentiated results (Bosello et al., 2009, 2012; Ciscar, 2009; Ciscar et al., 2014; Quiroga & Iglesias, 2008) show generally rather positive effects in Northern Europe but also potentially strong losses in the south (e.g. -1.26% of GDP compared to +1.09%, Ciscar et al. 2009, +5.4° climate change scenario). Blanco et al. (2014) show a map of regional agricultural income under climate change (instead of providing one aggregate number for different European regions), from which it is clear that the picture is even more differentiated when really looking at small scales, where this grouping in positively affected north and negatively affected south does not hold anymore.

The studies by Ciscar et al. (Ciscar et al., 2011, 2014) compare the effects in the agricultural sector with those in other sectors. The stronger climate change, i.e. the higher the warming, the more important the agricultural sector seems to get, in particular in Southern Europe (-0.05% for 2.5°C, -1% for 5.4°, where the former is 19% of the total effect, while the latter is

74%). In Northern Europe it is the dominating sector regardless of scenario, while in Europe overall, coastal system impacts are a bit stronger.

Aside from providing quantitative GDP effects, some of the papers use modeling frameworks to specifically target particular relevant issues which can affect the quantitative results. We briefly discuss those results in the following.

Effects in Europe are strongly influenced by global changes in production and food prices through trade connections and price mechanisms, although the direction of this depends on the assumptions of climate change effects (as increases in production are mirrored by decreases in prices and vice versa). Shrestha et al. (2013) find that allowing for a global price adjustment reduces European agricultural income, resulting in a shift from a 3.3% gain under climate change to a 0.2% loss. This is because the price reduction is larger than gains resulting from productivity increases. Stevanovic et al. (2015) report a liberal trade scenario which leads to overall gains of 101.8 bio US$ in European agricultural welfare rather than losses of 7.4 bio US in a scenario where trade remains fixed, supporting the role of trade as an adaptive mechanism.

Frank et al. (2014) discuss in particular the model-endogenous adaptation in economic models by which exogenous yield shocks are buffered . These mechanisms include the shift of production between regions or a shift in management systems. In principle, this economic adjustment highlights the need for the full modeling chain, as pure biophysical yield responses do not include the full adaptive capacity of the system. However, Frank et al. show that this adjustment may be less effective in Europe than elsewhere, because Europe has little additional adaptive capacity in the agricultural system. Climate change impacts in their study are compensated in Europe mostly through area expansion, which cannot compensate production losses as less suitable production areas have to be developed. Consumption is affected little in their study, confirming the relatively inelastic demand for agricultural products.

Blanco et al. (2014) discuss the CO_2 fertilization effect, one of the major sources of uncertainty for projections of agricultural climate change effects. They find that the positive yield effect for some crops in the EU seen without CO_2 fertilization changes into a negative production effect when the fertilization effect is included. This is due to increasing global production under the beneficial fertilization effects, which leads to less competitive prices in the EU and a worsening trade balance.

Finally, adaptation is a major influencing factor and an active research area. Trade as adaptive mechanism was already discussed. Shrestha et al. (2013) explicitly compare two scenarios of “no” and “best” technical adaptation of crops and find that, at least with fixed prices, this may change agricultural income effects by a factor of 8.5.

Box 1: Important qualitative results for Europe

- Aggregate effects are relatively small, both on the positive and on the negative side.
- Aggregation masks large regional differences, some evidence for positive effects in Northern and negative effects in Southern Europe.
- Effects in the agricultural sector are large compared to other sectors for Northern and Southern Europe, medium to small in other regions.
- Inclusion of international trade effects as well as explicitly including or excluding adaptation is decisive for results, can potentially reverse signs.
- No direct quantitative intercomparison of studies possible due to large differences in set-up.

6 Discussion

Issues hindering the integration of results

From this review, some key issues hampering the inter-comparison and integration of results and therefore the formation of a solid picture of agro-economic impacts of climate change in Europe can be collected. Most of these points are generally valid also for global studies. An overview is given in Box 2.

Studies vary widely in their basic setups, including time horizons, spatial resolution and regional setup. Results reported in Table 2 for Europe actually cover different regional aggregations, from Europe as a whole to EU27 or EU28 or others, e.g. including candidate countries. Furthermore, CGEs can differ in their sectoral breakdown and details.

Reported variables are very different and are often not well defined, making it hard to compare. This includes in particular world market prices, which are defined in a fundamentally different way between partial and general equilibrium models (von Lampe et al., 2014).

Results are generally reported as percentage changes with respect to a (no climate change) baseline. This makes the specification of this baseline a key factor in the comparison of the results, and different studies use different future scenarios. At the same time, even for given socio-economic scenarios like SRES or the new Socio-Economic Pathway (SSP) framework (O'Neill et al., 2014, 2015), economic models, in particular CGEs with their sectoral detail, have a high degree of freedom in interpreting and implementing these scenarios, still hampering a direct comparison of the results. Also, these types of models are calibrated to a given base year or are based on a given GTAP version, which results in another difference that is not easily resolved.

Specific to the agricultural sector is the need to incorporate information about crop yield changes under climate change. This gives way to another number of sources of difference between studies. This includes the emission scenarios (commonly SRES or the newer Representative Concentration Pathways (RCPs)), the Global Circulation Models (GCMs), for regional studies often combined with regional climate models, and the technique to project future crop yields (see Section 0), which in most recent cases includes the use of biophysical crop models. Some studies simply use literature values to create their yield inputs (e.g. Roson & van der Mensbrugghe, 2010) or some type of damage function (e.g. Bosello et al., 2009), but the full scale modeling on all levels is increasingly becoming the state-of-the-art. Differences between crop yield projections clearly have a large influence on the outcome of the economic study, but also the number and type of explicitly considered crops. For many types of crops there is little work on the influence of climate change, e.g. fruits and vegetables or types of cash crops like coffee. Also, most crop models only cover a limited number of crops, typically the four main staple crops maize, wheat, rice and soy (though there are a few exceptions like the LPJmL model (Bondeau et al., 2007) covering 11 crops), while economic models typically have larger detail in their agricultural sectors. This requires assumptions for the missing crops, which can be quite different. Müller & Robertson (2014) discuss in detail the process and related problems when preparing input from crop models for economic models.

