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RESEARCH ARTICLE

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What role will climate change play in EU agricultural markets? An integrated assessment taking into account carbon fertilization effects

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Abstract

Recent studies point to climate change being one of the long-term drivers of agricultural market uncertainty. To advance in the understanding of the influence of climate change on future agricultural market developments, we compared a baseline scenario for the year 2030 with alternative simulation scenarios that differ regarding: (1) emission scenarios; (2) climate projections; and (3) the consideration of carbon fertilization effects on crop growth. For each simulation scenario, the CAPRI model provides global and EU-wide impacts of climate change on agricultural markets. Results showed that climate change would considerably affect agrifood markets up to 2030. Nevertheless, market-driven adaptation strategies (production intensification, trade adjustments) would soften the impact of yield shocks on supply and demand. As a result, regional changes in production would be lower than foreseen by other studies focused on supply effects.

Additional key words: bio-economic modelling; agricultural market uncertainty; food security.

Abbreviations used: CAPRI (Common Agricultural Policy Regionalized Impact Modelling System); EU (European Union); GCM (General Circulation Models); GHG (Greenhouse Gas); MENA (Middle East and North Africa); NUTS (Nomenclature of Territorial Units for Statistics); RCP (Representative Concentration Pathway); SEA (South East Asia); SSP (Shared Socioeconomic Pathway); WOFOST (World Food Studies).

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Introduction

Agriculture is one of the most sensitive sectors to climate variations since production largely relies on climatic conditions (Adams *et al.*, 1998; Gornall *et al.*, 2010; Araujo-Enciso *et al.*, 2016). Climate change affects crop yields and, therefore, agricultural production and prices. The extent of these impacts is surrounded by several uncertainties linked to the climate evolution in the next decades, future socioeconomic development and the effects of rising CO_2 atmospheric concentration on crop physiology and productivity, referred to as carbon fertilization effect. Understanding the responses of the agricultural sector to alternative scenarios accounting for these uncertainties is vital to evaluate the potential influence of climate change on the future development of agricultural markets.

A number of studies focussing on the effects of climate change on crop yields have shown that while impacts on world food production are limited, geographical differences are significant (Parry *et al.*, 2004; Tubiello & Fischer, 2006). Considering not only biophysical effects but also economic ones, the first attempts to anticipate consequences of climate change on food production and prices concluded that the impacts of climate change on crop yields would

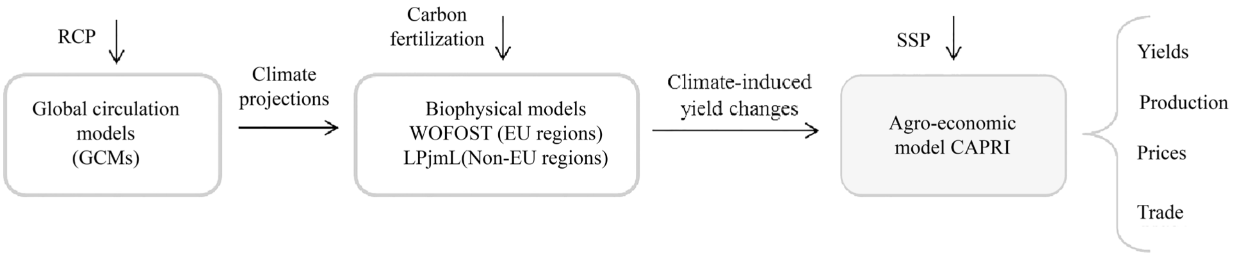

Figure 1. Bio-economic modelling approach. RCP: representative concentration pathway. SSP: share socioeconomic pathway. CAPRI: common agricultural policy regionalized impact modelling system.

be globally diffused through interregional adjustments in agricultural markets (Tobey *et al.*, 1992; Reilly & Hohmann, 1993). Over the last years, other authors have corroborated the important role of trade to counterbalance climate change impacts on crop productivity (Nelson *et al.*, 2010; Calzadilla *et al.*, 2013; Baldos & Hertel, 2015; Fernández & Blanco, 2015).

The release of a new set of climate scenarios eases the comparative assessment of future climate change impacts. These scenarios are based on a plausible combination of the Representative Concentration Pathways (RCP) and the Share Socioeconomic Pathways (SSP) (Kriegler *et al.*, 2012; van Vuuren *et al.*, 2012, 2014; Ebi *et al.*, 2014). The RCPs correspond to four different possible trajectories of future greenhouse gases concentration expressed by the level of possible radiative forcing values in the year 2100 (2.6, 4.5, 6 and 8.5 W/m^2) (van Vuuren *et al.*, 2011). The SSPs describe plausible alternative future socio-economic developments based on different aspects determinants of challenges to mitigation and adaptation: demographics, human development, economy and lifestyle, policies and institutions, technology and environment. Five narratives describe the likely combinations of high or low challenges to adaptation and mitigation: SSP 1 (sustainability), SSP 2 (middle of the road), SSP 3 (fragmentation), SSP 4 (inequality) and SSP 5 (conventional development) (O'Neill *et al.*, 2014).

