European Commission

JRC TECHNICAL REPORT

Analysis of climate change impacts on EU agriculture by 2050

JRC PESETA IV project – Task 3

Jordan Hristov, Andrea Toreti., Ignacio Pérez Domínguez, Franciscus Dentener, Thomas Fellmann, Christian Elleby, Andrej Ceglar, Davide Fumagalli, Stefan Niemeyer, Iacopo Cerrani, Lorenzo Panarello, Marian Bratu

2020

Joint Research Centre

EUR 30078 EN

Contact information
Name: Ignacio Pérez Domínguez
Address: Joint Research Edificio Expo, C/ Inca Garcilaso 3, 41092 Seville, Spain.
Email: Ignacio.perez-dominguez@ec.europa.eu
Tel.: +34954488421

EU Science Hub
https://ec.europa.eu/jrc

JRC119632

EUR 30078 EN

PDF ISBN 978-92-76-10617-3 ISSN 1831-9424 doi:10.2760/121115

Luxembourg: Publications Office of the European Union, 2020

How to cite this report: Hristov, J., Toreti, A., Pérez Domínguez, I., Dentener, F., Fellmann, T., Elleby C., Ceglar, A., Fumagalli, D., Niemeyer, S., Cerrani, I., Panarello, L., Bratu, M., *Analysis of climate change impacts on EU agriculture by 2050*, EUR 30078 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-10617-3, doi:10.2760/121115, JRC119632.

Contents

Executive summary

The 2013 EU strategy on adaptation to climate change aims at contributing to a more climate-resilient Europe. However, there are still large gaps in understanding and characterising climate impacts in Europe and how impacts in the rest of the world could affect Europe. This report provides quantitative modelling-based results from biophysical and agro-economic models as part of the PESETA-IV (Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis) project. We analyse climate change projections for 2050 considering the Representative Concentration Pathway (RCP) of 8.5 W/m^2 (with corresponding global warming levels ranging between 1.6 ºC and 2.7 ºC compared to pre-industrial levels), as well as for 1.5 °C and 2 °C warming conditions. Results show that climate change will pose a threat to global food production in the medium to long term, and that Europe will also be affected. Forced by the projected changes in daily temperature, precipitation, wind, relative humidity, and global radiation, grain maize yields in the EU will decline between 1% and 22%. In addition, wheat yields in Southern Europe are expected to decrease by up to 49%. However, in Northern Europe some of the negative productivity effects caused by climate change may be partially offset by higher levels of atmospheric CO_2 concentrations and changing precipitation regimes. Losses, especially in Southern Europe may be reduced by tailored adaptation strategies; e.g. changing varieties and crop types, increasing and improving irrigation practices for certain crops and when economically feasible. However, limitations on sustainable water abstraction levels could become a barrier to increase irrigation levels, specifically in the Mediterranean countries (particularly Spain, Portugal, Greece, Cyprus, Malta, Italy and Turkey) where duration of water scarcity under global warming are projected to intensify. As large negative climate change impacts on productivity outside of the EU are estimated, large market spill-over effects will push up production in both Northern and Southern Europe through higher demand for some agricultural commodities outside of EU, resulting in higher producer prices. This, in turn, may benefit farmers' income and have positive effects on the EU's agricultural commodity exports. However, other limiting factors (not all fully integrated into the used modelling system yet), such as increasing water shortage in Southern Europe (Task 10) and constraints on the expansion of irrigation, increasing impacts of heatwaves and droughts, consequences of reduction of nutrient use due to environmental and climate mitigation constraints, need to be further evaluated.

1 Introduction

The PESETA-IV (Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis) project provides quantitative modelling-based support to European Commission services on the impacts of climate change in the EU. Estimations of climate change impacts are essential to design adaptation and mitigation policies to minimise the negative effects of climate change and maximise the beneficial ones. As in the previous phases of the PESETA project, PESETA II (European Commission, 2014) and PESETA III (European Commission, 2018a), PESETA IV uses a three-stage approach: (1) bias-adjustment of selected regional climate model simulations in Europe, (2) biophysical impact modelling to estimate the sectorial impacts, and (3) model-based economic evaluations across multiple sectors of the estimated impacts. Compared to earlier PESETA projects, PESETA-4 benefits from some key modelling improvements in the biophysical modelling with respect to soil-crop interactions, the representation of the CO_2 related processes, the crop calibration, and a wider range of climate model scenarios. The economic evaluation for the first time includes a global climate perspective, profiting from the availability of a range of global crop-model climate change simulations. This report provides an integrated overview of biophysical (crop) modelling and agriculture economic modelling results.

2 Methodology

2.1 Biophysical crop modelling

The crop modelling approach chosen for PESETA IV takes advantage of a new modelling framework developed to deal with the high computational demand of high-resolution regional climate model simulations and address some of the issues identified in the prior PESETA III project, especially on the parametrised crop responses to elevated atmospheric CO_2 concentrations. This innovative modelling environment builds on the WOrld FOod Studies (WOFOST) crop model, as used and calibrated in the MARS crop yield forecasting system (MCYFS). This system is operationally used to provide end-of-season crop yield forecasts for Europe and neighbouring regions, and contributes to the global agricultural market information system (AMIS).

Ten EURO-CORDEX regional climate model simulations at a spatial resolution of approximately 12 km were selected to estimate climate change impacts under the mid-range mitigation emission scenario (RCP4.5) and the high-end emission scenario (RCP8.5). Gridded bias-adjusted daily temperature and precipitation from Dosio (2016) were used, together with other meteorological variables (e.g. wind, relative humidity, global radiation), as input to the crop model and to obtain yield estimates for the 21st century (until 2080) to be compared with the historical period (1981-2010). The simulations include the main annual crops grown in Europe: wheat, grain maize, barley, sunflower, winter rapeseed and sugar beet. In this report we focus on WOFOST results for wheat and grain maize, since the results are more robust due to availability of observational crop data allowing us to better calibration. The simulations are based on the assumptions of specific agro-management conditions and additionally integrate some simplified adaptation options.

Water limitation effects are evaluated by simulating both fully-irrigated (potential) and rain-fed conditions. As irrigation is an important agro-management option, differences in rain-fed and fully-irrigated simulation results provide information on the potential benefits of keeping the current irrigation infrastructure and installing additional capacity. It also provides insights for regions (in particular, Southern Europe, see Task 10 for details), where, due to depletion of groundwater extracted for irrigation or intensified and longer water scarcity due to global warming, future irrigation may become impracticable. However, these limitations are not quantified in the current analysis. The other tested adaptation strategies include changing sowing dates and crop varieties; practices that farmers to some extent will endogenously adopt as soon as new varieties (with better performance in terms of yield, quality and resistance to unfavourable climate conditions) enter the markets.

Several key-agronomic processes are not yet included in the current modelling framework (See Table 1). For instance, nutrient limitations are not considered here, as in most of Europe crops are (more than) sufficiently fertilized. This omission may become a larger issue when assessing ambitious climate mitigation scenarios that require substantial nutrient limitations. While the effects of drought events are integrated into the modelling system, heat stress effects in the critical plant-growth phase of flowering and grain filling are only partially considered, as the impacts of warm temperature extremes at anthesis are not represented. In addition, heavy rainfall conditions are not accounted for at all. Negative impacts of over-wet conditions, and biotic stresses ('pest and diseases') are not included, as reliable parameterizations are not yet available. Existing widespread as well as emerging pests in the EU may cause severe losses at some crops with rising temperatures. All these missing factors may lead to an underestimation of climate change impacts on agriculture; however, adapted agro-management practices may help in counterbalancing those negative impacts. In the coming years, efforts in crop modelling development should therefore go towards better representation of climate extremes and biotic stresses as well as dynamic locally adapted agro-management practices.

Projections of future atmospheric CO_2 concentrations from IPCC 2013 according to the RCP8.5 and RCP4.5 scenarios are used to run the crop growth model.

2.2 Agro-economic modelling

For the agro-economic analysis, a similar approach is followed in here as in PESETA III (Pérez Domínguez and Fellmann, 2018), but extending the analysis domain from Europe to global. The economic impacts of the biophysical yield changes on production, land use, consumption, income, prices and trade in EU by 2050 are simulated using the Common Agricultural Policy Regionalised Impact (CAPRI) modelling framework (www.capri-model.org). The CAPRI model is a partial equilibrium, large-scale economic, global multi-commodity, agricultural sector model (Britz and Witzke, 2014). The projected economic impacts are analysed in a comparative-static framework where the simulated results are compared to a baseline scenario that is calibrated on the Agricultural Outlook published by the European Commission (European Commission, 2017). This baseline socio-economic scenario considers by 2050 a Shared Socioeconomic Pathway 2, a 'middle of the road' world emerging from trends following historical patterns (Riahi et al., 2017).

Figure 1 displays the planned and realized integration between the biophysical and agro-economic models. It can be noticed that the initial idea was to use the simulated yield effects by the EURO-CORDEX regional climate models in CAPRI.

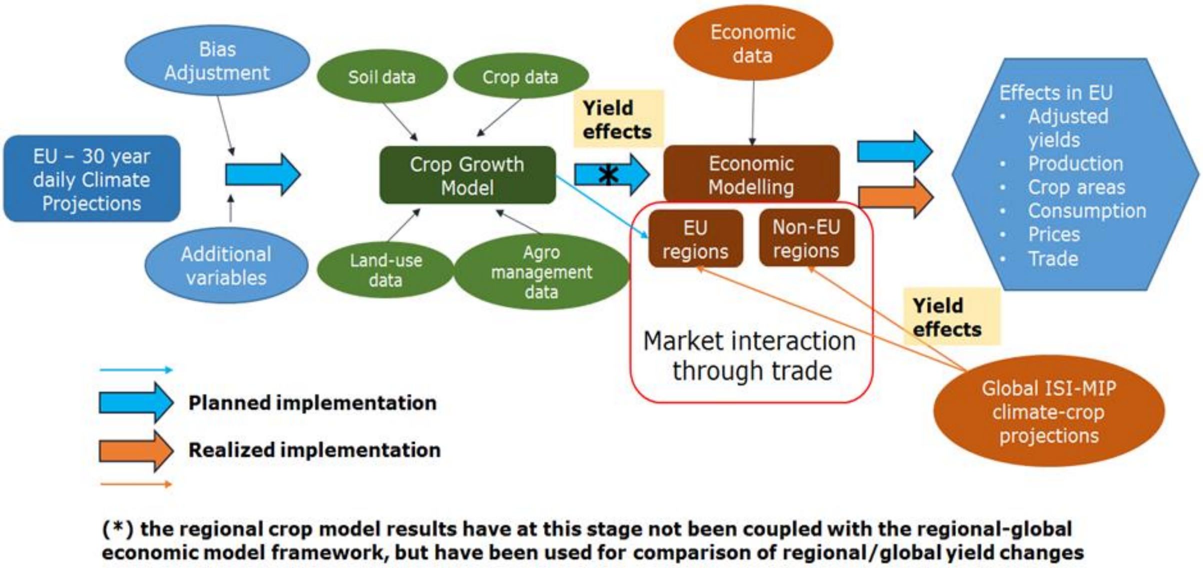


Figure 1. Information flow between biophysical and agro-economic models in PESETA IV.