As already discussed above, for regional studies using high resolution regional crop and economic models, the information of the effects of climate change outside the focus region is important due to trade relations and adaptation options. Therefore, these regional studies need to find another source for crop yield information for the rest of the world, which can be a source of inconsistency, as it seems to be taken from the literature in many cases (e.g. Blanco et al., 2014), or the impact of climate change outside the focus region is ignored completely.

Adaptation enters these types of studies on both the crop and the economic level. On the crop side it is technical adaptation through management changes (e.g. change of sowing dates, more efficient irrigation or other cultivars), on the economic side it includes endogenous measures like land-use change, shifts in production, trade. Often, these mechanisms are not transparently discussed in the studies and therefore assumptions are difficult to compare, but likely constitute another important source of differences.

Box 2: Areas of differences between studies hampering intercomparison

- Basic setups (time horizon, spatial resolution, regional setup, sectoral resolution for general equilibrium models).
- Different reported variables, different definitions of these variables (e.g. prices).
- Different baselines.
- Choice and implementation of future socio-economic scenarios.
- Derivation of biophysical crop yield changes (climate models, emission scenarios, crop models, CO_2 fertilization effect).
- Incorporation of crop yield changes (how, which crops, treatment of non-modeled crops, treatment of other regions in regional studies).
- Inclusion of global trade relations.
- Adaptation assumptions.

Ways forward: model validation and model intercomparison

Looking at this long list of sources of uncertainty and modeling differences makes the current status of patchy, incomparable and incomprehensive results in the field less surprising. However, due to the importance of the agricultural sector for economics and food security, this situation is unsatisfactory. There are two ways to move forward – model validation and model intercomparison. Both are tackled in two fairly young but quickly growing initiatives: the

Agricultural Model Intercomparison and Improvement Project (AgMIP)[1] and the Intersectoral Model Intercomparison Project (ISI-MIP)[2].

Validation

Model validation is an important way to ensure that at least for the historic period the model behaves sensibly within its abilities, i.e. reproducing major trends or being able to capture the effects of large extreme events. It is done by driving the models with historic data (e.g. observed climate data) and then compare the output with observations (e.g. for crop yields). For crop models this is currently underway through the ISI-MIP and AgMIP projects, which lead this activity for the first time in a comprehensive and systematic way including a large number of crop models. This is an important initiative as it is unclear, how well the crop models are currently suited to represent possible climate change effects, in particular as they only include some of the mechanisms through which heat and extreme events can affect crops (Hertel & Lobell, 2014; White, Hoogenboom, Kimball, & Wall, 2011).

For economic models, this is much harder as it requires a change in calibration of the model to a new base year in the past, where the data base at least for developing regions may not be sufficient. Validation faces the problem that real trends can often only be visible over the long-term, as short-term events like the oil crisis in the 1970s or the collapse of the Soviet Union dominate over shorter time scales. But the data availability prevents validation to go back much further than 1950. Also, ensuring sensible behavior of a model for the past does not at all guarantee that it will be able to capture all important effects in the future, in particular over the long-term and under climate change, which may bring unforeseen feedbacks and interactions and push systems beyond the known boundaries for example through tipping points.

Model validation can result in the identification of important processes not being adequately represented in the models and therefore to model improvement. As both biophysical and economic models face the problem of data availability for model calibration, validation also helps to understand if adequate methods are being employed to deal with lack of data.

In particular for economic models, one area of model improvement suggested recently is the question of the representation of land rents. Their lack could be one reason why economic impacts in the agricultural sector tend to be relatively small in the current literature (Kalkuhl & Edenhofer, 2015).

Model intercomparison

Model intercomparison helps to unveil and understand sources of differences between model results. It also makes the spread of results transparent to users, allowing them to get a more complete picture and better place results of an individual study. An intercomparison can be done based on various degrees of model harmonization. The ISI-MIP project follows the philosophy of limited harmonization, mainly harmonizing the climate and socio-economic input data, but leaving model-internal settings up to the best guesses of the individual modeling teams, allowing the full spread to show in the results. Increased harmonization will help to dig deeper into differences, but carries the problem of artificially decreasing natural model spread if models are tuned to avoid being an outlier. The first round of ISI-MIP and AgMIP intercomparisons resulted in a number of publications both on differences between crop

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[1] www.agmip.org

[2] www.isi-mip.org

models (Cynthia Rosenzweig et al., 2014) and economic models (von Lampe et al., 2014 and other papers in the related special issue).

One important result for the economic models was a systematic difference in the price responses of partial and general equilibrium models to different drivers, with that of the CGEs being generally lower. For climate change the two types of models also implement yield shocks differently, partially accounting for the lower price response. These kind of findings will greatly help place results of future studies in a larger framework.

7 Separating consumer and producer effects highlighting all levels of uncertainty – study by Stevanovic et al. (2015)

This study stands apart from previous work in the field in two ways. First, it explicitly discusses the different effects climate change will have on different economic agents (producers and consumers). This is generally hidden by the aggregation in most other global/regional studies. Second, it covers all relevant levels of uncertainty through an extensive sensitivity analysis. This includes the use of multiple GCMs for uncertainty in patterns of climate change, multiple crop models (including a test of the importance of the CO_2 fertilization effect), multiple socio-economic scenarios and a variation of adaptation with a focus on trade.

