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COACCH

CO-designing the Assessment of Climate CHange costs

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D2.2 Impacts on agriculture including forestry & fishery

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Version log

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Deliverable Summary

Climate change has the potential to affect the agriculture, forestry and fisheries sector, both negatively (e.g. from lower rainfall, increasing variability, extreme heat) and positively (e.g. from CO_2 fertilization, extended seasons). These effects will arise from gradual climate change and extreme events that will directly affect production, but also from indirect effects, e.g. changes in prevalence of pests and diseases. These will affect productivity and, in turn, production, consumption, prices, trade and land use.

This study analyses the impacts of slow-onset climate change on agriculture, forestry and fisheries, with a focus on the European Union. For this purpose, new estimates are derived from a suite of models to quantify the costs of climate change on these sectors. A broad range of climate models, crop models (EPIC, GEPIC and LPJmL 5), forest models (G4M, FLAM) and living marine resources models are combined with two bio-economic models (MAgPIE 4 and GLOBIOM) covering the land use and marine production sectors. The impact of additional factors such as socioeconomic pathways, level of warming, CO_2 fertilization, are also quantified.

This study finds that the magnitude of climate induced yield impacts highly differs across sectors. In the case of crops cultivated in the EU, climate impacts on winter wheat, oil seeds and sugar crops are of a much lower magnitude compared to impacts on corn. This induces large area reallocations for corn and other crops due to changes in relative profitability, resulting in agricultural losses in Southern and Eastern Europe, and gains in Northern and Western Europe.

When it comes to forest, two pathways of climate impacts are analysed: first, through the impact on forest increments and harvest potentials, and second, through the enhanced risk of forest fires. The biophysical forest model G4M estimates that increased temperature and decreased precipitation cause a reduction in the biomass and growth rate of forests in Southern Europe, especially towards 2070 under RCP8.5. Furthermore, the potential burned area in Europe will increase significantly in Europe especially under the RCP8.5 scenario, where burned areas could more than double compared to present-day. Climate-induced interactions between the agriculture and forestry sectors are however of limited magnitude.

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Fisheries will also be impacted by climate change. A global decline in marine capture is anticipated, although some strong regional differences should occur. Fisheries near the equator are to be affected more negatively and fish population may migrate to Northern latitudes, where fisheries may gain. Whether EU Member States are projected to experience declines in marine productive capacity depends strongly on the biophysical impact model applied and on the degree of warming.

This study highlights two important items for further research. First, considering the increased variability and likelihood of extreme events caused by climate change is of crucial importance to arrive with more comprehensive climate impact estimates for both the agriculture and forestry sector. This will be considered in Work Package 3 of the COACCH project. Second, the degree to which producers can adapt to climate change needs to be further researched. This adaptation, and the degree to which policies can help producers to adapt against climate change, and towards which direction, will be further researched in Work Package 4 of COACCH.

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1. Introduction

Agriculture, forestry and fisheries are among the most exposed sectors to climate change, due to their dependency on climate variables. These sectors are also critical for our economies and livelihoods, as they shape the development of rural areas, provide food and materials for societies and are a source of income for hundreds of million people around the world. In the case of the EU, even though it has turned towards a service economy, agriculture, forestry and fisheries still represents 230 billion Euros of added value, without considering the downstream industries that transform and distribute these products.

Climate change alters both trend and fluctuations in daily, seasonal and annual temperature and rainfall and, thereby, agricultural yields and production. There has been a vast amount of literature assessing long-term climate change impacts on agricultural production, mainly focussing on 50-100 year mean climate change effects on average levels of crop yields (Chen, McCarl, and Schimmelpfenning 2004; Challinor et al., 2014). These studies generally use an impact modelling chain starting from climate models that assess the effect of climatic trends on temperature and precipitation. Subsequently, crop models assess the effect of resulting temperature and precipitation changes, as well as increased atmospheric CO_2 concentration, on crop yields. To represent the economic effect of these yield changes on agricultural markets, Partial Equilibrium (PE) and Computable General Equilibrium (CGE) models, as well as various econometric approaches or simulation models are often used (Nelson et al. 2014). Because the assessment of economic impact of climate change is key to the determination of the need for mitigation policies, the chain of climate-crop and PE and CGE models is central to the study of climate change adaptation and mitigation, as well as its different feedback loops (Moss et al. 2010). Economic adjustments can indeed buffer a part of the direct effects of climate change on yields. For instance, Nelson et al. (2014) analysed, based on a comparison of nine global economic models with a focus on agriculture, that an estimated 17% yield reduction due to climate change by 2050 can be limited via endogenous economic responses to 11% overall yield loss, and together with an 11% increase in cropland area would lead to a reduction in consumption of just 3%. Similarly, Leclère et al. (2014) extend this analysis to 9 alternative climate scenarios using the crop model EPIC and the economic model GLOBIOM to study the adaptation response of the agricultural sector and find that management changes and crop reallocation should allow to buffer a significant part of the climate shocks. More recently, Hasegawa et al. (2018) compared the effect of climate change impacts on food security with those of climate mitigation policies deployed to avoid these, using a chain of impacts based on five global earth system and climate models, three global crop models, and eight agricultural economic models or Integrated Assessment Models (IAMs). They find that, in the case where stringent policies would be also applied to agricultural sectors in developing countries, food security would be even more negatively affected, due to high prices for key agricultural products.