Source: own illustration

However, the approach followed for the biophysical crop modelling needs to be modified for the agro-economic analysis, because yield projections from the EURO-CORDEX regional climate models used in section 2.1 cover only Europe, a limitation already present in PESETA III. Without taking into account explicit climate change effects in the other world regions, the economic response of global agricultural markets and the consequences for European agro-economic effects cannot be assessed appropriately, as this may lead to both under- or overestimation of the EU agro-economic effects. Since agricultural markets are globally connected via world commodity trade, it is necessary to consider consistent biophysical yield shocks in EU and non-EU countries (from global climate model simulations) to feed our agricultural economic model. Thus, we used the simulations provided by the Inter-Sectoral Impact Model Inter-comparison Project (ISI MIP) Fast-Track simulation database (https://www.isimip.org/). With this approach (orange arrows in Figure 1), we were able to quantify consistently the economic spill-over effects of climate change impacts globally for Europe through changes in agricultural commodity trade (red area in Figure 1), which is one of the novelties of PESETA IV. The ISI-MIP Fast-Track simulation database provides yield changes per region and crop over the period 2011 to 2100, relative to the average of historic 30-year period (1981-2010), taking into account interactions between five General Circulation Models (GCMs) and seven Global Gridded Crop Growth Models (GGCMs) . The ISI-MIP Fast-Track simulation database provides yield changes per region and crop over the period 2011 to 2100, relative to the average of historic 30-year period (1981-2010), taking into account interactions between five General Circulation Models (GCMs)[1] and seven Global Gridded Crop Growth Models (GGCMs)[2]. The ISI-MIP regional crop-specific yields also take into account the limitation of water availability as WOFOST, separating irrigated and rain-fed agricultural production. However, in the CAPRI version used for this project, yields are not separated and the ISI-MIP data had to be aggregated defining an average yield by combining both the irrigated and rain-fed yields with the total irrigated and rain-fed areas in the CAPRI world regions considered. In addition, it should be noted that the agricultural management options in the GGCMs differ from the ones in CAPRI. In some of the

---

[1] HADGEM2-ES (Jones et al. 2011), IPSL-CM5A-LR (Dufresne et al. 2013), MIROC-ESM-CHEM (Watanabe et al. 2011), GFDL-ESM2M (Dunne et al. 2013a; Dunne et al. 2013b), NorESM1-M (Bentsen et al. 2013; Iversen et al. 2013).

[2] EPIC (Williams 1995), LPJmL (Bondeau et al. 2007; Müller and Robertson 2014), pDSSAT (Jones et al. 2003; Elliott et al. 2014), PEGASUS (Deelman et al. 2015), LPJ-GUESS (Smith et al. 2001), GEPIC (Liu et al. 2007), IMAGE (Alcamo 1994).

GGCMs the management decisions (for example fertilizer application) are fixed by the historical average for all future years (i.e. no adaptation), whereas in CAPRI they depend on the input prices or the yield changes due to climate change (Table 1). As in the WOFOST biophysical modelling, extreme events and biotic stresses were not considered in the ISI-MIP simulations. Given the combination of five GCMs and seven GGCMs, we simulated 35 yield shock scenarios with CAPRI, focusing on yield changes ("shocks") in 2050 (compared to 1981-2010) for five crops: wheat, barley, grain maize, rice and soya. The yield shocks in the EU regions were added to the baseline projected yields in the year 2050, which only considers economic and technology-driven yield changes. For non-EU regions it was assumed that production changes according to the yield shocks, as non-EU yields are not specifically reported in CAPRI.

Table 1. Summary of features included in the models

	ISI-MIP GGCMs	WOFOST	CAPRI
CO_2 fertilization	yes	yes	no
no CO_2 fertilization	yes	yes	yes
water availability	yes	yes	no
management practices	fixed to historical averages	endogenous	endogenous
nutrient limitations	no	no	no
extreme events	no	partially	no
biotic stresses	no	no	no

Similar to the other sectoral analyses done in PESETA IV, simulations consider the Shared Socio-Economic Pathway 2 (SSP 2)[3], along with the RCP8.5 and assume no enhanced yield from CO_2 fertilization. The economic analysis was based on global ISI-MIP crop-model/climate scenarios, which did not include the potential yield increases from elevated CO_2 levels. While the general effect of CO_2 on crop yields (e.g. wheat) is now well understood, the effective impact will strongly depend on other management practices and climatic conditions, which are much less well understood in many other regions of the world. The generally larger uncertainties in other world regions, included in the ISI-MIP global simulations, did not justify inclusion of CO_2 effects in that modelling framework, although it may be included in future simulations. The effects of elevated atmospheric CO_2 can be substantial in Europe (Section 3.1) and other developed world regions where crop growing conditions are optimised, but high uncertainties remain in developing regions, where several yield-limiting factors (e.g. nutrients, water, management factors) may play a key role. In addition, the influence of extreme climate events may also influence the CO_2 fertilization yield effect. Future global climate-biophysical model ensembles are expected to include this extreme climate dimension, which will allow for a more accurate impact analysis.

[3] GDP and population projections for 2050 used by CAPRI are in line with the 2015 Ageing Report used in PESETA IV (European Commission 2015).

3 Results

3.1 Biophysical projected yield changes

In this section, we show the main results obtained from the RCMs projections analysed for a 20-year period when the mean global temperature increases reach 1.5 °C and 2 °C. In the ten RCP8.5 model realisations the central year of these two periods ranges from 2018 to 2029 for the 1.5 °C warming conditions, and from 2030 to 2044 for the 2 °C global warming conditions.

While other crops were also modelled and taken into account in the global crop yield projections used in CAPRI, in the discussion below we focus on the two most important crops (grain maize and wheat), which display rather different spatial responses to projected climate change. Results are presented separately for Northern Europe and Southern Europe (Annex 1).

3.1.1 Grain maize

Grain maize is projected to be the most affected crop by climate change in Europe. Under fully irrigated conditions, substantial yield reductions are estimated for most producing countries, being more severe in Southern Europe in all scenarios. For the 2 °C warming conditions (which under the RCP8.5 is reached in the 2030s/2040), Northern Europe is projected to experience mean yield decreases ranging from -1% to -14%; while larger decreases (-4% to -22%) are projected for Southern Europe. The benefits of limiting global warming to 1.5 ºC are clearly visible, with fewer regions exceeding yield losses larger than 10%. Nevertheless, overall patterns of yield losses and gains are similar for the two time periods. Positive changes, but with low agreement among climate model realisations, are projected in a few regions of Northern Europe (with somewhat larger areas in the 1.5 ºC warming scenario), resulting in 5% yield gains around 2050 in the Netherlands and Lithuania. As grain maize is in most of Europe an irrigated crop, these simulations assume that the full irrigation infrastructure will stay in place and sufficient water will be still available. If this were not the case, under rain-fed conditions, a collapse of the European maize production around 2050 is projected, with yield decreases larger than 23% in all the EU countries and exceeding 80% in some Member States such as Portugal, Bulgaria, Greece and Spain. Therefore, in regions with unsustainable water use (i.e. using ground water instead of renewable water) and where projected precipitation significantly decreases, maize production will no longer be viable. Tested adaptation strategies (e.g. changing sowing dates and sown variety to avoid heat stress and drought conditions, not shown) will not be sufficient to cope with negative impacts of climate change. Breeding new varieties more resistant to both drought and heat stress and having the same yield potential might contribute to partially alleviate the estimated impacts of climate change (e.g. Cairns et al. 2013), but its feasibility as an adaptation strategy for the future of the European agriculture must be investigated. A comprehensive assessment of the impacts of water-limitations would require a modelling framework coupling crop growth, hydro-dynamic and economic models. In the modelling system used in this section, there is no hydro-dynamic component, and the crop model assumes static (i.e. not changing in time) land-use and water-availability (i.e. unrestricted water for irrigation). Testing more complex adaptation strategies, with potentially larger benefits, would require the integration of dynamic agro-management modelling in the crop growth model which is at the moment still in the early phase of development.

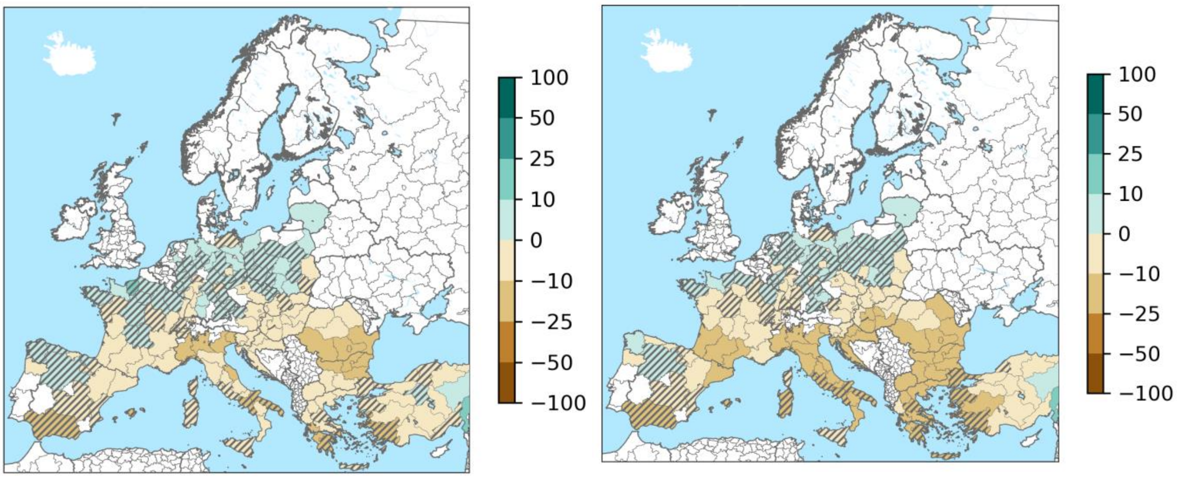


Figure 2. Ensemble mean changes of grain maize yield (% relative to the historical period) projected under the RCP8.5 for 1.5 oC (left panel) and 2 oC (right panel) warming conditions, and assuming irrigated conditions. Hatching denotes areas with low models' agreement (i.e. less than 66% of models agree in the sign of estimated changes).

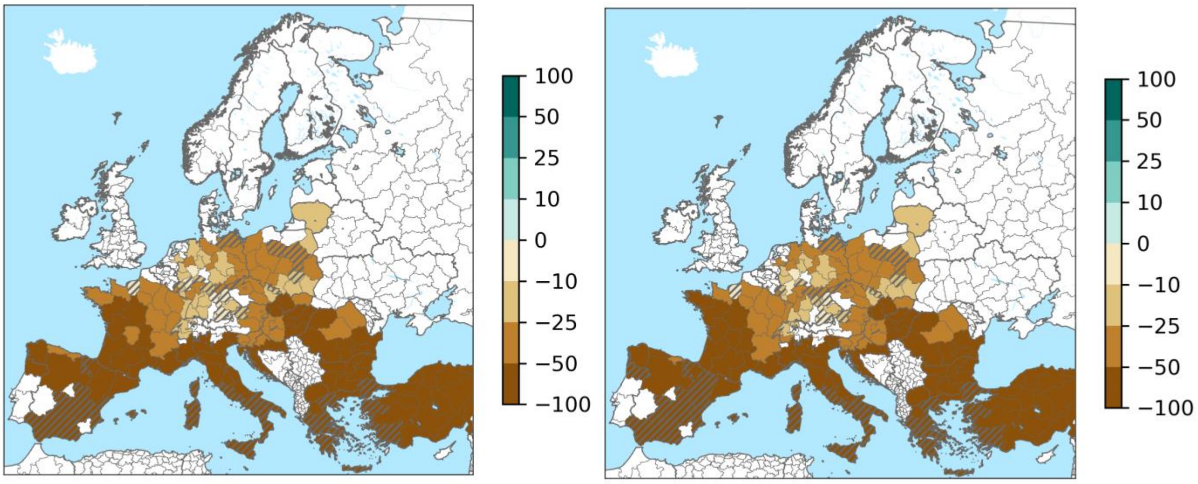


Figure 3. Ensemble mean changes of grain maize yield (% relative to the historical period) projected under the RCP8.5 for 1.5 °C (left panel) and 2 °C (right panel) warming conditions, assuming that no irrigation will be possible (i.e. rain-fed). Hatching denotes areas with low models' agreement (i.e. less than 66% of models agree in the sign of estimated changes).

3.1.2 Wheat

For wheat yield changes, there are large uncertainties in the estimated impacts of climate change, connected to highly variable projections of precipitation (Figure 4). In contrast to grain maize, wheat is mostly a non-irrigated, rain-fed crop in Europe. Simulations (under the RCP8.5 scenario) show yield increases for Northern Europe around 2050, ranging from 5% to 16% for eight out of ten models. Conversely, all models but one project yield reductions for Southern Europe around 2050 reaching up to -49%. No large differences are estimated among the two 1.5 oC and 2 oC warming conditions, with beneficial effects of staying within 1.5 oC mainly visible in the Iberian Peninsula and Italy. The yield increases in Northern Europe are driven by increasing amounts of precipitation combined with a shorter growing cycle and increasing atmospheric CO2, under RCP8.5 reaching mixing ratios of 540 ppm in 2050. The losses projected for Southern Europe corroborate the experimental evidence of limited/no positive CO2 effects on wheat under limited water conditions. Large uncertainties are, however, affecting these results.