Methodology

The study analyzes climate change impacts on agricultural welfare on global and regional scale, measured as changes in consumer and producer surplus. The impacts are dynamically assessed for the period from 1995 to 2095 using the agro-economic land-use optimization model MAgPIE (Model of Agricultural Production and its Impacts on the Environment) (Lotze-Campen et al., 2008; Popp et al., 2014). MAgPIE is well suited to translate bio-physical into economic impacts since crop yield patterns and water availability that are directly affected by climate change enter the economic model as spatially explicit biophysical constraints. The surplus concepts are standard analytical tools in welfare economics. As agricultural welfare we consider economic surplus from agricultural activities related only to plant cultivation and livestock production. Producer surplus is equivalent to the production profit, i.e. difference between total revenues and costs associated with production. Consumer surplus is the difference between a consumer's willingness to pay for a certain good and the amount he or she actually pays for it at the market price. In MAgPIE, consumer's behavior is deterministically defined by exogenous demand trajectories for agricultural products and therefore a change in consumer surplus is calculated as a difference between consumption levels. In the case of a negative impact on the production side, the agricultural supply curve shifts upwards (or leftwards) and the equilibrium price increases to a new level, implying shifts in surpluses. Climate change induced welfare impacts for food producers and consumers are calculated in this analysis based on differences in surpluses. Three indicators are considered: change in consumer surplus, change in producer surplus and change in total agricultural welfare, the last indicator being the sum of the first two.

The focus here is on the high-end of agro-economic effects from climate change, where the MAgPIE model is driven by a high population growth and high greenhouse gas emission scenario (SRES A2) and no beneficial effects from the CO_2 fertilization in the underlying crop yield simulations (performed with the gridded global crop model LPJmL (Bondeau et al., 2007; Müller & Robertson, 2014)) are assumed. In order to assess the potential of buffering the economic damage from climate change, we highlight the role of international trade by assessing two scenarios: the liberalized trade scenario (LIB), which resembles current trade liberalization trends by relaxing global trade barriers by 10% per decade, and the counterfactual, “fixed” trade scenario (FIX) which assumes the interregional trade patterns as fixed at the initial year levels, in terms of relative shares of regional trade flows. The international trade in MAgPIE considers trade regulations in the form of regional self-sufficiency constraints, but governmental trade policy revenues or spending are not explicitly estimated; instead, they become part of consumer or producer rents.

Results

The results indicate an overall adverse effect from climate change in global agricultural welfare, with an increasing magnitude of economic loss towards the end of the century. Some initial benefits for global agricultural welfare (an increase of 0.1% of projected GPD in SRES A2) occur from moderate warming in regions in higher latitudes (Europe, North America and Russia) in the first two decades of the century. These more favorable climatic conditions in temperate zones reduce marginal costs of production and lower agricultural commodity prices, leading to higher gains for consumers. However, already after 2030 impacts on agro-economic welfare become negative as climate change intensifies, reaching a loss of 0.3% of projected global GDP in the LIB (884 billion US$) and 0.8% (2,502 billion US$) in the FIX scenario, in the year 2095 (Figure 2). The negative impacts on global agricultural welfare are a consequence of increasing agricultural prices, which lead to a much higher loss in consumer surplus compared to the producers who profit on aggregate (Figure 2). This effect is, however, smaller for the liberalized trade case, where the shift in surpluses between consumers and producers shows an effect which is 65% smaller than in the counterfactual fixed trade case (Figure 2).

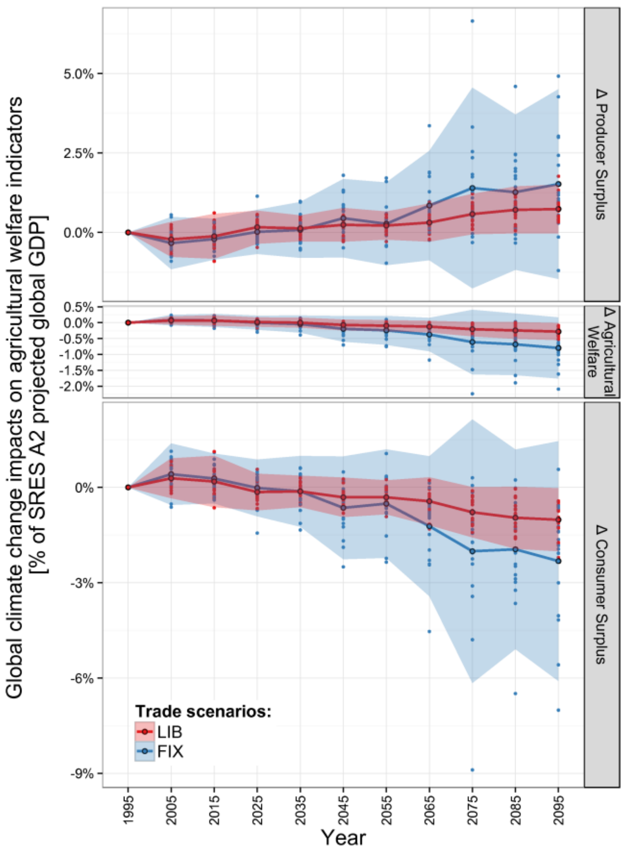

Figure 2: Global climate change impacts on agricultural welfare indicators (% of projected global GDP) in the SRES A2 scenario. For each climate scenario (19 GCMs) used in the analysis actual modeled changes in welfare are represented by dots, while solid lines for all three panels connect average values of calculated impacts for every simulated time step. Shaded areas depict double standard deviation from the mean.

Regional changes in surpluses reveal unequal distribution of climate change impacts on agricultural welfare. Irrespective of a trade policy, it is certain that consumers in all regions will pay more for agricultural goods. On the other hand, the magnitude of gains in profit for producers depends on how much their comparative advantage in agricultural production is affected by climate change. Increasing the share in global trade volume creates higher surplus for producers, while local consumers could at the same time suffer from increasing domestic prices influenced by global markets, thus creating a smaller benefit for overall agricultural welfare. In the LIB scenario, the global patterns of agricultural production shift towards northern regions, including Europe, North America and Russia, resulting in 160% higher export volume in 2095. For example, in Europe and Russia the created added value for the agricultural sector in 2095 accounts for approximately 0.5% and 1.3% of projected regional GDP respectively (100 billion US$ each), and around 0.5% of projected regional GDP in North America (60 billion US$) (Figure 3).