Several authors have applied these scenarios to assess the effect of climate change on crop yields taking also into consideration uncertainties linked to carbon fertilization effects (Deryng *et al.*, 2014; Rosenzweig *et al.*, 2014). They highlighted different effects on crop yields with and without carbon fertilization. Nonetheless, most economic impact assessments of climate change on agriculture concentrate on analysing uncertainties related to economic models (Nelson *et al.*, 2014; Von Lampe *et al.*, 2014; Delincé *et al.*, 2015) or to different plausible combinations of socioeconomic and emissions scenarios (Wiebe *et al.*, 2015), while omitting crop response to rising CO_2 atmospheric concentration.

In this paper, we assessed the influence of climate change on agriculture in terms of food prices and market balances up to 2030. This work extends the previous literature by exploring economic impacts of climate change both globally and for the main agricultural commodity traders, with particular focus on the European Union (EU), considering the effects of carbon fertilization in crop yields. Furthermore, we analysed the role of trade adjustments to counterbalance climate change effects on crop productivity.

Material and methods

Bio-economic modelling approach

The modelling approach employed in this analysis was based on a combination of biophysical and economic models to assess the impacts of climate change in agricultural markets. Biophysical models simulate climate change effects on crop productivity, incorporating climate projections as well as the degree of carbon fertilization. The projections on future climate are provided by Global Circulation Models (GCMs) based upon RCPs. Climate-induced crop yield changes derived from biophysical models are incorporated into economic models to simulate impacts on production, prices and trade flows based on SSPs (Fig. 1). In this study, we used the agro-economic model CAPRI to assess the impacts of climate change on global and EU-wide agrifood markets in 2030. We refrained from using longer term projections due to their high uncertainty with respect to macroeconomic and agricultural conditions.

The agro-economic model CAPRI (Common Agricultural Policy Regionalized Impact Modelling System) is a partial equilibrium model for the agricultural sector developed to assess the impact of agricultural and trade policies from global- to regional-scale with a focus on the EU (Britz & Witzke, 2014). It is a comparative static and spatial equilibrium model solved by iteration of supply and market modules:

• The supply module consists of a set of regional agricultural supply models, covering all EU regions (NUTS 2 level), Norway, the Western Balkans and

Turkey. This module captures the details of farming decisions as well as the interactions between production activities and the environment. Major outputs of the supply module include crop and livestock activity levels, yields, input use, farm income, nutrient balances and greenhouse gas (GHG) emissions.

• The market module is a global spatial multi-commodity model, where about 50 commodities – including primary and secondary agricultural products – and around 40 trade blocs (individual countries or country groups) are modelled as a constrained system of equations. Major outputs of the market module include bilateral trade flows, market balances and producer and consumer prices for the agricultural commodities and world country aggregates.

Accordingly to the spatial resolution of the CAPRI model, we used more detailed yield projections for EU regions than for the rest of the world. Thus, for EU regions we simulated climate change impacts on productivity using the biophysical model WOFOST (World Food Studies) (Van Diepen *et al.*, 1989; Boogaard *et al.*, 2014). EU crop yield changes were simulated for the year 2030[1] at a 25 km grid resolution for nine of the most produced crops (wheat, maize, barley, rye, field beans, rapeseed, sunflower, sugar beet and potato). The results of the simulations were aggregated to a regional level (NUTS 2) using regional statistics for cultivated crop areas. For more details on the biophysical simulations see Blanco *et al.* (2014).

For non-EU countries, we used crop yield projections from the ISI-MIP modelling initiative[2]. In particular, yield projections from the LPJmL model (Bondeau *et al.*, 2007) were used for the year 2030. These projections are available for the following seven crops: wheat, maize, rice, rapeseed, soybean, sugar beet and sugar cane. Statistics on crop areas were used to aggregate grid-level data to the spatial units of the global CAPRI model (trade blocs).

From the results of these biophysical models, we derived crop yield changes (between 2010 and 2030) for a distinct number of crops, depending on the crop model as mentioned above. To consider all crops within the CAPRI model, yield changes obtained from WOFOST or LPJmL were assigned to those crops not included in these models, based on similarities among crops or crop groups and considering the type of photosynthesis (C3 and C4) similarly to previous studies (Müller & Robertson, 2014).