If irrigation infrastructure would be built in wheat growing areas, and assuming sufficient water availability, losses could turn into yield gains in all Europe, and overall yield variability would decline. This option would need thorough analysis of economic feasibility and sustainability issues. While for grain maize the effects of the tested adaptation options are very limited, changing wheat varieties may have a larger beneficial potential. Under rain-fed conditions, the use of 'faster' wheat varieties, which reach the flowering stage earlier, may avoid negative climate change effects and in some cases even give rise to increasing yields (results not shown).

However, it is important to highlight that the effects of climate extremes, such as heat stress and drought, are likely underestimated due to missing processes (e.g. an accurate description of heat stress impact on crop development at anthesis) and oversimplified description of the soil-plant/canopy-atmosphere interaction in models. The extreme climate conditions experienced in 2018 have shown how heavy losses can be triggered by such events even in regions supposed to be (on average) experiencing positive agro-climatic changes (Toreti et al. 2019a). Europe-wide wheat production was estimated to be down by 5 % compared to the previous 5 years. Furthermore, nutritional aspects are not included in the model, while they are expected to be of concern under elevated atmospheric CO_2 concentrations.

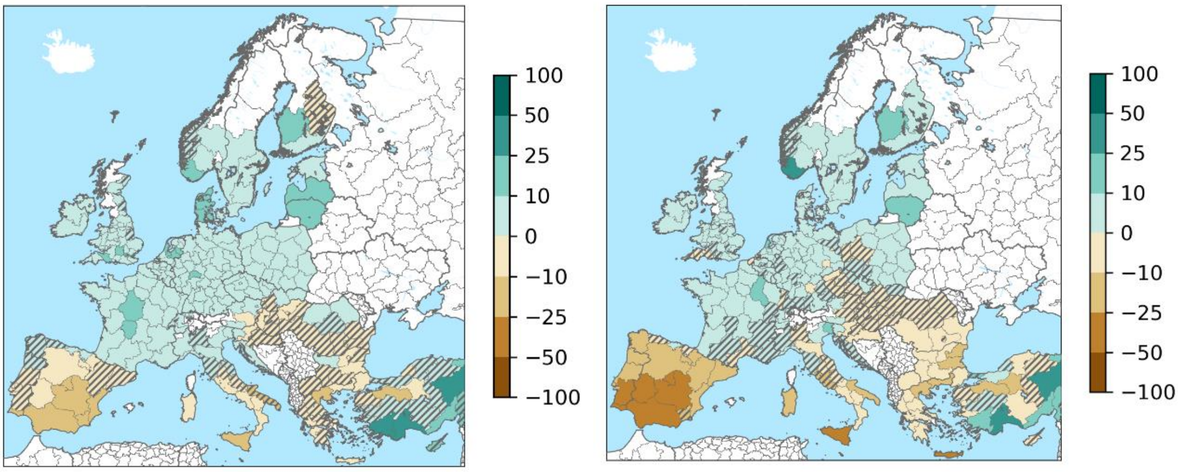


Figure 4. Ensemble mean changes of wheat yield (% relative to the historical period) projected under the RCP85 for 1.5 °C (left panel) and 2 °C (right panel) warming conditions under rain-fed (no irrigation) conditions. Hatching denotes areas with low models' agreement (i.e. less than 66% of models agree in the sign of estimated changes).

3.2 Agro-economic effects

The CAPRI simulation results are presented as box-whisker plots, displaying the variability and range by crop and country around the median of the different scenarios (see Annex 2 and 3). It is important to point out that due to the different underlying simulations with global climate models (GCMs), the variability in the obtained effects in 2050 can be linked to different global warming levels, ranging from 1.6 °C to 2.7 °C increase in temperature compared to pre-industrial (Table 2).

Table 2. Global warming levels in °C in 2050 and range for the simulated period 2010-2100 based on different global climate models.

GCM	Noresm	Miroc	IPSL	Hadgem	GFDL
°C in 2050	1.83	2.75	2.59	2.61	1.64
Range °C from 2010 to 2100	0.53-3.89	0.84-6	0.98-5.45	0.77-5.48	0.5-3.37

Source: Szewczyk, W. and Müller, C. (2019), Personal communication, 5 September.

In addition, it should be noted that there is also an important difference in how climate change projections are treated in the ISI MIP and the standard PESETA 4 approaches. For instance, a different set of GCMs is considered and there is no regional downscaling in ISI MIP. In contrast, the European WOFOST simulations are based on 10 bias-adjusted RCMs (Section 2.1) at approx. 12 km and then aggregated at the different NUTS levels by using current agricultural land and production data. Despite the differences in modelling the climate projections the ranges of global warming spanned by the GCMs in ISI-MIP (five models in Table 2) are consistent with the ones in PESETA, enabling a qualitative comparison of results obtained for Europe from WOFOST and CAPRI/ISI-MIP.

3.2.1 Market adjusted yield effects

Figure 5 shows both the direct (exogenous) biophysical climate change-related yield shocks in the EU from the WOFOST and the ISI-MIP projections and the indirect (endogenous) economic impact from these yield shocks in CAPRI after rebalancing domestic and international agricultural markets, using ISI-MIP. As explained above we only apply the ISI-MIP yield shocks in CAPRI and for comparison we show in Figure 5 the projected yield effects from the EU crop modelling exercise (WOFOST). It can be noticed that the WOFOST projections for wheat and grain maize in 2050 in Southern Europe as well as wheat in Northern Europe are in line with the ISI-MIP yield projections. However, the magnitude differs due to the different underlying assumptions between the models. Although statistically overlapping, the largest yield differences are found for grain maize in Northern Europe with negative median yield changes projected by WOFOST and positive changes by the ISI-MIP ensemble. Another reason for these differences may be due to resolution in the models and the soil modules.

The difference in the median, attributable to the different modelling approaches and assumptions, prevents a complete use of WOFOST in the economic assessment as associated global yield changes are not available. However, it is worth to note that the two ensemble ranges partially overlap.

It is important to understand that yields and economic responses to yield changes are endogenous in CAPRI. Therefore, the simulated yields do not necessarily need to follow the same spatial pattern as the exogenous yield shocks. Endogenous yield changes are caused by economic considerations driving farmer management decisions. To minimize their losses, farmers might opt to plant more of those crops that show more positive yield effects (or produce them in a more intensive way) and less of the crops that show more negative yield effects (or produce them in a more extensive way). However, this will influence prices, so that for instance, producer prices will decrease for those crops that are produced more, and reversely prices will increase for the crops that are produced less. The price changes further influence farmers' decisions, by modifying the use of inputs per hectare, thus yields, provoking more re-adjustment in crop allocation. Moreover, adjustments also take place outside the EU with regard to the EU production decisions, and vice versa. Market interactions through international trade of agricultural commodities occur simultaneously, so that depending on the region a further re-adjustment of markets is observed. Differently than in WOFOST, water availability constraints and the effect of elevated atmospheric CO_2 concentration are not considered in the adjustment of farm practices in CAPRI. In addition, changes in crop varieties and sowing dates are also not considered in the adjustment of farm practices. A comprehensive assessment of the impacts of water-limitation would require a modelling framework explicitly coupling crop growth, hydro-dynamic and economic models.

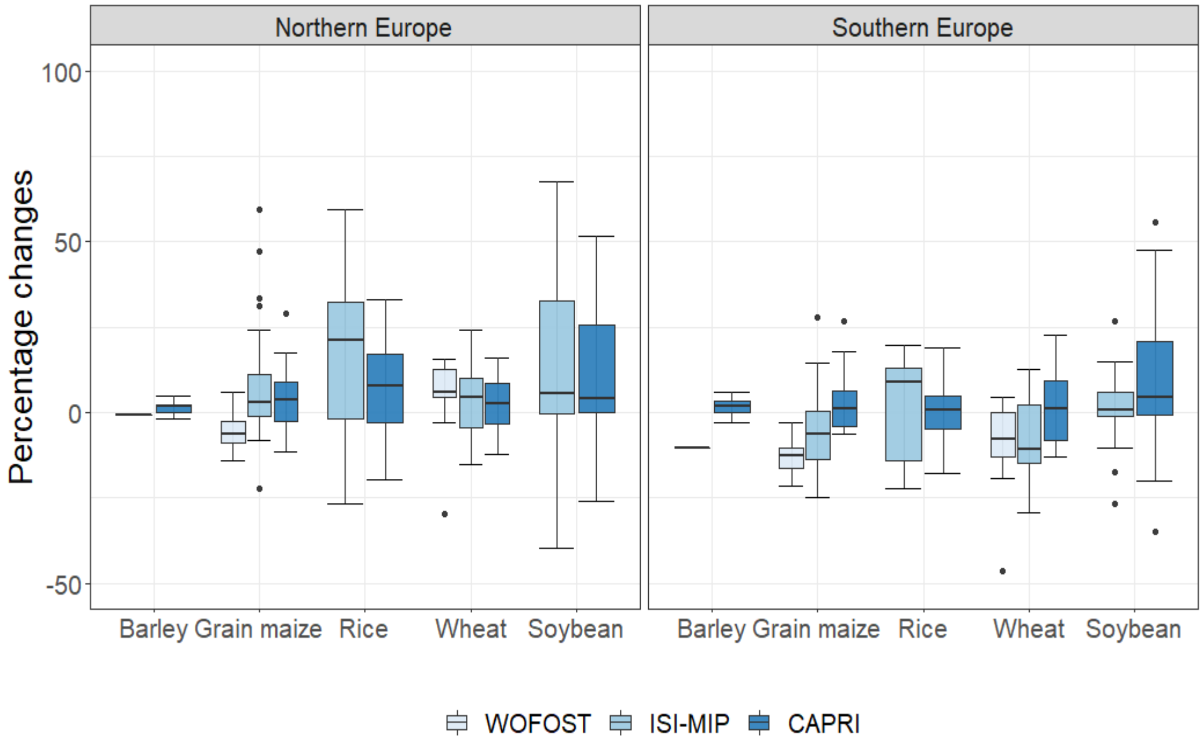


Figure 5. Northern and Southern Europe crop yield changes (exogenous yield shocks (WOFOST/ISI-MIP) and endogenous response (CAPRI)) in 2050 relative to the baseline.

Source: own elaboration, CAPRI model

<u>Note</u>: WOFOST uncertainty range reflects the range of 10 different RCP8.5 scenario results. ISIMIP and CAPRI uncertainty ranges reflect the different combinations of crop and climate model simulations.

*The boxplot displays the median, two hinges and two whiskers of a continuous variable distribution. The lower and upper hinges (coloured bars) correspond to the first and third quartiles (the 25th and 75th percentiles). The upper whisker extends from the hinge to the largest value no further than 1.5 than the inter-quartile range (IQR), or distance between the first and third quartiles. The lower whisker extends from the hinge to the smallest value at most 1.5 * IQR of the hinge. Data beyond the end of the whiskers are "outliers" points and are plotted individually as dots.*

Figure 5 shows that the median crop-specific yields in Northern Europe will be positively affected by climate change, as coming from the ISI-MIP climate-biophysical model ensembles. On the contrary, cereal producers in Southern Europe will be in general more negatively affected. Barley, grain maize and wheat are the crops most affected by climate change in Southern Europe, with a sizeable yield reduction (-10%, 6% and -9%, respectively), consistent with the WOFOST biophysical modelling results reported in section 3.1.1. However, the interplay (spill-over) of climate change impacts in other important production regions outside of Europe and trade adjustment leads to different changes in endogenous yields around the median with ±15% uncertainty in the European regions. In Northern Europe, despite bio-physical yield increases due to climate change (i.e. longer growing season and precipitation changes), endogenous yields are lower after market re-adjustments. As explained above, higher supply of crops with positive effects will result in price reductions and incentivize farmers to focus on other crops, here barley and grain maize. Nonetheless, the yields remain positive and, despite the large uncertainty, are consistent with the projected yield changes from both the ISI-MIP and WOFOST crop modelling. In Southern Europe, wheat yields, despite being heavily affected (-9% median effect) by climate change, respond positively to the global market adjustment (2% endogenous median yield increase). The same is noticeable for grain maize: -5% direct climate change median effect but 3% endogenous median yield increase with higher spread on the positive side. Due to the different market adjustments, the projected overall median yield changes in Southern Europe are not fully consistent with the projected changes from the WOFOST biophysical modelling.