Negative effects of climate change are exacerbated in tropical regions. There, total damage in terms of loss of projected GDP ranges from -1.5% in Indian Subcontinent to -0.5% in Pacific Asia (Figure 3). These losses are driven by the opposite dynamics than in the temperate regions in the LIB scenario, i.e. reduced market shares and thus lower production and producer surplus, but similar reductions in consumer surplus. However, if the international trade is more distorted as in the FIX scenario case, those regions in the tropics would be even worse off, as significant biophysical limitations (land, water) can put additional pressure on the domestic production of increasingly demanded agricultural goods.

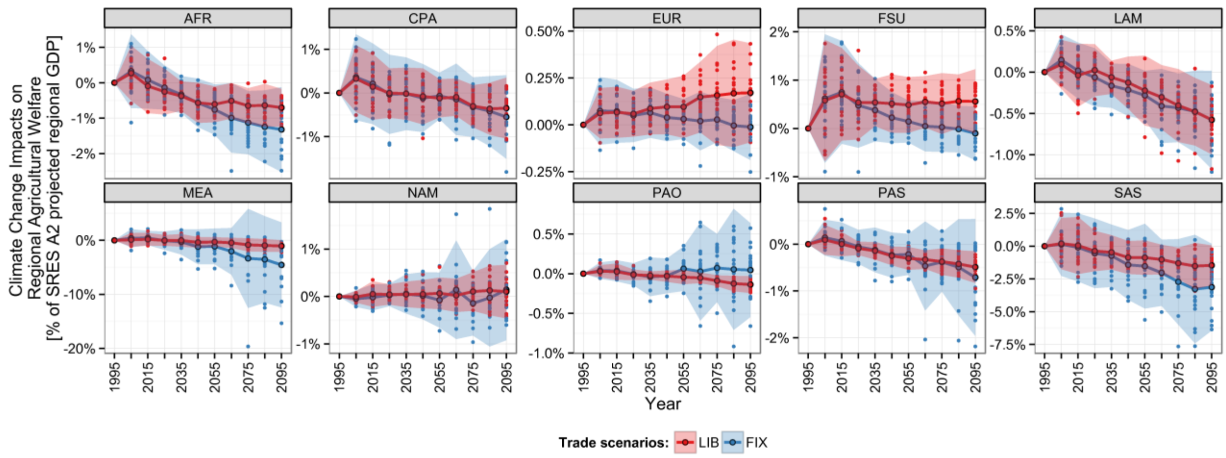

Figure 3: Climate change impacts on regional agricultural welfare for the SRES A2 scenario: Average values (lines) and uncertainty (double standard deviation from the mean; shaded area) across different climate model projections (19 GCMs). The figure shows outcomes for the ten socio-economic MAgPIE regions: AFR (Sub-Saharan Africa), CPA (Centrally Planned Asia), FSU (Former Soviet Union), EUR (Europe incl. Turkey), LAM (Latin America), MEA (Middle East – North Africa), NAM (North America), PAO (Pacific OECD), PAS (Pacific Asia), SAS (South Asia).

For Europe in particular, climate change will lead to higher food prices (~30% in 2095 in LIB scenario), as it is mentioned above. It is noticeable that the ensuing losses in the European consumer surplus are higher in the liberalized trade scenario than in the fixed trade scenarios with trade patterns and European export shares constant at the 1995 levels. This indicates that the supply from Europe to the global market with liberalized trade will increase the cost of domestic marginal production, and accordingly European domestic prices. Still, beneficial effects on production profit will, on average, positively affect European agricultural welfare. The uncertainty in climate patterns, however, leaves some concern on this positive effect (Figure 3). In the MAgPIE model, the European region is simulated as one geo-economic unit (including Turkey), and with the Mediterranean region that is already vulnerable to change in precipitation and increasing temperatures, the uncertainty in climate patterns is strongly reflected in the uncertainty of climate agro-economic impacts, as European comparative agricultural advantage and exporting potential depend also on intraregional climatic change patterns.

The departure from the high-end assumptions employed here could reduce the magnitude of agricultural damage caused by climate change impacts, for example by opting for SRES B1 and A1B socio-economic scenarios that are characterized by slower future demographic development and less dramatic climate change. On the other hand, if the positive atmospheric CO_2 fertilization effects on crop yields can be realized at large scales, our sensitivity analysis shows that the resulting beneficial influence on agricultural markets cannot compensate climate-driven damages towards the end of the 21st century, although the negative impacts can be offset by it earlier in the century. Another source of uncertainty is the choice of how to represent important bio-chemical processes as well as parameterization in the plant growth modeling approach. In additional sensitivity analysis, the resulting range of agricultural welfare loss across five different crop models is considerable (0.1% - 1.7% of projected global GDP), though the general pattern of gains for producers and losses for consumers proves robust.

Conclusions

In conclusion, climate change can have detrimental impacts on global agricultural welfare, reaching the damage levels of 0.3% of global GDP at the end of the century under the assumption of further opening of trade in agricultural products. The overall loss in welfare is a result of negative effects on the consumer side outweighing increasing producer profit from higher prices. Regionally, shifts of agricultural production to higher latitudes under a liberalized trade regime can alleviate pressure on consumers in the tropics, as global markets dominate domestic agriculture and decrease the prices, but could be harmful for local producers and smallholder farmers, or for many subsistence households living in the developing regions in the tropics. For Europe, beneficial conditions for agriculture under climate change are projected to increase the export and raise agricultural added value in the economy; however, some redistribution of producer trade revenues could be utilized for European consumers, who would face losses in surplus as prices increase, especially taking into account heterogeneity of local impacts and wealth across the European continent.