These crop yield changes were introduced into CAPRI as exogenous productivity shifters. In the case of EU regions, yield changes were explicitly incorporated into the supply module within the regional programming models at the NUTS 2 level, whilst for non-EU regions changes were incorporated into the market module within the supply functions defined for each trade block. CAPRI then provided simulated results about cropland allocation, yields, production, prices and trade for the roughly 60 commodities covered by the model.

Definition of simulation scenarios

Different scenarios were defined to analyse the variability of future agricultural market developments due to uncertainty about the impacts of climate change on crop yields. All scenarios analysed were based on the SSP2, to consider a storyline consistent with the socio-economic developments observed in recent decades.

The baseline scenario in 2030 assumes no climate change (current climate continues in 2030) and takes into account the likely developments in agricultural markets between 2010 and 2030 based on SSP2 socio-economic drivers (on a global to regional scale). For a detailed description of the baseline, see Frank *et al.* (2014).

The simulation scenarios incorporate crop yield shocks according to different climate projections and carbon fertilization effects. Both biophysical models (WOFOST and LJMmL) derived yield changes results using the scenarios presented in Table 1 and explained below:

Table 1. Scenario characterization

Code	RCP	GCM	CO_2 effects
HADGEM2_8.5_CO_2	RCP 8.5	HadGEM2	Simulated
IPSL_8.5_CO_2	RCP 8.5	IPSL	Simulated
HADGEM2_8.5_noCO_2	RCP 8.5	HadGEM2	Non-simulated
IPSL_8.5_noCO_2	RCP 8.5	IPSL	Non-simulated
HADGEM2_4.5_CO_2	RCP 4.5	HadGEM2	Simulated
IPSL_4.5_CO_2	RCP 4.5	IPSL	Simulated
HADGEM2_4.5_noCO_2	RCP 4.5	HadGEM2	Non-simulated
IPSL_4.5_noCO_2	RCP 4.5	IPSL	Non-simulated

RCP, representative concentration pathway; GCM, global circulation model.

[1] To represent crop productivity in 2030, we used the average of a period of 20 years around the year 2030. Similarly, for 2010 we used the average 2000-2020.

[2] Grid data are available for download from PIK (http://esg.pik-potsdam.de/esgf-web-fe/)

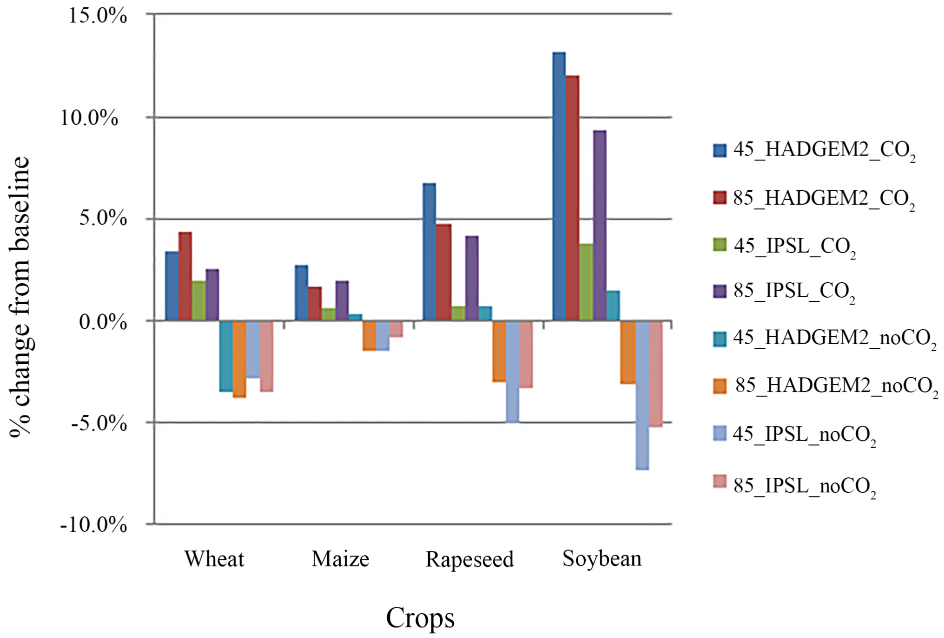

Figure 2. LPJmL-simulated global yields changes in 2030 for wheat, maize, rapeseed and soybean under different simulation scenarios.

1) Emission scenarios: two RCPs were selected in the development of this analysis, the RCP 4.5 (targeting stabilization at 4.5 W/m^2 after 2100) and the RCP 8.5 (with a radiative forcing of 8.5 W/m^2 by 2100 and a subsequent upward trend). The RCP 4.5 was chosen as we considered this pathway to be the most likely level by the year 2030, whilst the RCP 8.5 represented an extreme pathway.