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More detailed studies have been conducted in the case of the EU. Wolf et al. (2015) apply a model chain consisting of a crop-growth model (SIMPLACE), an agricultural sector model (CAPRI), a bio-economic farm model (FSSIM) and an environmental agricultural model for the quantification of nitrogen and GHG emissions (INTEGRATOR). They assess climate change impacts under different assumptions regarding technological development and policy changes on crop yields, commodity prices, net farm income, farm labour demand and nitrogen losses for five European regions. Ciscar et al. (2018) perform an analysis of the economic impacts of climate change in Europe across all sectors, using a CGE analysis. They find that under a high warming scenario, GDP loss at horizon 2050 could be up to 1.9%, i.e. 240 billion EUR, from which about 20% would be coming from agriculture. The impacts on the agricultural sector assessed through yields shocks are based on EURO-CORDEX simulations for the EU and ISI-MIP fast-track project results for rest of the world, but without consideration of CO_2 fertilisation effects. Once analysing the results of the shifters with the CAPRI model, Perez Dominguez and Fellmann (2018) report that impact without CO_2 effects lead to a slight increase (+1.3%) of EU Utilized Agricultural Area (UAA). Climate change is found to benefit crops in the Eastern part of Europe, whereas agriculture faces more stress in the Southern part. However, when CO_2 fertilisation effects are considered, negative impacts of climate shocks are offset in most EU regions and total UAA largely decreases in response to the increased yields (-5%).

The aim of this report is to revisit these findings and provide a broader analysis of the climate change impacts and related economic costs for agriculture in the EU, extended to the sectors of fisheries and forestry. We use a broad set of climate data sourced from EURO-CORDEX and ISI-MIP, and analyse these through two partial equilibrium models, GLOBIOM and MAgPIE 4. Our assessment focuses both on biophysical impacts but also estimates of economic costs for the EU economy.

The report is organized as follows. In Section 2, an overview of the methods and frameworks to estimate the impact of slow-onset climate change on the agricultural sector is provided. Climate change and socioeconomic pathways are briefly presented and their main elements compared. Each of these scenarios uses climate models to project how climate will evolve in the medium to long term. Measurements of impacts of climate change must rely on models that translate changes in climate to changes in crop productivity. Three different process-based crop models, LPJmL, EPIC and GEPIC, as well as the forestry model G4M, the forest fire model FLAM are compared in terms of their main elements, functioning and output parameters and the results these have on estimating climate impacts on productivity, input and biomass. The climate change impact results from these models are presented in Section 3, with successive focuses on crops, forests, and fisheries. Section 4 analyses how these impacts propagate to markets using the PE models covering the agricultural, forestry and fisheries sectors. These models provide economic estimates of the impacts of climate change, their effect on market prices, sector value and costs for the consumers, as well as the main adaptation responses. Section 5 draws upon the impacts found in Section 3 and 4 and

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summarizes the economic costs of climate change. A discussion on the current state and future research in slow onset climate change concludes the report.

2. Methods and scenario set-up

2.1. Impact assessment modelling chains

The analysis of climate change impact requires mobilizing different models and tools, each of those looking at different systems and informing on how these respond to changes in their environmental variables (see Figure 1). First, trajectories of GHG emissions define different level of radiative forcing, and the impact of these on temperature and precipitation patterns are studied through the use of General Circulation Models (GCMs). Second, the change in temperature and precipitation patterns, as well as the atmospheric concentration in CO_2, are used as input in different biophysical models related to crops and forest growth (GGCMs), forest fire (FLAM), or fisheries (Living Marine Resource models). The productivity impact of these models is last integrated into economic models, in the case of this study, GLOBIOM and MAgPIE.

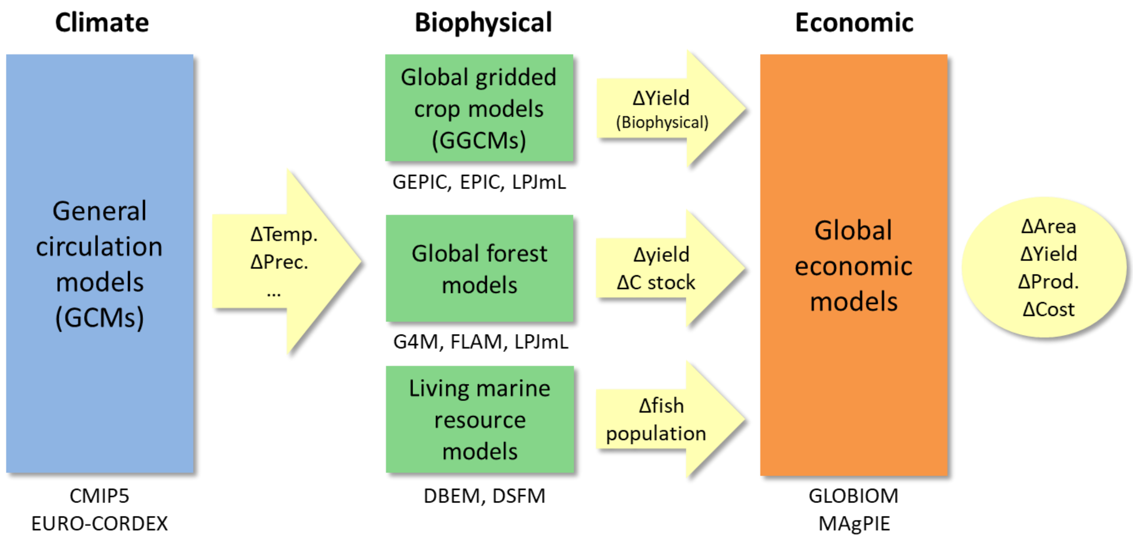

Figure 1. Climate change impact modelling chain for agriculture, forestry and fisheries in COACCH

For the COACCH project, two impact modelling chains were used, structured around the two economic models, GLOBIOM and MAgPIE. The GLOBIOM impact chain combines GCM results with the EPIC and GEPIC models for crops, the G4M and FLAM models for forestry and the DBEM and DSFM models for fisheries. The MAgPIE impact chain is based on the LPJmL model for crops and for forestry, and the DBEM model for fisheries.