8 Conclusions

What do we know, what can we know and what is the remaining uncertainty

The current state-of-the-art of knowledge on the economic impact of climate change in the agricultural sector, globally and in Europe, offers policy makers a large number of studies which are not directly comparable, making it impossible to form a reliable basis for developing policy measures like adaptation and mitigation strategies or giving concrete advice on how to integrate such strategies into the CAP. While the number of studies has strongly increased in the last two decades and the comprehensiveness and quality of the modeling has improved tremendously through relating biophysical crop models with detailed partial and general equilibrium economic models, the field is still very divergent and a clear picture fails to emerge. While the overall impacts in Europe seem to be small, only few studies provide more regional detail, but these show that especially in Southern Europe large negative impacts could be expected. At the same time, this region is also vulnerable to other impacts in the areas of water, health or tourism, making interactions and amplification of effects a critical question. This stresses the need for detailed, reliable regional projections. Also, close connections within Europe enable a propagation of effects into other regions, e.g. through migration. At the same time, adaptation measures can be planned more efficiently when taking into account all sectors and regions for example to capture cross-sectoral advantages.

The recent model intercomparison and validation initiatives in the AgMIP and ISI-MIP projects provide promising ways forward. Based on this work von Lampe et al. (2014) identify four categories of model differences, in order of increasing difficulty, that have to be addressed:

(1) “differences in model approaches or parameters where the existing literature suggests a more narrowly defined range could be achieved, without relying on substantial additional research” (page 7) – e.g. values for price and income elasticity

(2) “areas where more economic research and better economic data would likely narrow the differences between model outputs” (page 8) – e.g. level of technical change for labor or capital, or the level of technical change in agriculture vs. the rest of the economy

(3) “areas of uncertainty where economists need better information from their colleagues from other disciplines, such as on biophysical relationships” (page 8)

(4) “areas of uncertainty that will not be resolved by research within the foreseeable future” (page 9) – e.g. GDP growth, agricultural productivity changes.

This provides a useful framework for designing future research projects, in particular also across disciplines, to tackle some of the open issues. It however also acknowledges the existence of unresolvable uncertainty. This can partially be covered by study design as it includes things like future socio-economic development which requires scenario harmonization. But some degree of uncertainty will always remain, e.g. because on all levels of the modeling chain there are processes which are hard to understand and even harder to model. It should be an integral part of communication between scientists but even more so between scientists and policy makers or other stakeholders to be as transparent as possible about this and to develop strategies to counter the effects of climate change nonetheless, based on the large degree of existing knowledge.

Concrete recommendations

The recommendations are also summarized in Box 3.

A structured assessment of economic impacts of climate change in Europe on agriculture based on harmonized climate and socio-economic input data, harmonized impact input like yield changes and based on a suit of climate, impact and economic models would be a huge step towards a more comprehensive picture which transparently communicates related model spreads and uncertainties. The joint study of important related sectors like the water-food-energy nexus would offer an important additional input for stakeholders and policy makers. These efforts are still in their infancies.

A few more specific options for necessary improvements in the models can be identified (see also Fernández & Blanco, 2015). More types of agricultural products should be included in the studies to provide a more comprehensive picture of climate change effects in the sector. This includes more crops, in particular cash crops (when focusing on developing regions where these matter strongly for national economies), grasslands and livestock.

Studies largely exclude the effects of potential increases in the occurrence of weeds, pests and diseases under climate change. Both this and the previous point require improvements on the level of the crop models as well.

Global trade effects should be taken into account by all studies. This includes a consistent treatment of climate change effects on agriculture in all regions, not only the focus region of a regional study.

Adaptation remains an area of large uncertainties and modeling challenges. While some measures are taken into account explicitly or implicitly in the models, this is often not very transparent, and without explicit treatment, also including costs and consequences of adaptation options, it is difficult to use results for the development of adaptation strategies. Also policy-driven measures are rarely taken into account.

Finally, authors should ask themselves if the output of studies is as policy-relevant as it could be. Surely this depends on the region tackled and question asked. While in Europe economic questions may be more in the focus, globally the question of future food security is most prominent. This also relates to the correct framing of questions. When studying the impact of climate change on the global poor, a study of price effects may not be the most useful focus as higher prices resulting from reduced production can actually benefit even small-scale producers. Definitely, in light of the inherent uncertainty of future socio-economic development and the need for scenarios, a closer interaction with stakeholders will be useful in the development of future studies to ensure their relevance for policy makers.

Box 3: Summary of recommendations

- Transparent and efficient communication between scientists and stakeholders on uncertainties is a key requirement.
- A structured assessment of agro-economic impacts of climate change in Europe based on a suit of climate, crop and economic models would be a big step towards a more comprehensive picture. Including related sectors like water and energy would be an additional benefit in particular for policy planning.
- The list of agricultural products (crop types, grasslands, livestock) included in these studies needs to be extended.
- The occurrence of weeds, pests and diseases under climate change needs to be studied and included in the models.
- All studies need to include global trade effects and consistent climate change effects in all regions.
- Adaptation modeling needs to be improved and handled more transparently.
- The policy relevance of the studies needs to be ensured, also through a closer interaction with stakeholders, e.g. in the design phase of studies or projects.