2) Climate projections: two Global Circulation Models (GCMs) were used for each RCP, HadGEM2-ES (Hadley Centre, UK Meteorological Office) and IPSL-CM5A-LR (Institute Pierre-Simon Laplace, France). These two GCMs were selected because they provide data for the type of biophysical models employed in this study. Also, using more than one GCM allows for taking into account uncertainty linked to future climate projections, especially with regard to precipitation patterns at the regional level (IPPC, 2013).

3) Carbon fertilization effects: the crop simulation models were run with and without carbon fertilization effects on crop yields. Carbon fertilization refers to the effects that elevated atmospheric CO_2 concentrations have on crop physiology. These differ among species depending on the metabolic pathway performed to fix carbon during the photosynthesis process (C3 and C4). The enzyme involved in the CO_2 fixation (Rubisco) is not CO_2-saturated in C3 plants (*e.g.* wheat, soya, rapeseed) while is saturated in C4 plants (*e.g.* maize, sorghum, sugarcane). Therefore, increasing atmospheric CO_2 concentrations results in higher CO2 fixation and biomass accumulation in C3 plants, but has no additional effects on crop physiology in C4 plants. The consequences of carbon fertilization on crop yields have been extensively studied (Gifford, 2004; Ainsworth & Long, 2005; Tubiello *et al.*, 2007). Whilst most studies conclude that carbon fertilization has a positive effect on crop yields under idealized conditions, the real effect on crop productivity in the field remains an issue for further research as little is known about the interaction of elevated CO_2 concentrations with other factors such as crop diseases or nutrient availability.

Results

In order to assess the influence of climate change on agriculture in terms of food prices and market balances, the baseline (which assumes current climate in 2030) was compared with the different simulation scenarios outlined above for the year 2030. The analysis focused on climate change impacts on production globally and for the main traders for wheat, maize, soybean and rapeseed. We focus at these four products because they are four of the main commodities in international trade and are significantly important in terms of trade in the EU. To evaluate the role of trade adjustments, we particularized it for wheat market in the EU.

Climate-induced effects on global agricultural production and prices

Results from biophysical models showed variations in crop yields as a consequence of climate change. Overall, global average yields increased when CO_2 effects are considered and decreased when carbon fertilization was left out of the equation. An exception of such findings is the HADGEM2 scenario with RCP 4.5 and without CO_2 effects, where global yields for maize, rapeseed and soybean rise slightly (Fig. 2). These global results may reflect the regionalisation of production of these crops and, therefore, their sensitivity to climate projections.

Results provided by the CAPRI model showed how significant crop yield changes trigger moderate impacts in production (equivalent to a -1.5% to +2.5%), accompanied by big impacts on prices (ranging between -20% to +10%). Global prices changes had in turn an effect in crop production by softening the final impact of climate-induced yield changes (Figs. 3a and 3b).

Focussing on production (Fig. 3a), carbon fertilization determined the direction of the impacts for maize and rapeseed: production increased with full fertilization and the opposite applies without carbon fertilization. Wheat also followed this pattern with the exception of scenario HADGEM2 RCP 4.5 without CO_2 effects that presented a modest increase in production. Soybean production increased in all scenarios except for IPSL without carbon fertilization. Despite these differences, production for all crops increased when carbon fertilization effects were considered.

With regard to the differences between the scenarios based on the two RCP (4.5 and 8.5), the extreme pathway did not appear, surprisingly, to yield the highest production levels in the case of full carbon fertilization. This is because GHG concentrations projected for the two RCPs (4.5 and 8.5) were similar in 2030. This is evident in the case of the HADGEM2 projection, but does not apply to the IPSL model. The variability of the reported results corroborates therefore the need to use several climate models, as well as different RCPs, to comprehend and unveil uncertainty.

With respect to prices, Fig. 3b shows that uncertainty was significantly higher for oilseeds (rapeseed and soybean) than for cereals (wheat and maize). Overall, the price of crops appeared to fall (rise) when production increased (decreased), although this was not always the case for soybean. A possible explanation is the low elasticity of supply and demand for most agricultural commodities.

Climate-induced effects on agricultural production for main traders

Global average yield changes presented in Fig. 2 conceal regional differences as shown in Table S1 [suppl.]. Carbon fertilization led to global yield increases for all crops, with disaggregated results showing varied effects. In order to address the different effects of climate change throughout the world, we studied the variations in production of the main exporters and importers for the selected crops (wheat, maize, rapeseed and soybean).