3.2.2 Production effects

As a result of the positive yield adjustments, agricultural production indicators (i.e. area, gross/net farm income, production level) both in the Northern and Southern Member States are expected to be positively affected in most of the scenarios (Figure 6). It has to be noted that the indicated area expansion occurs at the expense of other crops with lower relative profitability. In addition, area expansion is not limited by factors such as water availability or quality, which is especially important, e.g., for rice producers as these factors are not considered in the current agro-economic analysis.

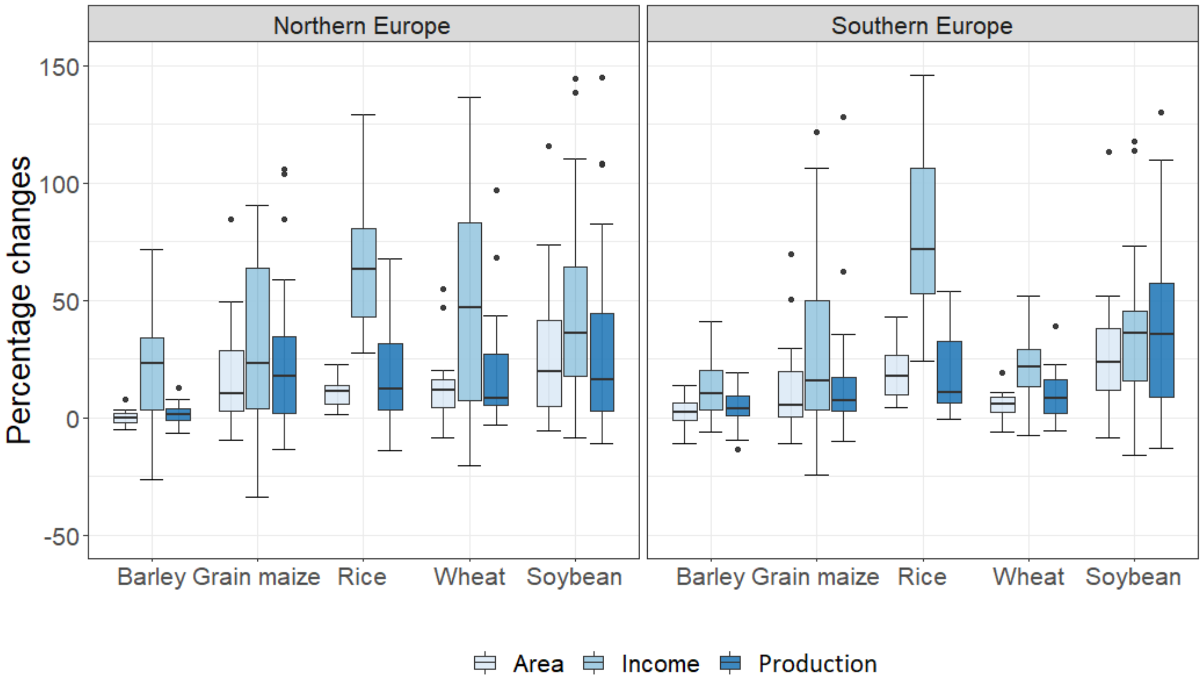


Figure 6. Changes in crop area, farm income and supply in Northern and Southern Europe in 2050 relative to the baseline.

Source: own elaboration, CAPRI model

<u>Note</u>: The boxplot displays the median, two hinges and two whiskers of a continuous variable distribution. The lower and upper hinges (coloured bars) correspond to the first and third quartiles (the 25th and 75th percentiles). The upper whisker extends from the hinge to the largest value no further than 1.5 than the inter-quartile range (IQR), or distance between the first and third quartiles. The lower whisker extends from the hinge to the smallest value at most 1.5 * IQR of the hinge. Data beyond the end of the whiskers are "outliers" points and are plotted individually as dots.

In Northern Europe, soybean area and supply are increasing the most, but they also display large variability around the median (20%), with increases up to 75% in some scenarios, and slightly negative in others. This large variability can be explained by the fact that soybean production in the EU is concentrated in a relatively small area (around 0.5% of the total utilized agricultural area (UAA) in the EU; European Commission, 2018b) and, therefore, production is quite sensitive to large yield changes induced by regional climate change (Figure 5). Grain maize, rice and wheat area, and consequently production, are also expected to increase in Northern Europe by about 10% (median effect). However, similar to soybeans, the EU rice production is concentrated on an even smaller area mainly in some regions in Southern Europe (0.25% of total UAA; European Commission, 2018b). Therefore, the large relative changes plotted for rice and soybean should be interpreted with care because these impacts are rather small in absolute terms. The production of barley in Northern Europe is projected to remain stable.

Similar to Northern Europe, area expansion and supply in Southern Europe is expected to increase for the five crops analysed. Again, soybean displays the largest variability. Rice supply (9% median effect) is lower than the area expansion due to lower yield effects than in Northern Europe (Figure 5). Even though wheat relative changes are smaller than rice and soybean, wheat changes are much more important because they involve a much higher volume at aggregated level. The same holds for grain maize and barley. Thus, the increase in barley area and supply in Southern Europe (4% around median) is more important because of the higher endogenous yields.

The higher crop production (area and supply) is reflected in lower producer prices. However, Figure 7 displays that in both parts of Europe producer prices are projected to increase, ranging from 3% (grain maize) to 30% (rice) around the median. The main reason is that the EU production is mainly export oriented (see next section for details). As a consequence of the large price increase for rice producers, their income is projected to increase by around 60% (median effect) in Northern Europe and more than 70% in Southern Europe (Figure 6). However, it can be noticed that there is high variability in the farm income as a result of the high variability in supply. Large price variation can also be seen for wheat and soybean producer prices, with positive median effects, which is reflected in very large farm income variability especially for wheat producers in Northern Europe. Consumer prices in both regions are in general much more stable due to inelastic demand (see next section for details).

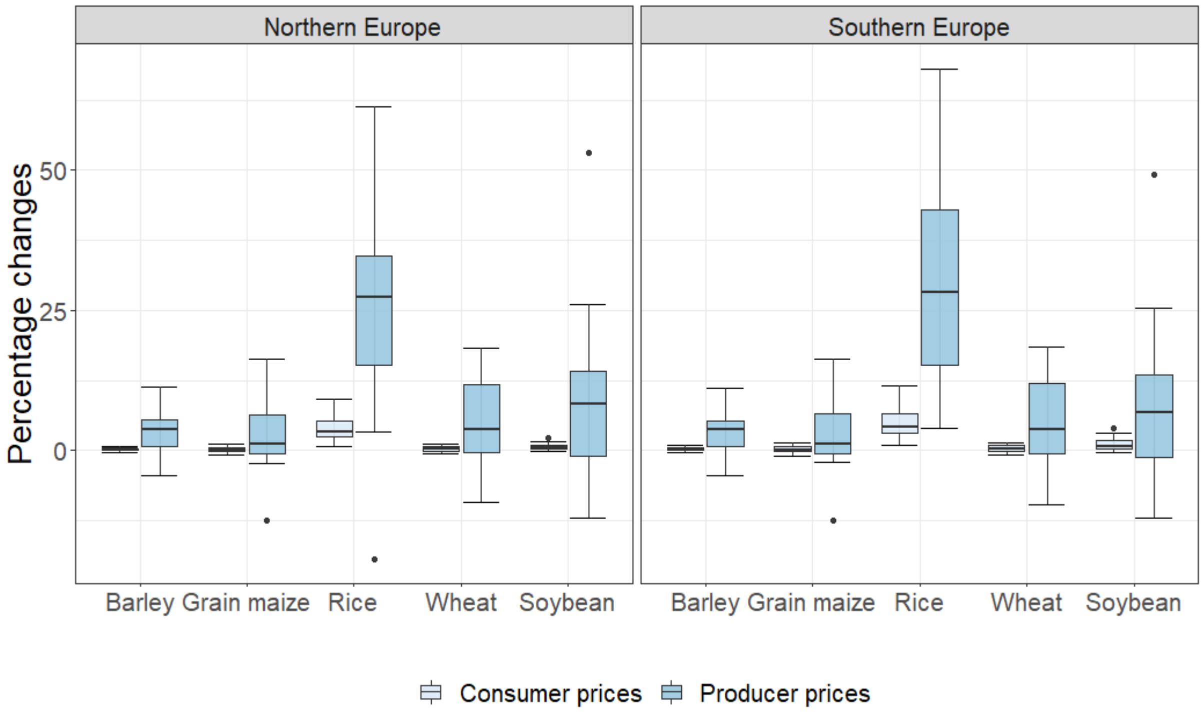


Figure 7. Changes in Northern and Southern Europe consumer and producer prices in 2050 relative to the baseline.

Source: own elaboration, CAPRI model

*<u>Note</u>: The boxplot displays the median, two hinges and two whiskers of a continuous variable distribution. The lower and upper hinges (coloured bars) correspond to the first and third quartiles (the 25th and 75th percentiles). The upper whisker extends from the hinge to the largest value no further than 1.5 than the inter-quartile range (IQR), or distance between the first and third quartiles. The lower whisker extends from the hinge to the smallest value at most 1.5 * IQR of the hinge. Data beyond the end of the whiskers are "outliers" points and are plotted individually as dots.*

Note that, due to a lack of quantitative data and models availability, in this study livestock commodities were assumed to be not directly affected by climate change (e.g. increasing temperature, higher flood risk) in the scenarios, but indirectly through the effects on feed prices and trade, which are transmitted to dairy and meat production. In reality, certain temperature increases due to climate change may severely threaten livestock productivity, especially if no adaptation strategies will be put in place. Since the EU barley and grain maize production is not decreasing in most of the scenarios, with very moderate price increases, the EU livestock production can profit and slightly increase for beef (0.5%), poultry (0.7%) and pork (0.3%) median results. Dairy production is also benefiting from the increase in the supply of barley and grain maize, but increases only marginally (0.1%). Nevertheless, the income effect is much larger for pork (6%), beef (5%), poultry (3.5%) and dairy (1%) producers. This is an effect of price increases, which are demand driven by higher exports: pork (2.5%), beef (2%), poultry (4%) and dairy products (2%). Climate change outside of the EU (see Annex 4) affects negatively barley and grain maize yields in regions such as the USA, Russia, Ukraine and Brazil, which results also in negative effects for livestock production in these regions. The livestock producers in the EU may benefit from these negative effects in the non-EU countries in addition to positive yield changes for feed grains in the EU.

3.2.3 Domestic use and trade effects

Domestic consumption in both Northern and Southern Europe is negatively affected (in the median) over the different scenarios for wheat and soybeans, slightly positive for barley, and positive for grain maize and rice (Figure 8). The higher domestic consumption of barley and grain maize can be explained by higher EU livestock production, which is, as explained above, actually benefitting from both higher adjusted endogenous yields in Europe and lower production in some non-EU countries (Figure 5). Grain maize domestic consumption in Northern Europe displays the largest uncertainty in regions where livestock production is more pronounced (Figure 8).