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2.2. Climate models

2.2.1. Climate data sources

A number of global climate research projects have calculated likely climate changes under various indicators such as alternative atmospheric concentration of CO_2 (Adams et al. 1990). The emergence of these model inter-comparison projects began in the late 1980s and these initiatives have developed and generate today a wide range of climate model results and model couplings. Four of these projects are the Atmospheric Model Inter-comparison Project (AMIP), the Coupled Model Inter-comparison Projects (CMIP), the Inter-Sectoral Impact Model Inter-comparison Project (ISIMIP), and the World Climate Research Program Coordinated Regional Downscaling Experiment (CORDEX). In this report, we make use of two of these projects: ISIMIP and the European part of CORDEX (EURO-CORDEX).

The CORDEX project is a framework fostering the development, comparison and improvement of regional climate scenarios. In the case of Europe, the EURO-CORDEX initiative provides regional climate projections based on downscaled CMIP5 global climate projections for the European continent at 50 and 12.5 km resolution (Jacob et al. 2014). Results of the EURO-CORDEX initiative showed that Europe may experience over 2°C of warming even if the Paris goals in terms of emissions are achieved. Furthermore, regionally, patterns may be differentiated; the Mediterranean region could experience 3°C of warming in summer, and Scandinavia and the Baltic 4°C of warming in winter. Under a 2°C global change scenario, increases in frequency and severity of extreme weather events will occur, specified by heat extremes in terms of daily maximum temperatures and heatwaves in South-Eastern and North-Eastern Europe. Under the same scenario, precipitation intensity will increase by 5 to 15%, with extremes to more than 20% in winter and fall times for Central and Northern Europe. Decreases in average precipitation combined with increased cases of extreme rainfall may occur in central Europe (Rajczak & Schär, 2017; Scoccimarro et al., 2017; Scoccimarro et al., 2016). Inter-model spread between simulations in terms of for example precipitation is however large. Such increased heavy precipitation may also lead to increased flood risk (Vautard et al., 2014).

The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) compiles numerous climate-impact models with the same climate and socio-economic indicators in an open-source platform. ISIMIP Fast Track, the first phase of the project, was novel in its achievement of providing a set of cross-sectoral consistent, multi-model impact projections. Its second phase is currently under completion, focusing more towards the assessment of extreme events by using historical and future climate and CO_2 concentrations and the effect of a 1.5 versus 2 degree warming (Frieler et al. 2017). The next generation of ISIMIP results (ISIMIP3) will aim at updating the large ensemble database across climate and crop model scenarios generated for ISIMIP fast track. As these model runs are still underway, this deliverable focuses on the ISIMIP-FastTrack results.

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Throughout the impact chain of climate models, crop models, and socio-economic models, uncertainty on the effects of climate become apparent. For this reason, this report will take an ensemble approach when analysing the results of climate change impacts, distinguishing results obtained among different climate models, crop models and socio-economic models.

2.2.2. Model types and climate scenarios

Climate models describe the processes by which climate responds to natural and anthropogenic changes to the Earth’s natural systems. They are derived from physical laws, based on the climate system and further approximated through mathematical discretization. The most complex of them – the Earth System Models (ESMs) – include interactions of the atmosphere, ocean, land, and sea ice and analyse land and biophysical processes at the level of thousands of grid cells. Anthropogenic influences on the climate system are often assessed by including greenhouse gas concentrations, pollution, and changes in land use and land cover (Claussen et al., 2002). ESMs are based on climate models, but additionally include ecological and chemical processes, such as carbon cycle, vegetation, and atmospheric chemistry, and estimate over a very long-time horizon.

General Circulation Models (GCMs) can be global or regional in terms of scale. Regional climate models are much more detailed in terms of atmosphere-ocean systems. For example, they provide higher daily precipitation intensities and model on a much finer spatial scale (Josephson, Ricker-Gilbert, and Florax 2014; Moss et al. 2010; Randall et al. 2007). Simpler GCMs are better suited to assess key uncertainties, processes and interactions in the climate system, such as the frequency and magnitude of monsoons and El Niño Southern Oscillation (ENSO) events.

Climate models are often used in an ensemble approach, using CMIP3 or CMIP5 datasets to disentangle model-related uncertainty from climate change-related ones. Criteria for the best selection of GCMs are assessed by Dubrovsky et al. (2014). They conclude that a subset of GCMs can either be selected using expert judgement or based on the quality of the GCM and the ability of the subset to represent inter-GCM variability.

Because GCMs differ in terms of how they model atmosphere, land, and ocean dynamics, model differences represent uncertainties in these dynamics as well as model construction uncertainties (Lobell and Burke 2008). GCM outputs are not well suited to direct application to sectoral climate impacts, and usually need additional downscaling. This adds one layer of uncertainties, as downscaled projections and climate statistics are influenced then by both variabilities in climate models and statistical downscaling techniques (Sunyer, Madsen, and Ang 2012; Asseng et al. 2013).

This report focuses on the impacts of climate change in Europe. Two different set of climate model ensembles, distinguishing global climate model results for the analysis of the climate change impacts outside of Europe, sourced from ISIMIP, and from downscaled model results from EURO-CORDEX for the analysis of climate change impacts in Europe, are combined. We distinguish four different contrasted trends

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across climate models: low and high temperature, and low and high precipitation. The climate models selected are featured in Table 1 below. EURO-CORDEX scenarios were classified based on the typology provided within the COACCH project, whereas the selection and classification of global GCMs from ISIMIP was based on patterns observed in Europe for climate model results in Rosenzweig et al. (2014).

Table 1. Climate model combination used for this analysis, at global and EU level

	High precipitation	Low precipitation
High temperature	IPSL-CM5A-LR (ISIMIP) WRF33 x IPSL-CM5A-MR (EURO-CORDEX)	HadGEM2-ES (ISIMIP) RCA4 x HadGEM2-ES (EURO-CORDEX)
Low temperature	NorESM1-M (ISIMIP)	GFDL-ESM2 (ISIMIP) RCA4 x EC-EARTH (EURO-CORDEX)

2.2.3. Representative concentration pathways

Climate models described above are used to project future climate patterns along different greenhouse gases trajectories, called Representative Concentration Pathways (RCPs). These scenarios have been standardized by the climate change community to facilitate the comparison of climate change model scenarios along the assessment chain (van Vuuren et al., 2011).