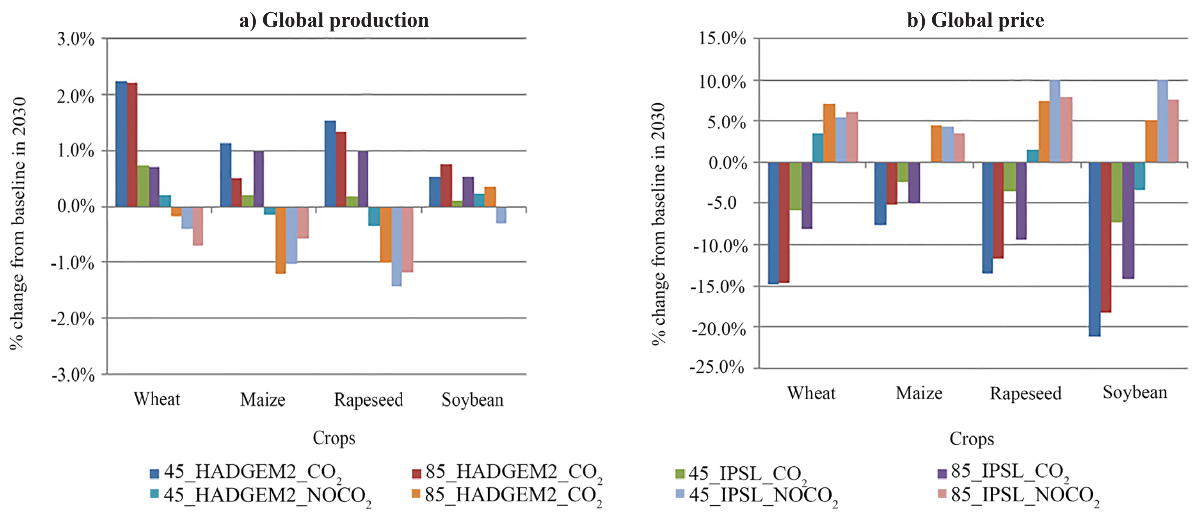

Figure 3. Changes in a) global production and b) global prices in 2030 for wheat, maize, rapeseed and soybean under different simulation scenarios (% change relative to baseline values by 2030). Source: CAPRI model.

The major net exporters of wheat are the European Union (EU-28), the USA, Canada and Australia and New Zealand, with the major importers being the Middle East and North Africa (MENA)[3], South-East Asia (SEA)[4], Sub-Saharan Africa (SSA) and Brazil (BRA). As shown in Fig. 4a, a common feature of wheat is that overall a major increase or decrease in production in these regions is caused by changes of the same sign in yields (Table S1 [suppl.]) rather than by global price variation (Fig. 3b), which might be a consequence of an inelastic supply. Canada presents the most significant variability in production, ranging from -9% in the IPSL projection without the CO_2 effect and with a RCP 4.5 to +13% in the HADGEM2 scenario with the CO_2 effect and a RCP 4.5. In the case of the EU, we observe that an increase in production is related to a RCP 4.5, whereas a decrease is caused by the RCP 8.5, irrespective of carbon fertilization.

In the case of maize, the key exporters in the world are the USA, Argentina and Brazil. The main importers that we identified are South and Central America (OSA) -excluding Brazil and Argentina -, SEA and MENA. As