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10 Annex

Table 1: Overview of Europe-focused studies on economic impacts of agriculture from climate change reviewed in this report

Reference	Project connection	GCMs, emission scenarios, climate projections	Biophysical model (estimation of potential changes in crop yields)	Economic model	Regional scope	CO2 fertilization	Time horizon	Farm-level adaptation measures	Included crops	Global trade connections included
Blanco et al. (2014)	ULYSSES	2 climate change scenarios: HadRM3 driven by HadCM3 with SRES A1B HIRHAM5 driven by ECHAM5 with SRES A1B	WOFOST (BIOMA platform) & LPJmL	CAPRI (PE)	Europe (280 regions) Global (77 countries in 40 trade blocks)	Yes	2030	No	Wheat, maize, barley, rye, field beans, rapeseed, sunflower, sugar beet, potato	Yes but inconsistent (different crop models)
Bosello & Zhang (2005)		Reduced-form Schneider-Thompson GCM	Yield-temperature relation from Tol (2002; 2002), based on data from Rosenzweig & Hillel (1998)	GTAP (CGE)	Global (8 regions)	Yes	2050	?	Rice, wheat, cereal crops	Yes
Bosello et al.	CLIBIO	SRES A2	Yield-temperature relation from	ICES (CGE)	Global (14 regions)	Yes	2050	No	Wheat, rice, other cereal crops	Yes

Reference	Project connection	GCMs, emission scenarios, climate projections	Biophysical model (estimation of potential changes in crop yields)	Economic model	Regional scope	CO2 fertilization	Time horizon	Farm-level adaptation measures	Included crops	Global trade connections included
(2009)			Tol (2002; 2002), based on data from Rosenzweig & Hillel (1998) and Moriondo & Bindi (2007)							
Bosello et al. (2012)	Climate Cost	SRES A1B	From Iglesias et al. (2009)	ICES (CGE)	Global (14 regions)	Yes	2050	Yes	Winter wheat, spring wheat, rice, grassland, maize, soybeans	Yes
Bosello et al. (2013)	GEMINA	EU population and GDP from 2012 Ageing Report for EU27 (EU Comission) Non-EU: UN population projections & SRES A2	?	ICES (CGE)	Global (22 regions)	?	2050	?	?	Yes
Calzadilla et al. (2013)		Climate change data from Falloon & Betts (2006) and Stott et al. (2006). Based on 1 GCM	Based on literature (Rosenzweig & Iglesias (1994) for crop yields, Tubiello et al. (2007)	GTAP-W (CGE)	Global (34 regions)	Yes	2020; 2050	No	Rice, wheat, cereal grains, vegetable/fruits/nuts, oil seeds, sugar cane, sugar beet	Yes

Reference	Project connection	GCMs, emission scenarios, climate projections	Biophysical model (estimation of potential changes in crop yields)	Economic model	Regional scope	CO2 fertilization	Time horizon	Farm-level adaptation measures	Included crops	Global trade connections included
		(HadGEM1-TRIP), 2 SRES scenarios (A1B, A2)	for CO_2 fertilization, Darwin et al. (1995) for water supply)							
Ciscar et al. (Ciscar, 2009; Ciscar et al., 2011)	PESET A I	5 climate change scenarios: RCA driven by ECHAM4 with SRES A2 (2020) HIRHAM driven by HadAM3h with SRES A2, B2 (2080) RCAO driven by ECHAM4 with SRES A2, B2 (2080)	DSSAT	GEM-E3 (CGE)	Europe (5 regions)	Yes	2020 2080	Yes	Winter wheat, spring wheat, rice, grassland, maize, soybeans	No
Ciscar et al. (2014)	PESET A II	4 climate change scenarios: ECHAM5 (UKMO) with	BIOMA DSSAT	GEM-E3 (CGE)	Europe (5 regions)	Yes	2085	Yes	Maize, wheat, soybeans	No

Reference	Project connection	GCMs, emission scenarios, climate projections	Biophysical model (estimation of potential changes in crop yields)	Economic model	Regional scope	CO2 fertilization	Time horizon	Farm-level adaptation measures	Included crops	Global trade connections included
		SRES A1B ECHAM5 (DMI) with SRES A1B EGMAM2006 with SRES A1B ECHAM5.4 with SRES E1								
Eboli et al. (2010)	EN-SEMBLES	World Bank population projections, assume global mean temperature increase of 1.5° by 2050	Yield-temperature relation from Tol (2002; 2002), based on data from Rosenzweig & Hillel (1998)	ICES (CGE)	Global (8 regions)	Yes	2050	No	Wheat, rice, other cereal crops	Yes
Frank et al. (2014)	AgMIP	RCP8.5, SSP2 with 2 GCMs (HadGEM-ES IPSL-CM5A-LR)	DSSAT LPJmL	CAPRI (PE) GLOBIOM-EU (PE)	Global-Europe focus (40/53 regions)	No	2050	?	Wheat, coarse grains, paddy rice, oil seeds, sugar crops	Yes
Hertel et al. (2010)		3 scenarios, differentiated by rate of temperature	Synthesis of values from the literature for the GTAP	GTAP (CGE)	Global (34	Yes	2030	No	Rice, wheat, coarse grains, oilseeds, cotton, others	Yes

Reference	Project connection	GCMs, emission scenarios, climate projections	Biophysical model (estimation of potential changes in crop yields)	Economic model	Regional scope	CO2 fertilization	Time horizon	Farm-level adaptation measures	Included crops	Global trade connections included
		change, sensitivity of crops to warming, effect of CO_2 fertilization): low productivity, central, high productivity	regions and six commodities		regions)					
Nelson et al. (2014b) **(see also Nelson, van der Mensbrugghe, et al., 2014; von Lampe et al., 2014)**	ISI-MIP/ AgMIP	RCP8.5, SSP2 with 2 GCMs (HadGEM-ES IPSL-CM5A-LR)	DSSAT EPIC LPJmL pDSSAT PEGASUS	5 CGE models (AIM, ENVISAGE, FARM, GTEM, MAGNET), 4 PE models (GCAM, GLOBIOM, IMPACT, MAgPIE)	Global (different regional resolution)	No	2050	?	Coarse grains, oil seeds, wheat, rice	Yes
Quiroga & Iglesias (2008)	PESETA I	HIRHAM driven by HadCM3 with SRES A2 RCA3 driven by ECHAM4 with	DSSAT for Europe Rest of the world: data from Parry	GTAP (CGE)	Global with focus on Europe (7 European regions ,1 ROW)	Yes	2085	Yes	Winter wheat, spring wheat, rice, grassland, maize, soybeans	Yes but inconsistent (different crop models)