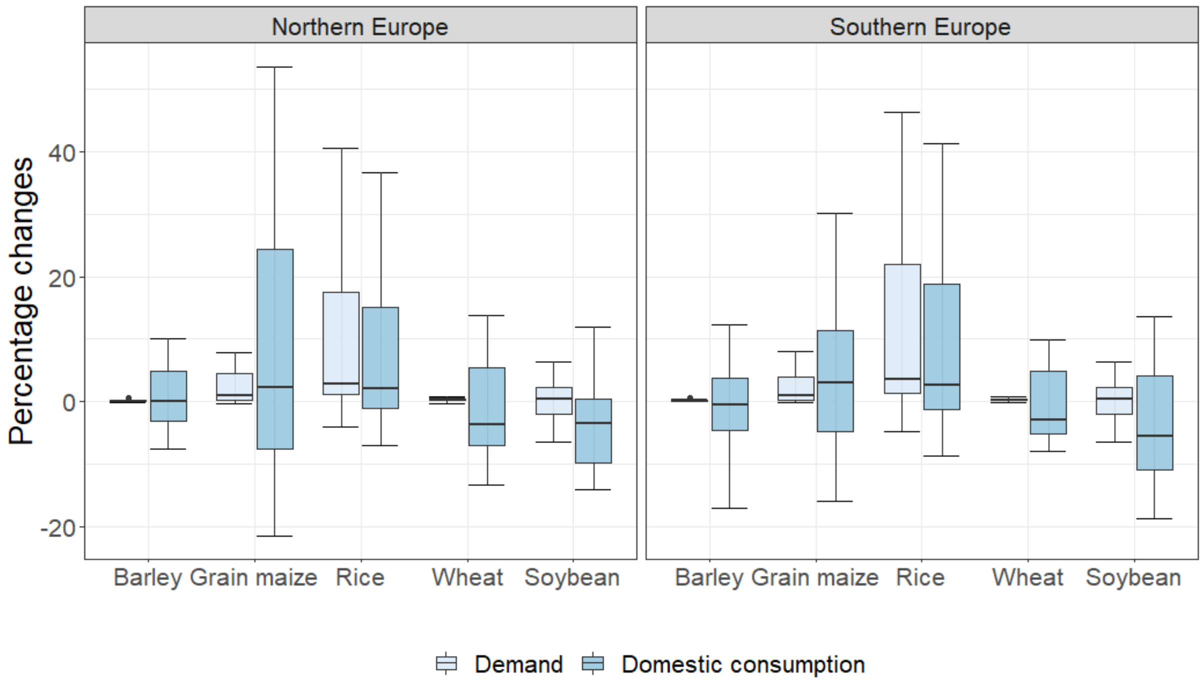


Figure 8. Changes in EU demand and domestic consumption in 2050 relative to the baseline.

Source: own elaboration, CAPRI model

*<u>Note</u>: The boxplot displays the median, two hinges and two whiskers of a continuous variable distribution. The lower and upper hinges (coloured bars) correspond to the first and third quartiles (the 25th and 75th percentiles). The upper whisker extends from the hinge to the largest value no further than 1.5 than the inter-quartile range (IQR), or distance between the first and third quartiles. The lower whisker extends from the hinge to the smallest value at most 1.5 * IQR of the hinge. Data beyond the end of the whiskers are "outliers" points and are plotted individually as dots.*

Rice demand and domestic consumption in the EU are both projected to increase. This is mainly driven by the export-oriented production (Figure 9), because other countries outside of the EU such as India, China and the USA (Annex 4) are expected to have negative effects on rice production due to climate change. Hence, EU rice production becomes more export-oriented leading to higher demand and use. However, the EU will still remain a large net importer of rice[4]. Despite the high relative changes, the absolute quantities concerned for all these changes are rather small. As a result of the production development, consumer and producer prices for rice are expected to increase (Figure 7). However, the large price variability is reflected into large uncertainty (spread) for domestic use.

The projected decline in domestic use for wheat and soybean in both regions is mainly due to the increase in exports (Figure 9), with most of the export-oriented production originating from Northern Europe, i.e., more than 50% and 25% increase in exports median effect for wheat and soybean, respectively. However, soybean exports are rather small in absolute terms. Wheat exports relative changes should be considered as more important given that the EU is already a big wheat exporter in the baseline. The increases in producer prices indicated in the previous section are also driven by the trade effect at the expense (losses) of wheat producers in the USA, Brazil, India, Africa, etc. as well as soybean producers in Brazil (see Annex 4). Southern Europe exports for wheat and soybean are not increasing as much as Northern Europe due to the lower endogenous yield effects (Figure 5). Still, the small relative changes for wheat are actually large in absolute terms due to the high production volumes. Barley production in Southern Europe will be mainly export-oriented due to negative climate effects in the USA, China, Russia, and Africa (Annex 4). The interplay between production changes in the EU and other major producing countries leads to export increases in wheat, barley, grain maize and soybean (Figure 9), with the EU producer prices increasing between 1% to around 7% (median) in both regions. This results in increases in the EU producers' income between 25% and 50% in Northern Europe and 10% to 30% in Southern Europe.

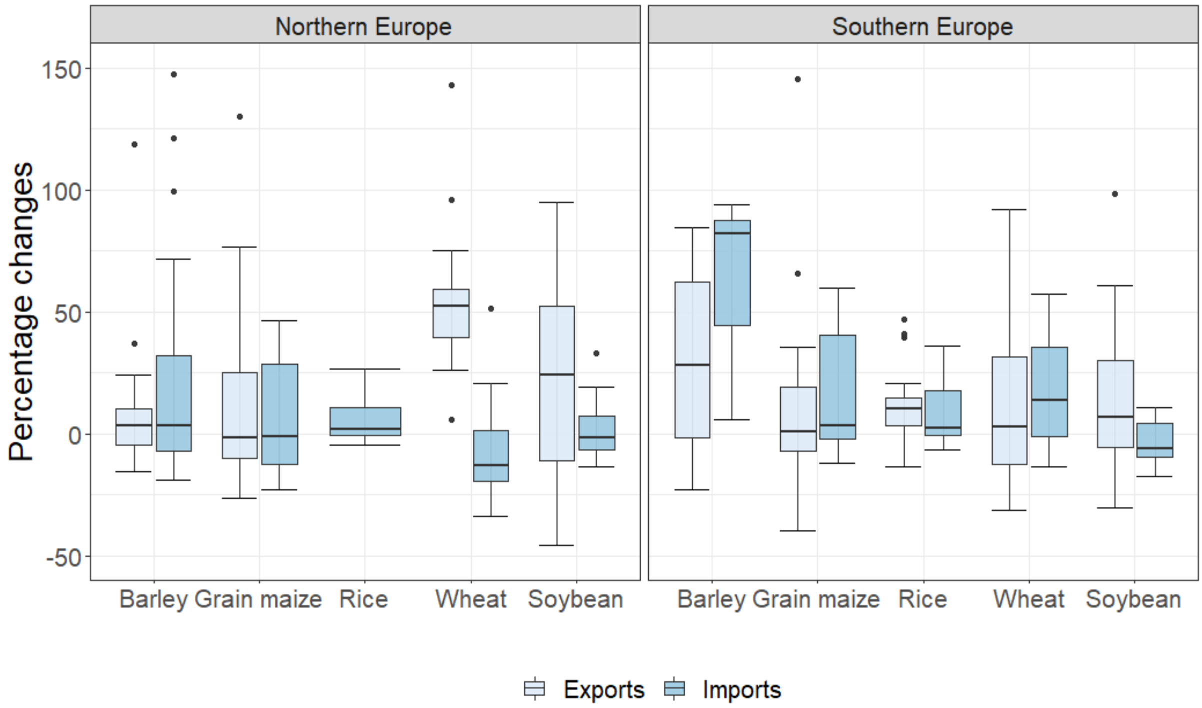


Figure 9. Changes in EU exports and imports in 2050 relative to the baseline.

Source: own elaboration, CAPRI model

*<u>Note</u>: The boxplot displays the median, two hinges and two whiskers of a continuous variable distribution. The lower and upper hinges (coloured bars) correspond to the first and third quartiles (the 25th and 75th percentiles). The upper whisker extends from the hinge to the largest value no further than 1.5 than the inter-quartile range (IQR), or distance between the first and third quartiles. The lower whisker extends from the hinge to the smallest value at most 1.5 * IQR of the hinge. Data beyond the end of the whiskers are "outliers" points and are plotted individually as dots.*

The higher supply of cereals (Figure 6) allows improving the trade balance in the regions for some crops by reducing the imports (wheat and soybean). Wheat imports in Northern Europe as well as soybean in Southern Europe are declining considerably due to the positive effects of climate change on yields. Barley imports in

[4] The rice variety Japonica (small/medium grain) is mainly produced and also mainly used in the EU, and for which the EU is self-sufficient and even a small net exporter. For Indian long grain rice, the EU is a large net importer.

Southern Europe are projected to increase substantially. The Member States in Southern Europe are mainly importers of barley (on average around four times more imports than exports). Thus, the increase in exports is compensated by import increases to keep demand and domestic use balanced. In general, compared to the baseline, the EU still remains a net exporter of wheat and barley, and a net importer of grain maize, rice and soybean.

Compared to domestic consumption, the demand in both regions is fairly inelastic for all crops, leading to almost no changes in consumer prices median effect. This does not hold for rice domestic demand, which displays a small increase because of the increase in domestic consumption.

4 Conclusions

Climate change clearly poses a threat to global food production in the medium to long term, and Europe will not be an crops such as wheat or maize in the agro-economic analysis. Pérez Domínguez and Fellmann (2018) based on the PESETA III agro-economic analysis, also concluded that considering market-driven effects and production adjustments is important when analysing the overall impacts of climate change on the agricultural sector. Moreover, our analysis in PESETA IV confirms their conclusion on the need to improve agro-economic assessments in terms of consistency in the climate driven biophysical shocks in the EU and the non-EU countries. Using a consistent set of biophysical yield shocks as input for the agro-economic analysis in the present PESETA IV project shows, for example, considerable smaller positive effects on EU cereals production than the ones indicated in PESETA III (16% increase compared to the currently projected 7%). In any case, given the growing awareness of opportunities and risks in Europe resulting from agronomic developments in the other producing regions of the world, it seems opportune to increasingly invest in understanding EU agricultural production exception (e.g. Webber et al., 2018; IPCC 2019). Future crop yields and crop production will depend on an array of technological, agro-management, climate-related and socio-economic factors. Moreover, the need for adaptation (i.e. in response to future CO_2-levels and associated climate trajectories) will depend on the success of coordinated international climate change policies.

In Europe, some of the negative effects of climate change for the so-called C_3 crops (i.e. wheat, barley, and sunflower) may be partially compensated by higher levels of atmospheric CO_2 concentration. This is true for Northern Europe (although models show large uncertainty) but not for Southern European Member States, where crop yields are strongly limited by the lower availability of water under projected climate conditions. For these crops, tailored adaptation strategies may partly compensate for the estimated crop production losses and, in some cases, even increase the production compared to the current levels. Maize, a C_4 crop , cannot equally (compared to wheat) profit from the projected higher CO_2 levels. Grain maize is one of the most affected crops by climate change throughout Europe, with simple adaptation options not providing much relief. Therefore, climate change might trigger crop replacements in the future, especially with favourable economic factors.

For Europe as a whole, an increasing divergence of production in Southern Europe (declining) and Northern Europe (potentially increasing) may have profound impacts on the mutual reliance and trade patterns across the EU Member States if no adaptation strategies will be locally implemented. Changes in agro-management (e.g. introducing new varieties and relocating crops, changes in rotation patterns and diversification strategies), supported by a well-functioning European market buffering production shocks across Europe, would be needed to increase climate resilience of the European food system. Nevertheless, the presented agro-economic results provide insights that, the agriculture as an economic sector, in the EU could also have benefits from climate change due to the market spill over effects provoked by larger negative impacts on agricultural productivity in large producers outside of the EU. Table 3 displays a simple example of such effect for soybean production in the EU. Argentina and Brazil soybean yields and production are expected to be affected more than the ones in the EU. Despite the negative effects of climate change, EU producers may adapt and reduce yield losses. This occurs due to consistent feedback between the EU and the non-EU regions in terms of trade, with direct effects on market prices which are affecting farmers' management decisions with regard to farm practices, crop mix and input use (fertilizers, seed and plant protection, maintenance and fuel costs, etc.) in both domestic and international markets. Since Argentina and Brazil are the major soybean producers and a reduced global production leads to an increase in producer prices, this may incentivize EU farmers to increase production (area and supply) and make profits despite the climate change induced reduction in biophysical yields. This trade feedback and the related market adjustments are the reasons for the projected positive effect on median yield for systems, assessing the limitations and risks they are exposed to.