For our current approach, we use mainly four RCPs, indexed by their level of atmospheric radiative forcing at time horizon 2100. Our main scenario is RCP4.5 (forcing of 4.5 W/m^2), and we also pay specific attention to the results for RCP2.6, which corresponds to a stabilisation of climate change at around 2°C above the preindustrial level, and RCP6.0, which corresponds to a situation of strong climate change degradation under business as usual. For some specific analyses, we also use the RCP8.5, which represents a worst-case climate change, under a business as usual scenario with high economic growth.

As the time horizon for many aspects of our analysis is 2050, it is important to note that, due to the differing dynamics of the RCPs, the hierarchy of RCPs is not well reflected by the 2100 level of radiative forcing. Indeed, by 2050, the CO_2 concentration under RCP4.5 is still slightly higher than under RCP6.0. Therefore, when looking at results at time horizon 2050, RCP4.5 is usually expected to be the one having the largest impacts from climate change when compared to both RCP2.6 and RCP6.0.

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2.3. Biophysical models

2.3.1. Crop models

Different climate scenarios result in different probabilities and magnitudes of weather variability. To analyse their effects on the agricultural sector, we first need to quantify the impact of such climate variabilities on crop yields, using process-based crop models or econometric approaches. In our analysis, we choose to rely on a global implementation of process-based models, based on a gridded representation of climate and agronomic condition at global scale, also referred to as Global Gridded Crop Models (GGCM).

Process-based crop models simulate the effect of a wide range of exogenous variables such as weather, plant genotypes, environmental factors and management styles on plant growth, by representing key processes affecting plant biochemistry and exchange with its environment. They were initially developed for the purpose of field-level cropping decisions but have been increasingly used to analyse climate change impacts at larger scale. Especially in the last two decades, crop models have been tailored more to the inclusion of environmental and management indicators, such as temperature, CO_2, and ozone, allowing them to analyse crop and management options under different climate patterns (Hatfield et al. 2011; Pathak and Wassmann 2009). Currently, crop models can roughly be grouped into three strands: (1) site-based crop models that simulate crop growth at the field scale and focus on the feedbacks between crop growth and soil, atmosphere and management; (2) dynamic global vegetation models that simulate carbon and water cycles; (3) agro-ecological zone models that focus on the regional and global scale (Rosenzweig et al. 2014).

In our study, we use results from three different crop models: GEPIC, EPIC and LPJmL. Table 2 below provides an overview of the main differences between these three crop models.

Table 2. Comparison of the three GGCMs used in this report.

Model name	Characteristics	Climate input variables	Outputs	Main Reference
Environmental Policy Integrated Climate Model (EPIC)	Dynamic simulation based on development and growth processes using water, temperature, heat, oxygen, nitrogen, phosphorus, bulk density and aluminium stress as inputs.	Minimum temperature, maximum temperature, precipitation, relative humidity, wind speed.	Plant growth, crop yield, tillage, wind and water erosion, runoff, soil density, and leaching, water and fertilizer requirement. Actual yields under management systems, including irrigation.	Williams (1995); Izaurralde et al. (2006)
Geographic Information System (GIS)-	As EPIC. While EPIC employs transient simulations for	Minimum temperature, maximum	Total biomass, crop yield, wind and water erosion, soil hydrology,	Williams et al. (1995); Liu et al. (2007) ; Folberth

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based Environmental Policy Integrated Climate Model (GEPIC)	defined globally uniform crop management scenarios that are spatially attributed ex post, GEPIC simulates each decade separately with a 30-year spin-up mimicking soil nutrient depletion to presently likely levels in low-input regions while avoiding complete depletion in the long run.	temperature, precipitation, relative humidity, wind speed, tillage.	soil density, and CNP fluxes, water and fertilizer consumption. Actual yields under business-as-usual N and P fertilizer inputs, including sufficient irrigation water supply or rainfed-only systems according to land use data.	et al. (2012)
Lund-Potsdam-Jena managed Land Dynamic Global Vegetation and Water Balance Model (LPJmL)-	Global gridded vegetation, crop and hydrology model. Process based representation of photosynthesis and phenology. Land use, precipitation, water, soil type, CO_2 concentrations and radiation are model inputs. Simulates transient changes in carbon and water cycles.	Average temperature, precipitation, CO_2 concentration, cloud cover.	Yield patterns under management systems, including irrigation. Carbon stocks in vegetation and soils. Water availabiltiy and water withdrawals by crop irrigation.	Von Bloh et al (2017)

2.3.2. Forestry models

2.3.2.1. G4M

IIASA Global Forest Model (G4M)[1] is used to model forest growth, the G4M uses a dynamic NPP model in order to consider how growth rates are affected by changes in temperature, precipitation, radiation, as well as soil properties. G4M can be used to model parameters based on a country's own statistics, for example, forest cover, species composition, age class distribution, and live biomass, to check their accuracy. G4M works with a monthly step and the highest spatial resolution is 1 km^2. G4M produces important output variables including Net Primary Productivity, Mean Annual

[1] www.iiasa.ac.at/g4m

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Increment, Standing Biomass, Harvestable Biomass. Results are used as input for FLAM and GLOBIOM models.

The methodology implemented in G4M is schematically illustrated in Figure 2. NPP model is based on the historically observed values of NPP coming from the remote sensing products. For this project NPP values from MODIS were used. G4M identifies how spatial input data, i.e. climate, soil, and land cover determine the values of NPP for various forest types using statistical methods. The main idea consists in the fact that various input variables, e.g. temperature, precipitation, have limiting effects on the forest productivity. Besides routine for calculating evapotranspiration and water balance with the monthly time-step is implemented in that block of G4M.