Reference	Project connection	GCMs, emission scenarios, climate projections	Biophysical model (estimation of potential changes in crop yields)	Economic model	Regional scope	CO2 fertilization	Time horizon	Farm-level adaptation measures	Included crops	Global trade connections included
		SRES A2	(2004)							
Roson & van der Mensbrugghe (2012)		UN population projections	Non-linear relationship between GMT change and yields, based on Easterling et al. (2007)	ENVISAGE (CGE with an endogenous climate module - IAM)	Global (15 regions)	?	2100	?	Wheat, maize, rice	Yes
Shrestha et al. (2013)	PESETA	2 climate change scenarios: HadRM3Q0 driven by HadCM3 with SRES A1B, HIRHAM5 driven by ECHAM5 with SRES A1B	BIOMA platform	CAPRI (PE)	Europe (280 regions) Global (77 countries in 40 trade blocks)	Yes	2020	Yes	Maize, wheat, sunflower, rapeseed modeled with BIOMA, assumptions for other CAPRI crops	Trade yes, but crops outside of Europe are not affected by climate change
Stevanovic et al. (2015)	Econ-Adapt	19 GCMs, SRES A2 (sensitivity tests with A1B and B1)	LPJmL (sensitivity tests with pDSSAT, EPIC, Pegasus)	MAgPIE (PE)	Global (10 regions)	No (but sensitivity tests)	2095	Yes	Temperate cereals, maize, tropical cereals, rice, soy bean, rapeseed, groundnuts, sunflower, oil palm, pulses, potato, cassava, sugar cane, sugar beet, cotton,	Yes

Reference	Project connection	GCMs, emission scenarios, climate projections	Biophysical model (estimation of potential changes in crop yields)	Economic model	Regional scope	CO2 fertilization	Time horizon	Farm-level adaptation measures	Included crops	Global trade connections included
									fruits and vegetables	

Table 2: Overview of results of the studies

The category column is based on the categorization scheme for studies with the structural approach developed by Fernández and Blanco (2015). The categories are as follows: 1 – global study using a general equilibrium model, 2 – global study using a partial equilibrium model, 3 – global study using a Basic Linked System (not part of this review), 4 – regional study using a general equilibrium model, 5 – regional study using a partial equilibrium model, 6 – regional study using a farm level economic model (not part of this review)

Paper	Category	GCM	economic scenario	Other scenario specifi-cation	Time horizon	Results for Europe			
						Regional welfare effect [% of crop sector value added]			
						Direct impacts *	Terms of trade changes *	Efficiency *	total *
Hertel (2010)	1			Central	2030	9	0.5	-1.5	8
				Low productivity		-10	-7	-3	-20
				High productivity		25	5	1	31

Paper	Category	GCM	economic scenario	Other scenario specification	Time horizon	Results for Europe		
Calzadilla (2013)	1	HadGEM 1-TRIP		“All factors”		Regional welfare change wrt baseline [mio US$]		
						Western Europe	Eastern Europe	Total
			A1B		2020s	1248	618	1866
					2050s	13617	-7011	6616
			A2		2020s	1325	538	1863
					2050s	11767	-7797	3970
Roson & van der Mens-brugghe (2010)	1					GDP change from agricultural sector [%]*		
					2100	-0.1		
Eboli et al. (2010)	1					GDP change from agricultural sector[%]*	World prices of agricultural products [% change]	
				1.5°	2050	0.02	3-6	

Paper	Category	GCM	economic scenario	Other scenario specification	Time horizon	Results for Europe			
Bosello et al. (2009)	1		A2		2050	Mediterranean Europe	Northern Europe	Eastern Europe	World prices of agricultural products [% change]*
						GDP change from agricultural sector[%]*			
				1.2°		0.2	0.2	0	
				3.1°		0.5	0.6	-0.7	8-12
						Terms of trade [% change]*			
				3.1°		1.5	4	1.5	
						International capital flows [% change]*			
				3.1°		0.8	6	-2.2	

Paper	Category	GCM	economic scenario	Other scenario specification	Time horizon	Results for Europe				
Bosello et al. (2012)	1		A1B			GDP change from agricultural sector[%]*				World prices of agricultural products [% change]*
						Mediterranean Europe	Northern Europe	Eastern Europe	EU total	

Paper	Category	GCM	economic scenario	Other scenario specifi-cation	Time horizon	Results for Europe				
				1.92°	2050	0.07	0.225	0.15	0.12	2
Bosello et al. (2013)	1		A2 (GDP)		2050	GDP change from agricultural sector[%]* (EU27)$^{+}$		World prices of agricultural products [% change]		
				2°		0.1		2		
				4°		0.1		5.42		
Bosello & Zhang (2005)	1			0.93°	2050	GDP change from agricultural sector[%]	Private Utility Index [% change]	Terms of Trade [% change]	International Capital Flows [% change]	
						0.006	-0.005	-0.048	0.019	
						Results on EU Prices [% change]				
						Rice	Wheat	Cereal Crops	Land	Labor
						-2.311	-1.569	1.976	-0.003	-0.037
Frank et al. (2014)	2	RCP8.5	SSP 2		2050	Total productivity change	Impacts on crop land [% change]	Impacts on production	Impacts on consumption of agricultural	Impacts on prices

Paper	Category	GCM	economic scenario	Other scenario specifi-cation	Time horizon	Results for Europe				
						[% change]***		[% change] ***	goods [% change]***	[% change] ***
		IPSL		LPJmL crop model		-7 to -11	4-9	-3 to -4	-3 to -4	24 to 26
		HadGEM		DSSAT crop model		-9 to -14	6-9	-4 to -7	-3 to -5	25 to 35
Nelson et al. (2014b)	1 & 2	RCP8.5 HadGEM IPSL	SSP 2	2 GCMs, 5 crop models, 10 economic models		Total productivity change [% change]***	Impacts on crop land [% change] ***	Impacts on production [% change] ***	Impacts on consumption of agricultural goods [% change]***	Impacts on prices [% change] ***
					2050 range	-20 to -10	-5 to 30	-12 to 20	-2 to 1	0 to 40
					2050 median	-5	7	2	-1	6
Stevanovic et al. (2015)	2	19 GCMs	A2		2095	Producer surplus [bio US$]*		Consumer surplus [bio US$]*	Agricultural welfare [bio US$]*	
				LPJmL, fixed		188.8 [sd: 256.1]**		-196.2 [sd: 280.9]	-7.4 [sd: 52.5]	