Table 3. Example of the market adjustment effects: Soybeans.

EU	Exogenous yield shock	-10.7%
	Endogenous yield	-3.4%
	Income	37.1%
	Area	23.9%
	Supply	19.7%
	Producer prices	19.4%
	Imports	-0.4%
	Exports	42.4%
	Net trade	-6.4%
USA	Exogenous yield shock	-9.0%
Argentina	Exogenous yield shock	-27.0%
Brazil	Exogenous yield shock	-26.0%

Source: own elaboration, CAPRI model simulations based on LPJml yield shocks.

It is also important to understand the limitations of this study. An important limitation is represented by the availability of water in Southern Europe and in parts of Northern Europe, which may aggravate under climate change conditions (see task 10 sectoral report). Even though water availability is projected to be an issue for many parts of Southern Europe, the economic analysis in this study has not yet taken water limitations into account, which is expected to have consequences for the entire agro-economic production system. Therefore, including irrigation water pricing, limitations on sustainable water abstraction or investment cost for more efficient irrigation systems should be considered in future work.

It is also important to stress that increased inter-annual variability may have more important implications for farmers and markets than the long-term average response. Furthermore, current impact assessments underestimate the effects of climate extremes (e.g. heat waves, extreme drought), as these processes are not fully taken into account or not included (e.g. the impacts of heavy precipitation on production, quality and harvest conditions) in the impact models. Extreme climate events observed in 2018 and 2019 have shown the heavy losses that can be induced in the agricultural sector (Toreti et al. 2019a). The expected increase in frequency and intensity of climate extremes as well as the projected recurrent and concurrent events in key producing regions of the world (Toreti et al. 2019a, 2019b) may trigger yield and production losses, inducing higher price variability and altering global food markets (Chatzopoulos et al. 2019; Toreti and Perez-Dominguez, 2019), which can be a serious threat to food security. Within the proposed agro-economic framework, the trade-adjustments will take place endogenously. The extreme events can be offset or food security facilitated by stockholding of agricultural commodities or tailored trade policies. However, these aspects are currently difficult to quantify with the current modelling framework, which evaluates long-term changes in average conditions. Indeed, shocks induced by recurrent and concurrent large-scale extreme events may destabilise the global production system and have highly non-linear and long-term effects.

With respect to the long-term effects it is also important to point out that in the agro-economic modelling, investments in infrastructure are not considered. Not being able to have an explicit link between capital investments and production, the market adjustments and the net costs of adverse exogenous shocks due to climate change may be under/overestimated. However, the comparative static framework of CAPRI makes it difficult to incorporate investor and producer behaviour.

Moreover, some nutritional aspects of crop production are not taken into account in the current modelling framework. Protein and mineral concentrations are expected to decrease under elevated atmospheric CO_2 concentration, but these changes in the crop quality and related impacts on producer prices are not reflected in the projected positive production effects in Northern Europe.

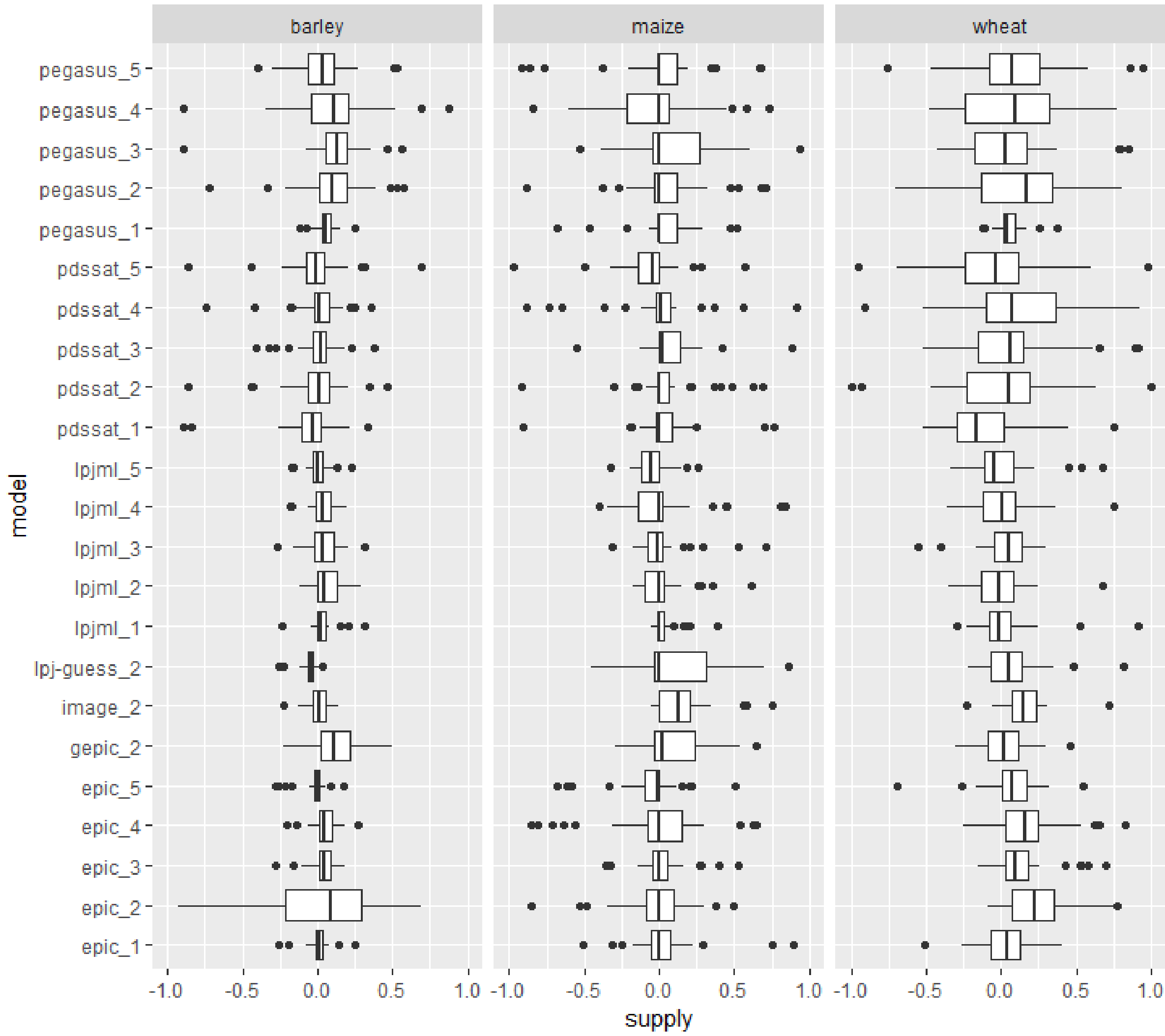
Nevertheless, this study shows that careful management of agricultural producer practices under climate change conditions, may also give rise to new export-demand opportunities for farmers. These benefits combined with targeted breeding programmes (e.g. towards drought and heat-stress resistant varieties or increased genetic diversity crops) may limit yield losses, but need to be evaluated against other constraining factors on production.

Annex

Annex 1. Aggregation of Member states in North/South Macro regions.

Note: the geographic borders are purely a graphical representation and are only intended to be indicative. The boundaries and the aggregation do not necessarily reflect the official position of the European Commission.

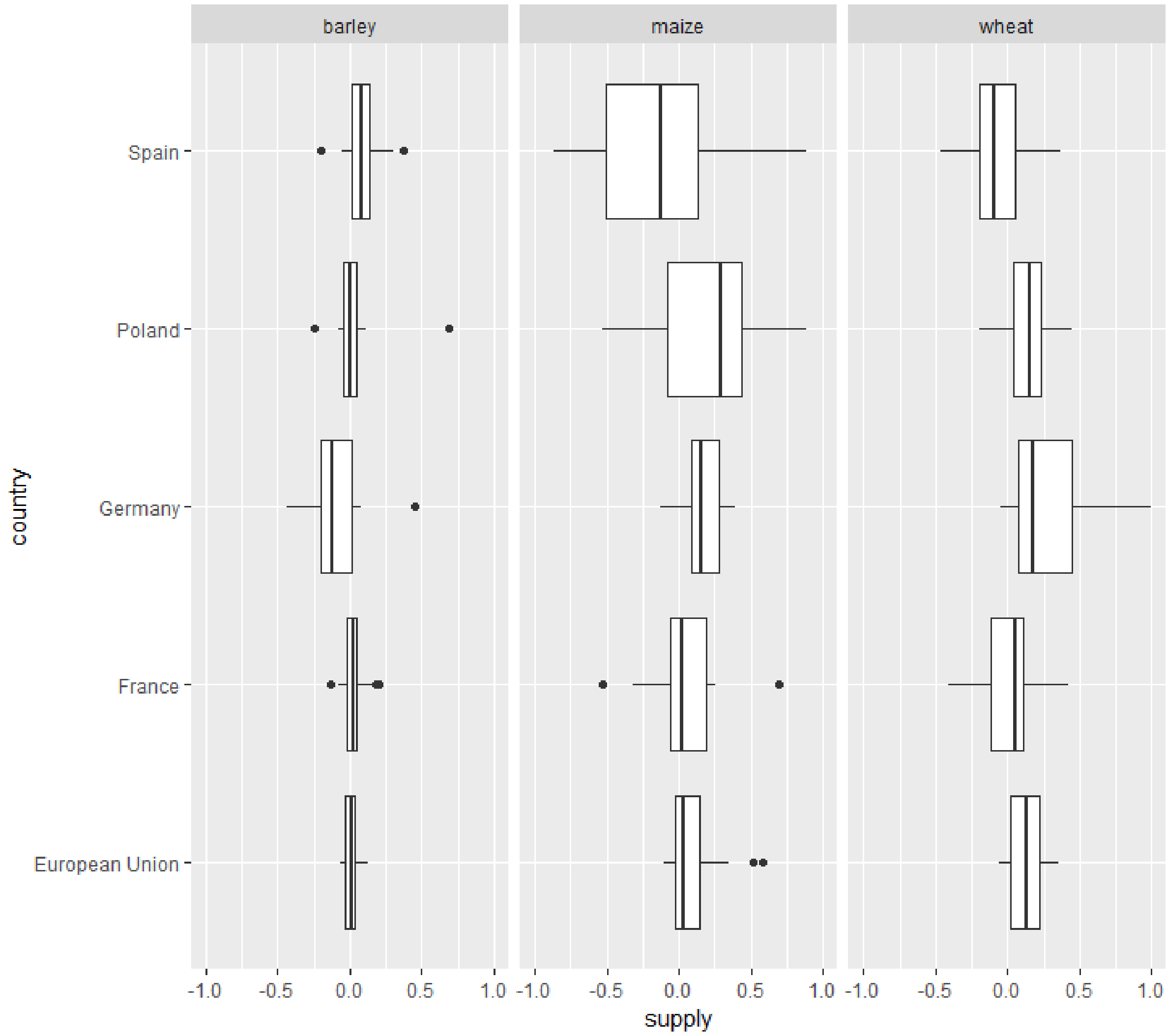
Annex 2. Specific supply (production) and full variability around the median in 2050 by crop and GGCM from the ISI-MIP fast track simulations



Source: own elaboration, CAPRI model.