Therefore, one block (green in the figure) allows to project NPP based on the future climate conditions. Another block consists in calibration of growth curves for different forest types and species based on the yield tables or sample plots data. The curves are calibrated using statistical functions from forestry science. Finally, the NPP model and growth curves are combined to identify the growth dynamics in a grid cell by means of identifying spatially explicit site index per species. The overall structure allows projecting key biophysical variables, such as mean annual increment, aboveground biomass, harvestable biomass, etc. under changing climate conditions. G4M can choose the optimal species per grid cell in terms of MAI, biomass stock, etc.

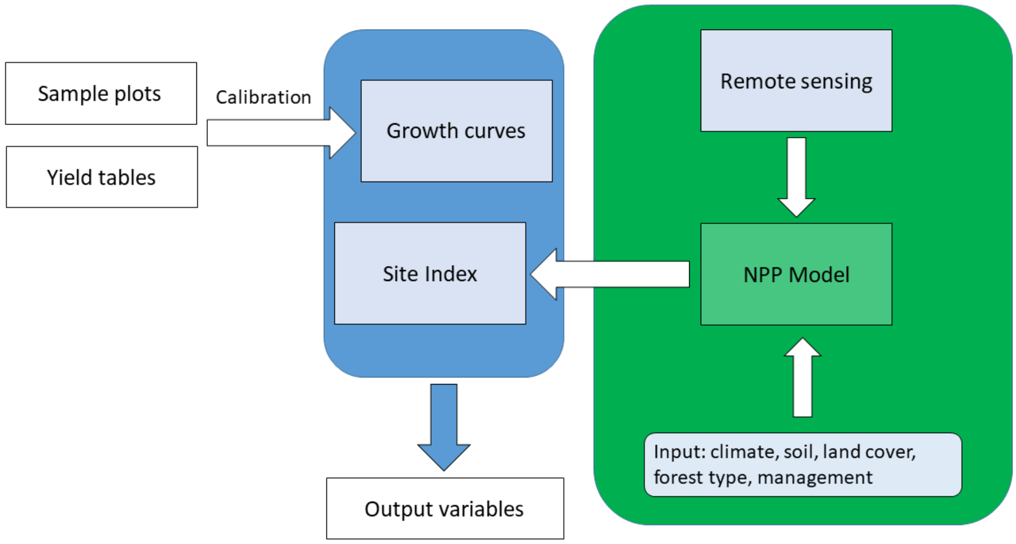

Figure 2. Scheme of the G4M methodology

2.3.2.2. LPJmL and MAgPIE forestry module

Biophysical impacts of climate change on forestry are calculated using the LPJmL model (Schaphoff, S. *et al.* 2018). The model calculates carbon fluxes (gross primary production, auto- and heterotrophic respiration) and the respective changes in carbon

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pools (leaves, sapwood, heartwood, roots, storage organs, litter and soil), as well as water fluxes (interception, percolation, evaporation, transpiration, snowmelt, runoff). Closed mass balances across all fluxes and pools are ensured for carbon and water, while carbon and water pools adjust dynamically according to the in- and outgoing fluxes. Natural vegetation is represented in LPJmL at the biome level by nine PFTs. Processes of carbon assimilation and water consumption are parameterized on the leaf level and scaled to the simulation unit. Carbon assimilation by photosynthesis, water fluxes and plant and soil respiration are computed at daily time steps, whereas the allocation to the vegetation carbon pools is updated at annual time steps. Intra-annual dynamics of leaf area, and thus light interception, are computed by scaling the leaf biomass with a phenology-dependent factor. Carbon and water dynamics are linked so that the effects of changing temperatures, water availability and CO_2 concentrations are accounted for. Physiological and structural plant traits of each PFT determine its water requirements and consumption.

Forests in MAgPIE are modelled using two different modules namely forestry and natural vegetation. The forestry module in MAgPIE describes the conditions under which managed forest (age-class forest) exists and the dynamics of forestry land, production and demand. At the same time, it calculates the corresponding carbon stocks. Natural vegetation module in MAgPIE encompasses primary forest, secondary forest and other natural land.

To calculate timber yields, carbon density for vegetation carbon from LPJmL is used. This carbon density is converted into volumetric yields based on biomass conversion and expansion factors in different climate-classes (based on Köppen Climate Classification) and is the basis for the MAgPIE 4 simulations.

MAgPIE 4 is a spatially explicit dynamic-recursive model with an averall objective of global production cost minimization. MAgPIE usually runs on five-year time steps. The methodology implemented for forest sector in MAgPIE is illustrated in Figure 3. Forestry and natural vegetation modules from MAgPIE can be used to produce two different timber products, namely, wood and wood-fuel based on domestic demand for timber in each country (aggregated to MAgPIE regions). Timber demand is met by harvesting a combination of both managed plantations and natural vegetation. The model also accounts for self-sufficiency based trade for timber products.

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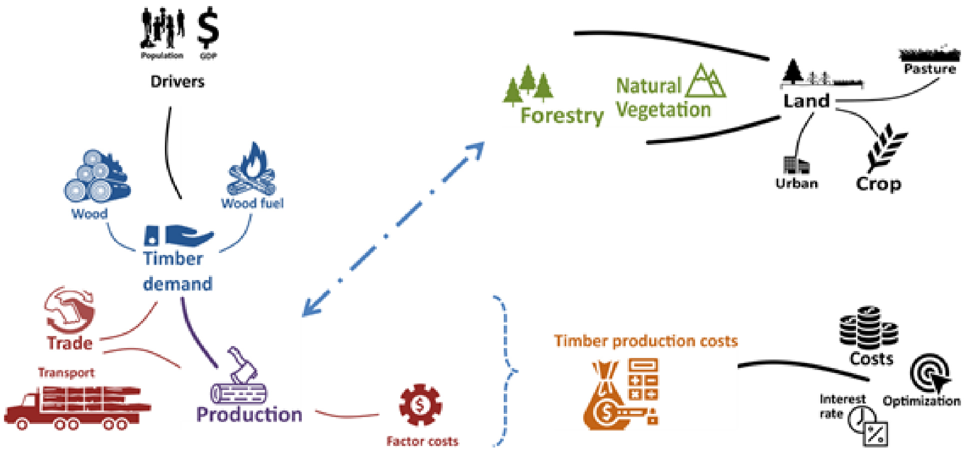