Paper	Category	GCM	economic scenario	Other scenario specifi-cation	Time horizon	Results for Europe					
				trade							
				LPJmL, liberal trade		299.9 [sd: 125.9]		-198.1 [sd: 97.3]		101.8 [sd: 78.9]	
Ciscar et al. (Ciscar, 2009; Ciscar et al., 2011)	4				2085	Southern Europe	Central Europe South	Central Europe North	British Isles	Northern Europe	EU
						Annual household welfare change from agricultural sector [%]					
		HadAM3 h/ HIRHAM	B2	GMT change Europe 2.5°		-0.05	0.06	0.01	-0.09	0.58	0.01
			A2	GMT change Europe 3.9°		-0.37	0.02	-0.05	-0.11	0.59	-0.1
		ECHAM4 -RCA0	B2	GMT change Europe 4.1°		-0.15	-0.01	0.04	0.09	0.56	0.02
			A2	GMT change Europe 5.4°		-1	-0.27	-0.19	0.06	0.72	-0.32
						GDP change from agricultural sector [%]					
		HadAM3 h/ HIRHAM	B2	GMT change Europe 2.5°		-0.13	0.11	-0.02	-0.1	0.81	0.02
			A2	GMT change Europe 3.9°		-0.52	0.06	-0.06	-0.11	0.85	-0.09

Paper	**Category**	**GCM**	**economic scenario**	**Other scenario specifi-cation**	**Time horizon**	**Results for Europe**					
		ECHAM4 -RCA0	B2	GMT change Europe 4.1°		-0.22	0	0.05	0.12	0.76	0.04
			A2	GMT change Europe 5.4°		-1.26	-0.28	-0.17	0.16	1.09	-0.29
Ciscar et al. (2014)	4				2085	Southern Europe	Central Europe South	Central Europe North	British Isles	Northern Europe	EU
						Welfare change [equivalent variation as % GDP]*					
		ECHAM5 (UKMO)	A1B	Reference (GMT change global 3.5°)		-0.4	-0.15	-0.18	-0.05	0.1	-0.2
		ECHAM5 (DMI)	A1B	Reference variant 1 (warmer, drier, 3.9°)		-0.65	-0.2	-0.05	0	0.15	-0.25
		EGMAM2 006	A1B	Reference variant 2 (cooler, wetter, 2.4°)		-0.2	0	0	0	0.15	-0.02
		ECHAM5 .4	E1	2° scenario (2.4°)		-0.3	-0.05	0	0.4	0.2	0
						GDP change [%]*					

Paper	Category	GCM	economic scenario	Other scenario specifi-cation	Time horizon	Results for Europe						
		ECHAM5 (UKMO)	A1B	Reference		-0.65	-0.15	-0.2	-0.05	0.3	-0.25	
		ECHAM5 .4	E1	2°		-0.6	-0.13	0	0.75	0.45	0	
Quiroga & Iglesias (2008)	2		A2		2085	Boreal	Atlantic North	Atlantic Central	Alpine	Continent al	Mediterra-nean North	Mediterra-nean South
						GDP change [%]* +++						
		HadCM3				0.02	0.01	0.01	0.04	0.08	-0.01	-0.03
		ECHAM4 / OPYC3				0.01	0.02	0.01	0.03	0.03	-0.045	-0.09
						Change in per capita utility [%]*						
		HadCM3				0.03	0	0	0.03	0.16	-0.02	-0.03
		ECHAM4 / OPYC3				0.04	0.01	0	0.03	0.02	-0.04	-0.07
						Change in crop prices [%]*						
		HadCM3				-2.8	0.2	-0.1	-3	-2	0.4	1
		ECHAM4 / OPYC3				-4.2	-1.8	0.1	-2.8	0	1.5	2.7

Paper	Category	GCM	economic scenario	Other scenario specification	Time horizon	Results for Europe		
Blanco et al. (2014)	4		A1B		2030	EU agricultural income change [%]	Global producer prices [% change]* (range of crops)	EU production [% change]* (range of crops)
		ECHAM5		With CO_2 fertilzation		-3.4	-2 to -16	-12 to 1
		HadleyCM3		With CO_2 fertilzation		0.5	-11 to 2.5	-13 to 1
		ECHAM5		W/o CO_2 fertilzation			5 to 15	-8 to 0.5
		HadleyCM3		W/o CO_2 fertilzation			9 to 19	-11.5 to 12.5
Shrestha et al. (2013)	4		A1B		2020	Total welfare EU27 [% change]	Agricultural income EU27 [% change]	
		HadCM3 (GMT change Europe 3°)		No adaptation, fixed prices		0	3.3	
				Best adaptation, fixed prices		0	8	
				No adaptation, free prices		0.08	-0.2	
				Best adaptation, free prices		0.02	-0.1	

Paper	Category	GCM	economic scenario	Other scenario specification	Time horizon	Results for Europe	
		ECHAM5 / HIRHAM (GMT change Europe 1°)		No adaptation, fixed prices		0	0.8
				Best adaptation, fixed prices		0	6.8
				No adaptation, free prices		0	-0.2
				Best adaptation, free prices		0.2	-0.3

* results estimated from a figure

** sd = standard deviation

+ country-level results available, also on labor demand and terms of trade

++ range from various model combinations participating in the study

+++ also have results on crop imports/exports, labor and capital price