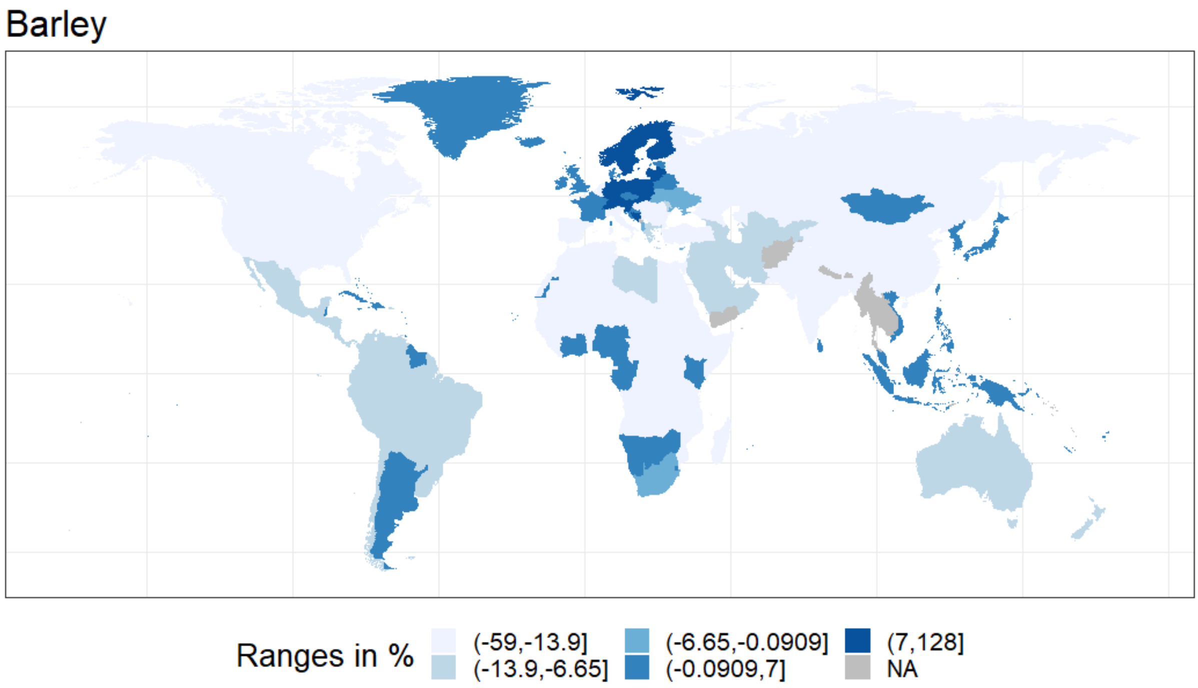
Note: we include here 23 simulation results because in 12 combinations the above displayed crops were not exogenously shocked due to unavailable yield changes from the ISI-MIP database

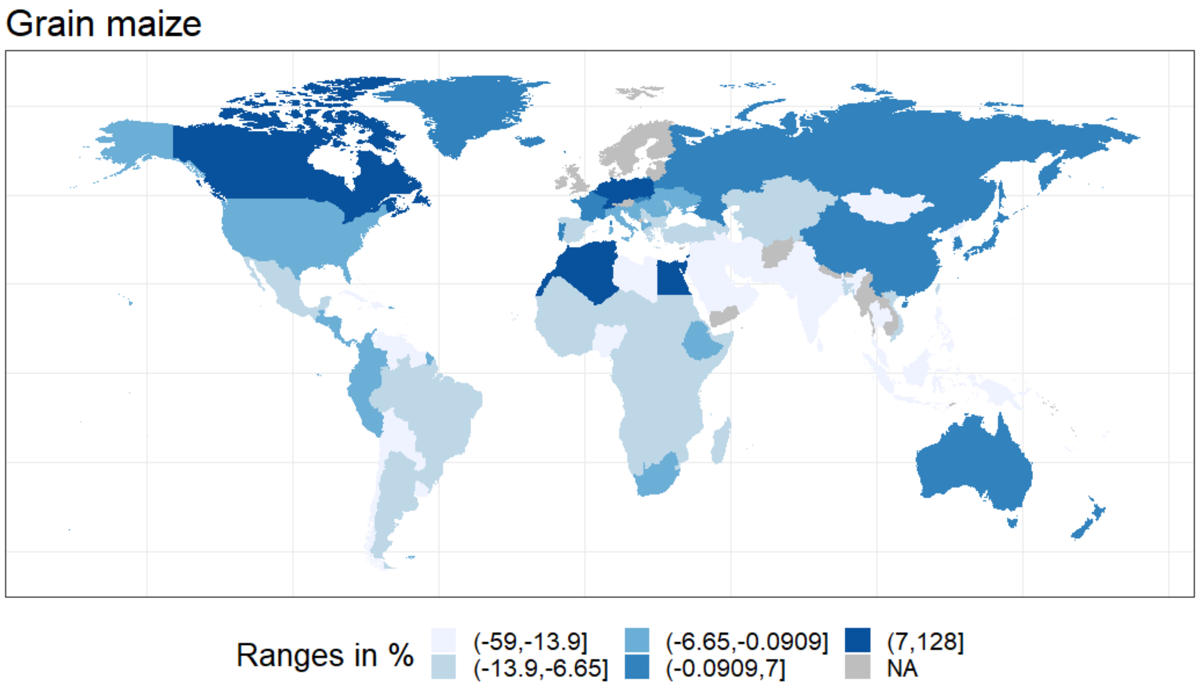
Annex 3. Specific supply (production) and full variability around the median in 2050 by country and crop



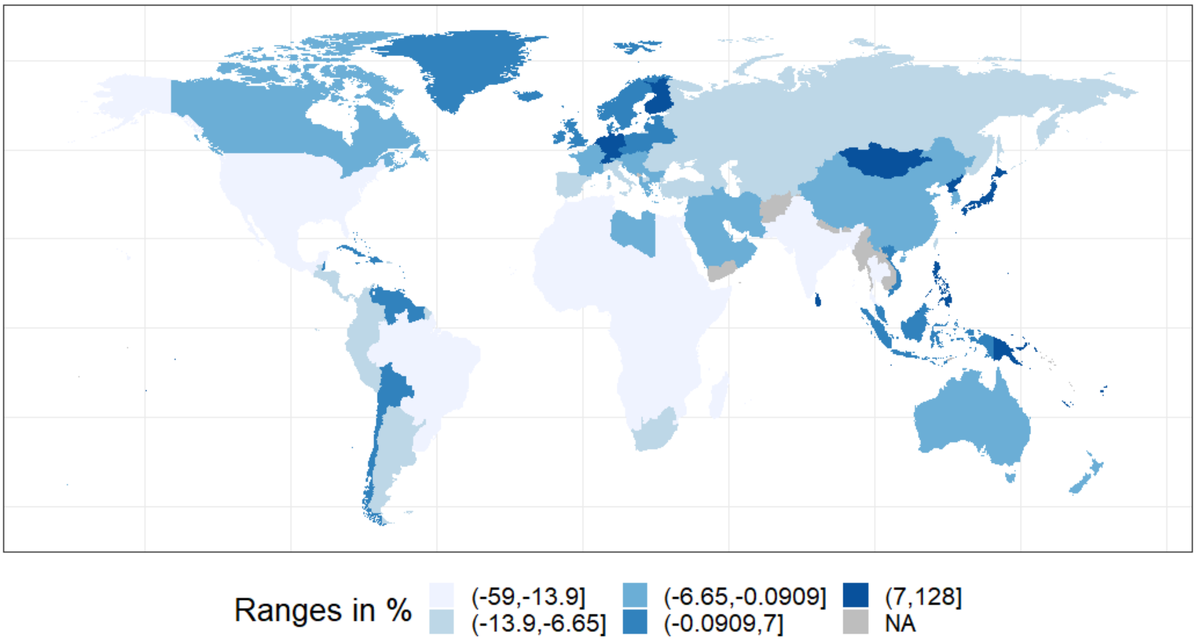
Source: own elaboration, CAPRI model.

Annex 4. Global climate change ISIMIP-Fast Track median yield changes under the RCP 8.5 and SSP2 scenarios for the selected crops in 2050 relative to the baseline.

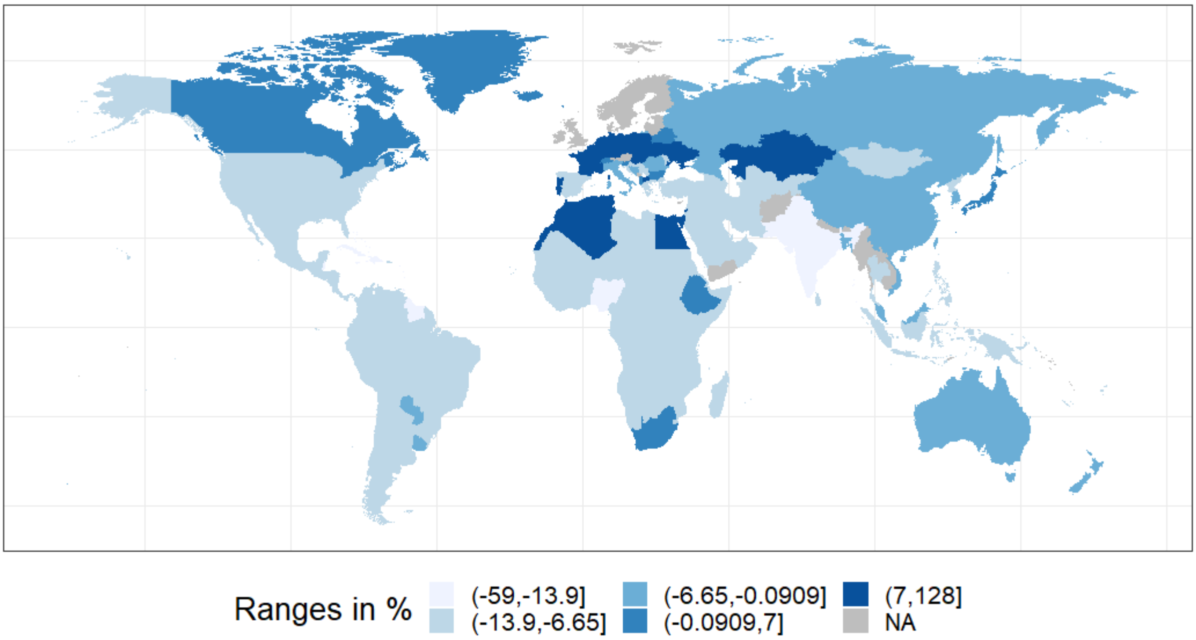




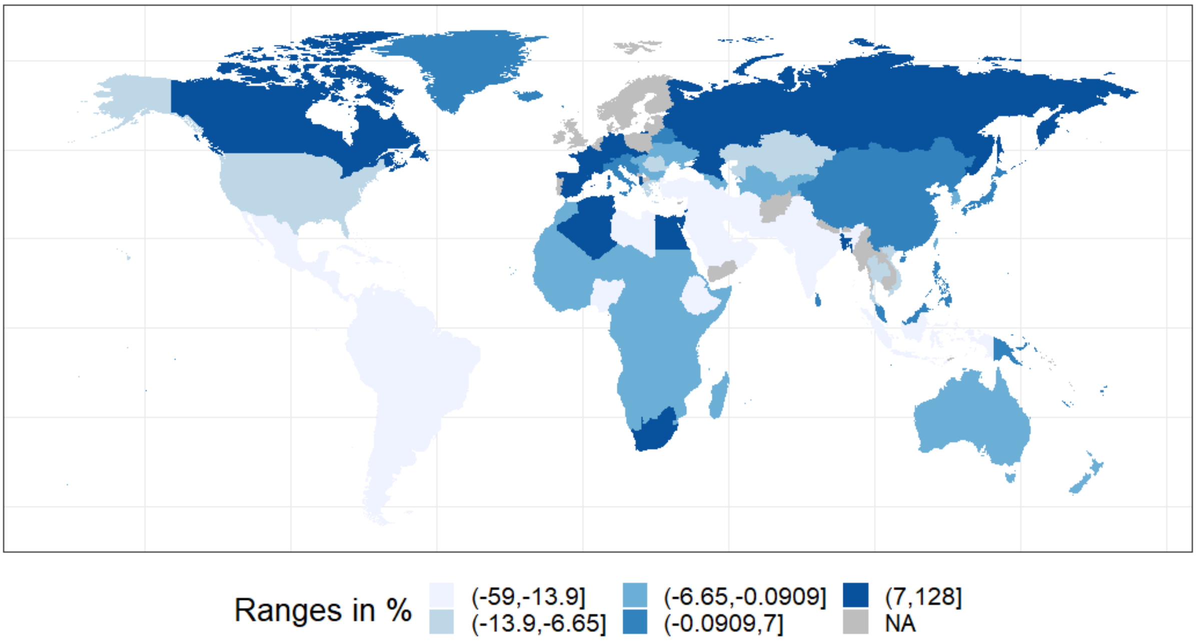
Wheat


Ranges in %
(-59,-13.9]
(-13.9,-6.65]
(-6.65,-0.0909]
(-0.0909,7]
(7,128]
NA

Rice


Ranges in %
(-59,-13.9]
(-13.9,-6.65]
(-6.65,-0.0909]
(-0.0909,7]
(7,128]
NA

Soybean



Source: own illustration based on ISI-MIP database mapped to CAPRI regions.