Figure 3. Forest sector methodology in the MAgPIE model

Timber demand is currently only calculated for SSP2 scenario with a non-linear projection for future demand based on historical FAO data. MAgPIE is free to decide between the sources of production of timber while respecting the trade as well as forest protection constraints. During the optimization, MAgPIE also identifies where new plantations have to be established in order to meet increasing share of future timber demand to be produced from plantation forests. MAgPIE also identifies how changes in rotation length in forest plantations and the extent of clear-cutting or selective logging allowed in natural vegetation determines the demand for various land-use types using global production cost minimization.

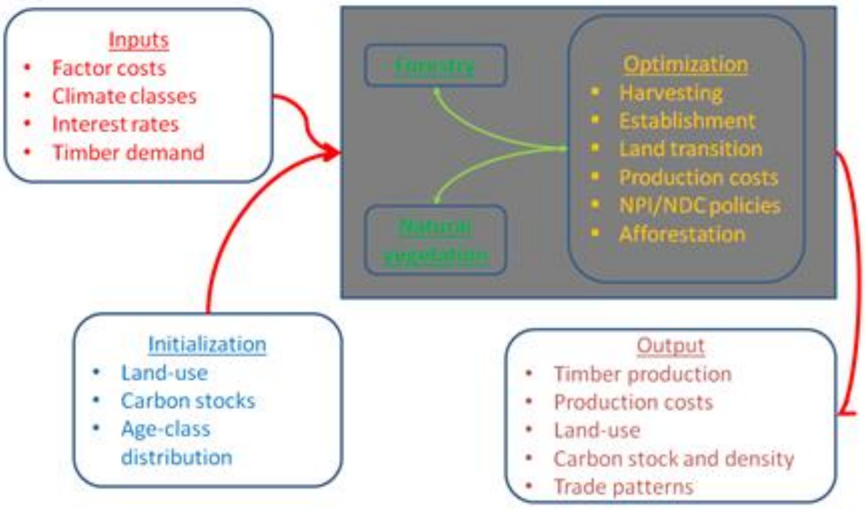

Figure 4. Modelling mechanism for the forestry sector in MAgPIE

The model is initialized with land patterns of the LUH database (http://luh.umd.edu/) for natural vegetation of plantations are initialized with the FAO plantation data downscaled on cellular level using wood removals as weights. Land is equally distributed in all age-classes from a rotation in plantations and both primary and secondary forests are assumed to exist in highest age class for the first year of

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simulation. In climate-change scenarios, the model can re-calculate optimal rotation lengths in plantations by comparing the instantaneous growth rates with existing market interest rates in order to determine harvesting time in plantations. Depending on the slope of instantaneous growth rate curve (which depends on interest rates, carbon stocks and growth function of forests), a higher interest rate results in shorter rotation in plantations and vice-versa.

2.3.2.3. FLAM model of forest wildfire

This study also analyses the extent of burned areas under projected climate change. The Wildfire Climate Impacts and Adaptation Model (FLAM) is able to capture impacts of climate, population, and fuel availability on burned areas. FLAM uses a process-based fire parameterization algorithm that was originally developed to link a fire model with dynamic global vegetation models. The key features implemented in FLAM include fuel moisture computation based on the Fine Fuel Moisture Code (FFMC) of the Canadian Forest Fire Weather Index (FWI), and a procedure to calibrate spatial fire suppression efficiency.

Currently FLAM operates with a daily time-step at 0.25-arc degree spatial resolution. All inputs in FLAM are adjusted to fit this resolution. FLAM uses daily climate data for temperature, precipitation, wind, and relative humidity. When calculating the human ignition probability, a gridded population density is used. Fuel available for burning is defined as a combination of litter and coarse woody debris (CWD) pools, excluding stem biomass. We use integrated modeling approach, where biomass dynamics is provided by the IIASA's global forestry model G4M. We used the same climate change scenarios as were used by G4M (previous section).

The fire suppression efficiency is implemented in FLAM as the probability of extinguishing a fire on a given day.

For this study, FLAM is calibrated using the historical data on burned areas from the European Forest Fire Information System – EFFIS[2]. The calibration period is 2009-2018. We calibrate spatially explicitly suppression efficiency using the shapes of historical burned areas provided by EFFIS aggregate to 0.5 arc degree resolution applied in this study to match the climate data resolution. Around 10% of burned area reported by EFFIS is excluded from the analysis, as the corresponding pixels were not covered by the weather data in ISIMIP. Those pixels are all located on the coastal area. Afterwards

[2] Acknowledgement: Data were provided by the European Forest Fire Information System – EFFIS (http://effis.jrc.ec.europa.eu) of the European Commission Joint Research Centre. Reference: San-Miguel-Ayanz, J., Schulte, E., Schmuck, G., Camia, A., Strobl, P., Libertà, G., Giovando, C., Boca, R., Sedano, F., Kempeneers, P., McInerney, D., Withmore, C., Santos de Oliveira, S., Rodrigues, M., Durrant, T., Corti, P., Oehler, F., Vilar L., Amatulli, G. (2012) Comprehensive monitoring of wildfires in europe: the European Forest Fire Information System (EFFIS), in John Tiefenbacher (Ed.), Approaches to Managing Disaster - Assessing Hazards, Emergencies and Disaster Impacts, pp. 87-105, InTech, ISBN 978-953-51-0294-6.