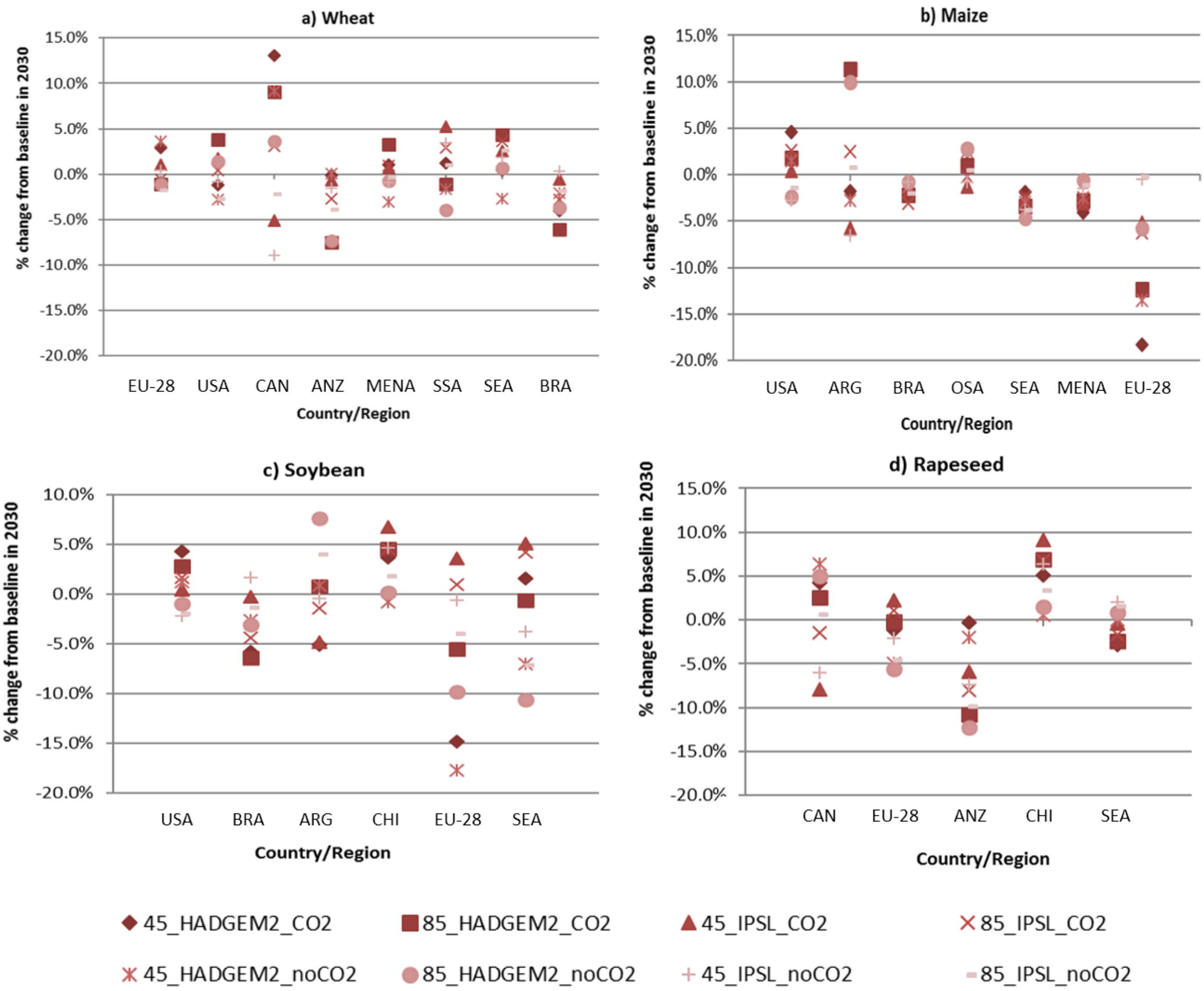

Figure 4. Production changes for the major country/region traders of a) wheat, b) maize, c) soybean and c) rapeseed in 2030 under different simulation scenarios (% change relative to baseline values by 2030). Country/ Regions: European Union (EU-28), United States (USA), Canada (CAN), Australia and New Zealand (ANZ), Middle East and North Africa (MENA), Sub-Saharan Africa (SSA), South East Asia (SEA), Argentina (ARG), Brazil (BRA), Other South and Central America (OSA), China (CHI). Source: CAPRI model.

[3] Middle East and North Africa (MENA) includes Middle East, North Africa and Turkey.
[4] South-East Asia (SEA) consists of Indonesia, Malaysia, South Korea, Vietnam, Thailand, Japan, Taiwan.

our focus was the EU, we also included it although it is not among the main traders of this product. Following the pattern of wheat, maize production also appeared to be more influenced by yields than by global prices (Table S1 [suppl.] and Fig. 3b), with Argentina, the USA, and EU-28 having the biggest variability in production (Fig. 4b).

With regard to soybean, the main exporters are the USA, Brazil and Argentina, while the major importers are the China, EU-28 and SEA. As shown in Fig. 4c, different scenarios produce extreme values: the highest positive variation was observed for a 4.5 RCP, except in Argentina where the highest change coincided with 8.5 RCP. Taking into account yield changes (Table S1 [suppl.]), these were significantly higher in the case of Argentina and USA when carbon fertilization effects were taken into account. This suggests that there was a price-related adjustment in production (Fig. 3b) since the world soybean market price increased when CO_2 effects were disregarded.

In the case of rapeseed, Canada, EU-28 and Australia and New Zealand were the main exporters, whereas China, EU-28 and SEA were the main importers. Fig. 4d highlights that, contrary to expectations, rapeseed production in Canada increases most when carbon fertilization was not considered even though that major increases in yields were observed in scenarios with CO_2 effects. This could be explained by taking into account changes in market prices, as illustrated in Fig. 3b, where rapeseed prices rose when CO_2 effects were not taken into account.

Results of this analysis demonstrated the negative impacts of climate change in some regions, which were found to suffer reduction in production even when carbon fertilization was considered (*e.g.* wheat in Australia and New Zealand and maize in Brazil). They also showed the effects of prices in driving reductions in production despite climate-induced positive yield changes (*e.g.* soybean in Brazil). The analysis at disaggregated level highlights then that global projections of production mask regional disparities. These were not only determined by regional changes in yields, but also by global price variations. Whilst the production of wheat and maize, considered staple crops, followed the pattern of regional changes in yields, soybean and rapeseed production varied significantly with global prices.