References

Alcamo, J. (1994). IMAGE 2.0 Integrated Modelling of Global Climate Change, Kluwer Academic Publishers, Dordrecht / Boston / London.

Bentsen, M., Bethke, I., Debernard, J. B., Iversen, T., Kirkevag, A., Seland, Ã., Drange, H., Roelandt, C., Seierstad, I.A., Hoose, C., Kristjá¡nsson, J.E. (2013): The Norwegian Earth System Model, NorESM1-M - Part 1: Description and basic evaluation of the physical climate. Geoscientific Model Development, 6, 687-720.

Bondeau, A., Smith, P. C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Müller, C., Reichstein, M., Smith, B. (2007): Modelling the role of agriculture for the 20th century global terrestrial carbon balance. Global Change Biology 13, 679–706. https://doi.org/10.1111/j.1365-2486.2006.01305.x.

Britz, W., and P. Witzke (2014). "CAPRI model documentation 2014". http://www.capri-model.org/docs/CAPRI_documentation.pdf (accessed June 23, 2018).

Cairns, J.E., Hellin, J., Sonder, K. et al. (2013). Food Security, 5: 345-360. https://doi.org/10.1007/s12571-013-0256-x.

Chatzopoulos, T., I. Pérez Domínguez, M. Zampieri, and A. Toreti (2019). Climate extremes and agricultural commodity markets: a global economic analysis of regionally simulated events, Weather and Climate extremes, doi:10.1016/j.wace.2019.100193.

Deelman, E., Vahi, K., Juve, G., Rynge, M., Callaghan, S., Maechling, P. J., Mayani, R. , Chen, W., Ferreira da Silva, R., Livny, M. and Wenger, K. (2015). Pegasus: a Workflow Management System for Science Automation, Future Generation Computer Systems, vol. 46, p. 17–35. https://doi.org/10.1016/j.future.2014.10.008.

Dosio, A. (2016). Projections of climate change indices of temperature and precipitation from an ensemble of bias-adjusted high-resolution EURO-CORDEX regional climate models, Journal of Geophysical Research: Atmospheres, 121, 5488-5511. doi: 10.1002/2015JD024411.

Dufresne, J. L., Foujols, M. A., Denvil, S., Caubel, A., Marti, O., Aumont, O., Balkanski, Y., Bekki, S., Bellenger, H., Benshila, R., Bony, S., Bopp, L., Braconnot, P., Brockmann, P., Cadule, P., Cheruy, F., Codron, F., Cozic, A., Cugnet, D., Noblet, N., Duvel, J. P., Ethé, C., Fairhead, L., Fichefet, T., Flavoni, S., Friedlingstein, P., Grandpeix, J. Y., Guez, L., Guilyardi, E., Hauglustaine, D., Hourdin, F., Idelkadi, A., Ghattas, J., Joussaume, S., Kageyama, M., Krinner, G., Labetoulle, S., Lahellec, A., Lefebvre, M. P., Lefevre, F., Levy, C., Li, Z. X., Lloyd, J., Lott, F., Madec, G., Mancip, M., Marchand, M., Masson, S., Meurdesoif, Y., Mignot, J., Musat, I., Parouty, S., Polcher, J., Rio, C., Schulz, M., Swingedouw, D., Szopa, S., Talandier, C., Terray, P., Viovy, N., and Vuichard, N. (2013): Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5. Climate Dynamics, 40, 2123-2165. https://doi.org/10.1007/s00382-012-1636-1.

Dunne, J.P., John, J.G., Adcroft, A.J., Griffies, S.M., Hallberg, R.W., Shevliakova, E., Stouffer, R.J., Cooke, W., Dunne, K.A., Harrison, M.J., Krasting, J.P., Malyshev, S.L., Milly, P.C.D., Phillipps, P.J., Sentman, L.T., Samuels, B.L., Spelman, M.J., Winton, M., Wittenberg, A.T., Zadeh, N. (2013a): GFDL's ESM2 Global Coupled Climate-Carbon Earth System Models. Part I: Physical Formulation and Baseline Simulation Characteristics. Journal of Climate 25, 6646-6665. https://doi.org/10.1175/JCLI-D-11-00560.1.

Dunne, J.P., John, J.G., Shevliakova, E., Stouffer, R.J., Krasting, J.P., Malyshev, S.L., Milly, P.C.D., Sentman, L.T., Adcroft, A.J., Cooke, W., Dunne, K.A., Griffies, S.M., Hallberg, R.W., Harrison, M.J., Levy, H., Wittenberg, A.T., Phillips, P.J., Zadeh, N. (2013b): GFDL's ESM2 Global Coupled Climate-Carbon Earth System Models. Part II: Carbon System Formulation and Baseline Simulation Characteristics. Journal of Climate 26, 2247-2267. https://doi.org/10.1175/JCLI-D-12-00150.1.

Elliott, J., Kelly, D., Chryssanthacopoulos, J., Glotter, M., Jhunjhnuwala, K., Best, N., Wilde, M., Foster, I. (2014): The parallel system for integrating impact models and sectors (pSIMS). Environmental Modelling & Software 62, 509-516. https://doi.org/10.1016/j.envsoft.2014.04.008.

European Commission (2018a) Climate impacts in Europe. Final report of the JRC PESETA III project, JRC Scientific and Policy Reports, doi:10.2760/93257, Luxemburg

European Commission (2018b), EU agricultural outlook for markets and income, 2018-2030. European Commission, DG Agriculture and Rural Development, Brussels.

European Commission (2017). EU Agricultural Outlook. For the agricultural markets and income 2017 - 2030. DG Agriculture and Rural Development, Brussels.

European Commission (2015). The 2015 Ageing Report. Economic and budgetary projections for the 28 EU Member States (2013-2060), EUROPEAN ECONOMY 3/2015. 74 Publications Office of the European Union, Luxembourg. ISBN: 978-92-79-44746-4, https://doi.org/10.2765/877631.

European Commission (2014) Climate Impacts in Europe. The JRC PESETA II Project, JRC Scientific and Policy Reports, doi:10.2791/7409, Luxemburg.

IPCC, 2013. Annex II: Climate System Scenario Tables [Prather, M., G. Flato, P. Friedlingstein, C. Jones, J.-F. Lamarque, H. Liao and P. Rasch (eds.)]. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2019): Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, et. al (eds.)]. In press.

Iversen, T., Bentsen, M., Bethke, I., Debernard, J. B., Kirkevag, A., Seland, Ã., Drange, H., Kristjansson, J. E., Medhaug, I., Sand, M., Seierstad, I. A. (2013): The Norwegian Earth System Model, NorESM1-M - Part 2: Climate response and scenario projections, Geoscientific Model Development 6, 389-415. https://doi.org/10.5194/gmd-6-389-2013.

Jones, C. D., Hughes, J. K., Bellouin, N., Hardiman, S. C., Jones, G. S., Knight, J., Liddicoat, S., O'Connor, F. M., Andres, R. J., Bell, C., Boo, K. O., Bozzo, A., Butchart, N., Cadule, P., Corbin, K. D., Doutriaux-Boucher, M., Friedlingstein, P., Gornall, J., Gray, L., Halloran, P. R., Hurtt, G., Ingram, W. J., Lamarque, J. F., Law, R. M., Meinshausen, M., Osprey, S., Palin, E. J., Parsons Chini, L., Raddatz, T., Sanderson, M. G., Sellar, A. A., Schurer, A., Valdes, P., Wood, N., Woodward, S., Yoshioka, M., and Zerroukat, M. (2011): The HadGEM2-ES implementation of CMIP5 centennial simulations. Geoscientific Model Development 4, 543-570. https://doi.org/10.5194/gmd-4-543-2011.

Jones, J. W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L. A., Wilkens, P. W., Singh, U., Gijsman, A. J., Ritchie, J.T. (2003): The DSSAT cropping system model. European Journal of Agronomy 18, 235-265. https://doi.org/10.1016/S1161-0301(02)00107-7.

Liu, J., Williams, J., Zehnder, A., Yang, H. et al. (2007). GEPIC – modelling wheat yield and crop water productivity with high resolution on a global scale. Agricultural Systems 94, 478 493. https://doi.org/10.1016/j.agsy.2006.11.019.

Müller C, Robertson R. (2014): Projecting future crop productivity for global economic modeling, Agricultural Economics 45, 37-50. https://doi.org/10.1111/agec.12088.

Pérez Domínguez, I., and T. Fellmann (2018). PESETA III: Agro-economic analysis of climate change impacts in Europe, doi:10.2760/179780, Luxemburg.

Smith, B., Prentice, I.C. & Sykes, M.T. 2001. Representation of vegetation dynamics in the modelling of terrestrial ecosystems: comparing two contrasting approaches within European climate space. Global Ecology & Biogeography 10: 621-637. https://doi.org/10.1046/j.1466-822X.2001.t01-1-00256.x.

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., … Tavoni, M. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environmental Change, 42, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009.

Toreti, A., A. Belward, I. Pérez Domínguez, G. Naumann, J. Luterbacher, O. Cronie, L. Seguini, G. Manfron, R. Lopez-Lozano, B. Baruth, M. van den Berg, F. Dentener, A. Ceglar, T. Chatzopoulos, and M. Zampieri (2019a). The exceptional 2018 European water seesaw calls for action on adaptation, Earth's Future 7, 652-663. https://doi.org/10.1029/2019EF001170.

Toreti, A., O. Cronie, and M. Zampieri (2019b). Concurrent climate extremes in the key wheat producing regions of the world, Scientific Report 9, 5393. https://doi.org/10.1038/s41598-019-41932-5.

Toreti, A., and I. Pérez Domínguez (2019). Concurrent climate extremes and agricultural shocks, Science for Policy Brief, European Commission.

Watanabe, S., Hajima, T., Sudo, K., Nagashima, T., Takemura, T., Okajima, H., Nozawa, T., Kawase, H., Abe, M., Yokohata, T., Ise, T., Sato, H., Kato, E., Takata, K., Emori, S., and Kawamiya, M. (2011): MIROC-ESM 2010: model description and basic results of CMIP5-20c3m experiments. Geoscientific Model Development 4, 845-872. https://doi.org/10.5194/gmd-4-845-2011.

Webber, H., Ewert, F., Olesen, J.E. et al. (2018) Diverging importance of drought stress for maize and winter wheat in Europe. Nature Communication 9, 4249. https://doi.org/10.1038/s41467-018-06525-2.

Williams, J. R. (1995): The EPIC Model. In: V.P. singh (ed), Computer models of watershed hydrology, Water Resources Publications, Littleton, USA, 909-1000.

List of figures

List of tables

GETTING IN TOUCH WITH THE EU

In person

All over the European Union there are hundreds of Europe Direct information centres. You can find the address of the centre nearest you at: https://europa.eu/european-union/contact_en

On the phone or by email

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

- by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),

- at the following standard number: +32 22999696, or

- by electronic mail via: https://europa.eu/european-union/contact_en

FINDING INFORMATION ABOUT THE EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website at: https://europa.eu/european-union/index_en

EU publications

You can download or order free and priced EU publications from EU Bookshop at: https://publications.europa.eu/en/publications. Multiple copies of free publications may be obtained by contacting Europe Direct or your local information centre (see https://europa.eu/european-union/contact_en).

KJ-NA-30078-EN-N

The European Commission's science and knowledge service

Joint Research Centre

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub

EU Science Hub - Joint Research Centre

EU Science, Research and Innovation

EU Science Hub

Publications Office of the European Union

doi:10.2760/121115

ISBN 978-92-76-10617-3