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projected burned areas are calculated for the period 2019-2099 for four RCP-scenarios coming from the ISIMIP2b HagGEM2-ES model.

In the FLAM setup, population density is based on the dynamic maps of the Gridded Population of the World, v4. We use maps for the years 2000, 2005, 2010 and 2015, inside the modeling interval 2001–2015, and 2020 for years after 2016. Lightning represents a natural ignition source in the model. Here, we use monthly climatology averaged from 1995–2014 at 0.5-degree resolution from LIS/OTD Gridded Lightning Climatology Data Collection Version 2.3.2015. To model fuel available for burning, we need information about litter and Coarse Woody Debris (CWD). Data from the Global Forest Resources Assessment 2015 (FRA 2015) of the Food and Agriculture Organization of the United Nations are used to obtain the shares of these components in the above-ground biomass (AGB), coming from annual G4M outputs for each RCP.

The FLAM's modeled burned areas in the historical period (2009-2018) showed good agreement with observed data coming EFFIS. For entire Europe the correlation of annual burned areas modelled by FLAM and reported by EFFIS was around 0.7.

2.3.3. Fishery models

Global warming may affect fish production in various ways (Allison et al. 2009): Sea level rise may affect coastal fish habitats as well as harbour infrastructure, and a change in the frequency and strength of storms may affect both harbour and aquaculture infrastructure, as well as the possible fishing days and the risk of fishing operations. Warming of ocean surface water may shift plankton production northwards and change the timing of plankton blooms and composition. The reduction of O_2 concentration in oceans, enhanced by eutrophication, will further decrease fish stocks. Moreover, fish population may migrate into colder, deeper water and from coastal waters towards the oceans to avoid warm temperatures. Changing habitats may increase the risk from invasive species and destabilize population of current target species. This will result in overall negative effects for marine biodiversity (Worm et al, 2016). Different ocean currents and upwelling may change the spatial location, timing and the technical equipment required for fishing activity. Additional to global warming, ocean acidification through increased levels of atmospheric CO_2 will have strong negative effect on calciferous animals and lead to a decline in coral reefs. This may have severe consequences on the marine food webs and fish production. Cumulative impacts and feedback effects for marine fish are therefore difficult to disentangle and to predict.

2.3.3.1. Living Marine Resource (LMR) models

To derive estimate of the impact of climate change on marine fisheries, we rely on a recent study by the Food and Agriculture Organisation of the United Nations, which used an array of climate models to estimate a range of 2005/2100 fisheries projections for the RCP2.6 and RCP8.5 scenarios (Barange et al., 2018). In order to translate the climatic estimates into projections of changes in catch potential at the level of individual country Exclusive Economic Zones (EEZ), the study used two alternative

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approaches: a dynamic bioclimate envelope model (DBEM) and a dynamic size-based food web model (DSFM).

The DBEM approach (Cheung et al., 2016) is based on an estimation of the effect of elevated sea surface temperature, reduced surface oxygen and shifted primary production on fish catch potentials in the large marine ecosystems. Large marine ecosystems classify the world ocean's coastal areas in 66 different zones based on ecological characteristics (Sherman et al 2007). The extent to which climate impacts are modelled on a global scale is still rather limited. Our estimate does not, for example, account for the effect of ocean acidification or the effect of storms.

The DSFM approach (Blanchard et al., 2012) relies on a similar representation to the DBEM but does not distinguish fish species, focusing solely on fish size and their dynamics. The model study how climate change impacts the plankton size spectrum along the different functional types and subsequently impact the depth distribution of the fish in the surface ocean across size spectra. This information is also aggregated at the level of the different EEZs.

The LMR model results were used as an input for the two economic models, GLOBIOM (both LMRs) and MAgPIE (DBEM), as described below.

2.3.3.1. GLOBIOM fish module

The GLOBIOM Fish module is a representation of the global production, trade, and utilization of seafood, fishmeal, and fish oil products; it's also a representation of the mass balances of inputs and outputs which flow between the capture, aquaculture, agriculture, and livestock sectors. The model encompasses all fish, crustaceans, and molluscs (henceforth "fish") in Divisions 1-5 of the International Standard Classification of Aquatic Animals and Plants (ISSCAAP) and it disaggregates production into 20 species-group production systems (FAO, 2019). In fish production, the model covers output both from capture and aquaculture, differentiating between four aquatic environments and two levels of production system intensification. Geographically, the model tracks production at the country level and also at the level of 27 FAO Major Fishing Areas (FAO, 2019).

The model differentiates between four utilizations of fish (food for human consumption, reduction, feed, and other). Fishmeal and oil (henceforth "marine ingredients") are produced from reduction of whole fish, as well as the reduction of fish by-products and fish processing waste. Marine ingredients can be utilized for either aquaculture feed, livestock feed, or other uses. The yield of marine ingredients varies between different fish species groups, and feed requirements in aquaculture production also vary between different fish species groups. This variation of feed ingredients extends to the five most widely used crop feed ingredients in aquaculture production. Through the explicit accounting for the sources of marine ingredient production, and the detailed representation of the utilization of marine ingredients in aquaculture feed, the model ties together the capture and aquaculture sectors; through the accounting for crop feeds used in aquaculture production, the model links

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the fish sector with the agriculture sector, and through the accounting for marine ingredient use in livestock feed, the model links the fish sector to the livestock sector.

Capture production in the GLOBIOM Fish model is not modelled endogenously; future production is an extrapolation of historical trends at a detailed geographical and species level. To estimate the effects of climate change on capture fisheries, we rely directly on the analysis from the two models DBEM and possible changes in annual production. For this project, we map the EEZs to individual countries, or where possible, to the FAO Major Fishing Areas in the GLOBIOM model, and we use the changes in catch potential to adjust the exogenous projections of capture production in our model. Thereafter, we analyse the direct effects on fish production and fish availability, as well as the indirect effects on changes in aquaculture production potential, which is affected by changes in the availability of fishmeal and fish oil.