The role of trade adjustments

To illustrate how trade adjustments counterbalance the effects of climate change on production, we concentrated on the wheat trade, considering the EU and its trading partners. The analysis was focussed for one GCM, HADGEM2, with and without CO_2, for a 4.5 and 8.5 RCP, since it highlights sizeable variations in global production (Fig. 3a).

As explained above, wheat production in the EU increased when considering RCP 4.5 with and without CO_2 but decreased for RCP 8.5 (Fig. 4a). Surprisingly, increased production results in import increases, whilst exports reduce, especially for those scenarios that consider carbon fertilization (Fig. 5).

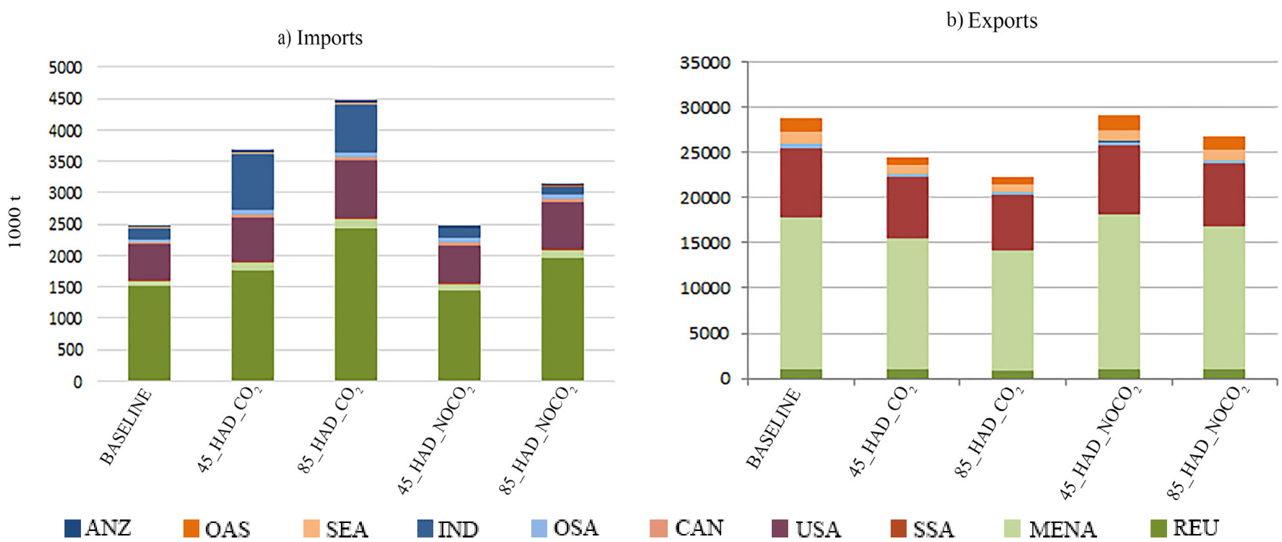

Figure 5. Wheat trade in the European Union in 2030 by trading partner under different simulation scenarios: a) imports and b) exports. Country/Regions: Australia and New Zealand (ANZ), Other Asia (OAS), South East Asia (SEA), India (IND), Other South and Central America (OSA), Canada (CAN), United States (USA), Sub-Saharan Africa (SSA), Middle East and North Africa (MENA), Rest of European Union (REU). Values in thousand tons. Source: CAPRI model.

This remarked decline in wheat exports was related to a drop in the price of this product in scenarios considering CO_2 effects (Fig. 3b), but also to an increase in wheat demand. Therefore, a significant increase was observed in the use of wheat for animal feed, which varied between 4% and 16% for all scenarios with respect to the baseline, whereas human consumption rose by only 0.01-0.06%. As shown in Fig. 6, this change in wheat demand is linked to maize demand since wheat partially substitutes maize, whose production in the EU is negatively affected by climate change.

In response to the increase in feed demand, the EU-28 increased wheat imports and reduced exports (Fig. 5). The significant decline in exports from EU-28 to MENA and SSA was compensated mainly by an increase in imports in these regions from Canada (Table S2 [suppl.]).

Discussion

This paper explored the effects of climate change on agricultural markets both globally and for the main traders, with a focus on the EU, up to 2030. To account for uncertainty surrounding climate change effects, a bio-economic approach was applied analysing different scenarios that differ with respect to: (1) the climate projection (HadGEM2-ES and IPSL-CM5A-LR), (2) RCP (4.5 and 8.5) and (3) the influence of carbon fertilization effects.

Similar to Deryng *et al.* (2014) and Rosenzweig *et al.* (2014), we also observed that the impacts of climate change on crop yields varied widely across regions and crops depending on RCPs and carbon fertilization effects. On the one hand, the RCP determined the magnitude of the climate change impacts but the highest range of variation was not always related to the extreme RCP. This was because larger uncertainties for RCP 8.5 emerge at the end of the century, while in the coming decades observed differences between RCP 4.5 and RCP 8.5 were reduced (Rosenzweig *et al.*, 2014; Wiebe *et al.*, 2015). On the other hand, the carbon fertilization effect influenced the direction of impacts in such way that when it was not considered yields decreased. Results showed that the highest range of uncertainty corresponded to rapeseed and soybean because of the regional concentration of these productions that make these crops more sensitive to climate projections. The lowest range was observed for maize due to the limited response of this C4 crop to the carbon fertilization effect. Global average in yield changes hided geographical differences, showing that the effects of carbon fertilization could counterbalance negative climate-induced productivity changes in high latitudes, whilst it was not always the case in medium and low latitudes.

Changes in crop prices in response to yield changes soften the impacts of climate change on agricultural production at global level (Nelson *et al.*, 2010; Wiebe *et al.*, 2015) in such a way that global changes in yields between -8% and 12% results in changes in production of -1.5 to 2.5%. Focussing on the main producer regions, results showed that Canada and the USA would be the regions most positively affected by climate change, whilst Australia and New Zealand and Brazil would be most negatively impacted. In the case

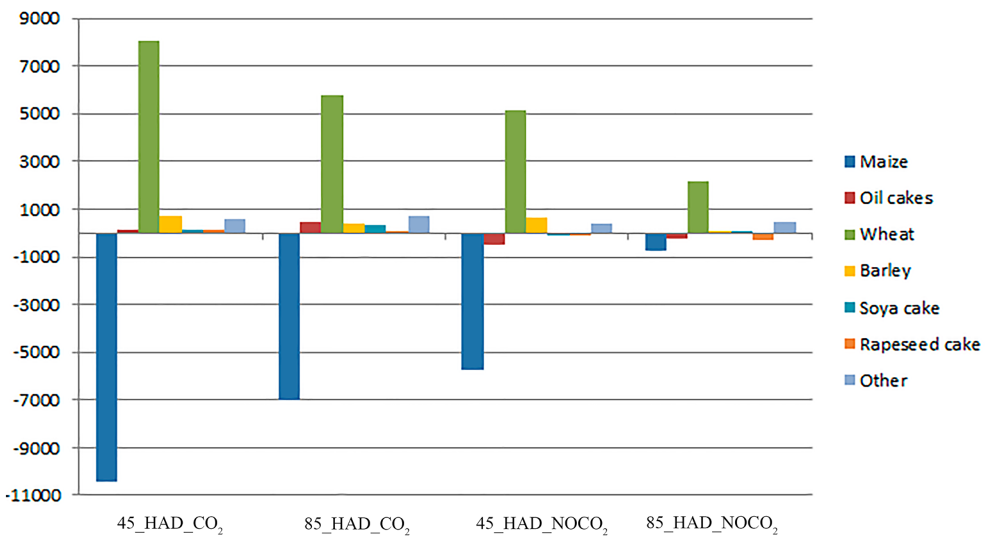

Figure 6. Feed use in European Union by product in 2030 under different simulation scenarios (absolute change relative to baseline by 2030). Values in thousand tons. Source: CAPRI model.

of the EU, production decreased for maize, soybean and rapeseed while increasing for wheat.

The diverging effect of climate change on production across regions is counterbalanced by trade (Tobey *et al.*, 1992; Reilly & Hohmann, 1993; Baldos & Hertel, 2015). Considering wheat production, the EU generally shows an increase in both production and consumption that leads to a reduction of exports to its main trading partners. This reduction is compensated by exports from Canada and the USA. Therefore, trade can act as an adaptation strategy to cope with climate change impacts on agriculture throughout the world.

It is important to highlight several limitations in this study with regard to bio-economic modelling approach. First, biophysical models omit many restricting factors such as extreme weather events or changes in diseases prevalence. Second, the economic model includes several assumptions with regard to macroeconomic environment and behavioural parameters over the long run (*e.g.* price elasticities), as well as simplify diversity across farms and regions. Third, adaptation strategies to climate change, as for example irrigation application or the implementation of adaptation policies, were not taken into account.

In conclusion, assessments of climate change impacts on agriculture need to consider not only biophysical effects on crop yields but also economic impacts in order to take into account market-driven adaptation strategies. Furthermore, considering different climate change scenarios enables to account for the range of uncertainty linked to the effects of climate change. In this sense, results show that carbon fertilization effect is a key factor on the impact of climate change on agriculture. Therefore, despite the controversial results of previous experimental studies, our study suggests that the carbon fertilization effect should be taken into account in bio-economic assessments to evaluate the whole range of variability of climate effects on agriculture.

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