To estimate the effects of climate change on aquaculture, we use a recent paper which modelled and mapped the effect of warming ocean conditions (RCP8.5) on marine aquaculture production potential based on thermal tolerance and growth data of 180 cultured finfish and bivalve species (Froehlich, 2018). We map the finfish and molluscs in the study to the fish species groups in the GLOBIOM model, and we also map the EEZ areas studied to countries and, where possible, FAO Major Fishing Areas in the GLOBIOM Fish model. We analyse the direct effects on fish production and availability as a result of the decreased production potential. We also analyse the indirect effects of decreased fishmeal and fish oil production from processing waste, the decreased marine ingredient availability, and the resulting additional decrease in aquaculture production potential. In cases of both capture and aquaculture, the effects are analysed at the global as well as regional level, as climate effects are distributed disproportionately across the globe (generally benefiting higher latitudes and adversely impacting areas closer to the equator).

2.3.3.2. MAgPIE fish methodology

In the case of MAgPIE, the land-system consequences of climate change impact on fisheries was assessed by assessing the land substitution between marine fisheries and aquaculture.

We applied the relative changes of catch potentials in large marine ecosystems on current (2010) marine capture fish production from FAO FishStat. The selection of marine fish catches was based on the fish species (source) as well as the capture area. We mapped the 66 Large marine ecosystems to the 19 FAO major fishing areas used in FAO FishStat in order to harmonize the different geographical units. FAO FishStat distinguishes aquaculture and capture fisheries. We only applied the climate impacts on capture fisheries, as managed aquacultures have more possibilities to adapt to changing and managed environmental conditions in favour of fish growth. Total climate-induced change in fish production is therefore lower than the climate impacts on marine fish catches.

In their simulations, Cheung et al (2016) distinguish climate impacts of 1.5, 2.5 and 3.5° Celsius. According to CMIP5 simulations of the RCPs, all RCPs have a global warming

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potential that ranges between 1.5 and 2.5 degree Celsius by 2050. In order to estimate a high-end scenario of climate change impacts, we assumed a pathway in which the world will warm by 2.5° until 2050 and by 3.5° until 2100 – a scenario that is in between RCP6.0 and RCP8.5. We then assumed that the reduction of marine fish catches will be substituted by increased consumption of chicken meat. A substitution by aquaculture fish may be even more likely due to the similar properties of the products, but would have similar consequences on agricultural markets, as also aquaculture receives farmed feed.

2.4. Economic impacts

According to Ricardian theory, the economic rent of a piece of land should represent, at the equilibrium, the revenues obtained from the land in its most productive use. The most profitable farming activity at any location is dependent on the local climate and biophysical context. Climate change may alter the relative productivity of crops in certain regions, making the conditions more favourable (unfavourable) for a given crop if, on average, climate moves closer to (further away from) the economic optimum for farmer decision of growing that crop. Models covering the agricultural sector typically find an optimal pathway for adapting agricultural production under climate change. With their economy-wide structure, CGE models can not only assess the effect on land-based sectors that are primarily affected by climate change but also the other sectors via indirect income and price effects. For example, a climatic shock on agricultural yields may affect consumption not only through a loss of production but also through a loss of consumer income. This comes however at the expense of sectoral details. PE models focus on the land-based sectors only but describe the agricultural and other land use sectors more extensively and contain a larger number of endogenous variables. A detailed comparison regarding outputs and input data of these two types of models used in agricultural modelling took place as part of the Agricultural Model Intercomparison and Improvement Project (AgMIP) (Nelson et al. 2014). The aim of the AgMIP project is to identify the sources of divergence between the models and to improve their input and output homogeneity.

For the analysis of economic impact of climate change in the agricultural, forestry and fisheries sectors, we will rely in this report on two broadly used models that are part of the AgMIP ensemble: GLOBIOM-EU and MAgPIE 4.

2.4.1. GLOBIOM

GLOBIOM (Havlík et al. 2014) is a partial equilibrium model that covers the agricultural and forestry sectors, including the bioenergy sector. Commodity markets and international trade are currently represented at the level of up to 58 economic regions. The spatial resolution of the supply side relies on the concept of Simulation Units (SimU), which are aggregates of 5 to 30 arcmin pixels belonging to the same altitude, slope, and soil class, and also the same country (Skalský, Tarasovičová et al. 2008). For crops, grass, and forest products, Leontief production functions covering alternative production systems are parameterized using biophysical models like EPIC (Williams

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1995), G4M (Kindermann, McCallum et al. 2008; Gusti 2010), or RUMINANT (Herrero, Havlík et al. 2013). The biophysical models allow a precise calculation of agricultural GHG emissions (N_2O and CH_4). Emissions from forestry and other land use (FOLU) include emissions of CO_2 originating from the conversion of land between the different land use types, and carbon sequestration from the establishment of short rotation tree plantations, afforestation, and forest management.

For the European Union, GLOBIOM has been enhanced to make use of available European datasets (Frank, Schmid et al. 2015, Frank, Böttcher et al. 2016). A more detailed SimU architecture (Balkovic, Skalsky et al. 2009) is used and the unit of analysis of the model is the NUTS2. Information on land cover is based on CORINE land cover map (CLC2000) and crop sector representation includes alternative tillage systems (conventional, reduced, and minimum tillage), crop rotations, residue management and additional crops i.e. sugar beet, rye, oats, flax, fallow, green fodder and corn silage. The model relies also on a detailed representation of the forest industries including industrial by-products (e.g. black liquor, sawdust, saw chips) (Lauri et al. 2014). In terms of trade and demand, every country of the EU is represented by its own demand and trade flows. All countries in the EU can trade with other countries in the EU or with regions in the rest of the world through a common EU market. Hence, trade flows go towards or away from a single EU country, to an EU-level market, and subsequently to another EU country or a world region outside Europe.

2.4.2. MAgPIE 4

MAgPIE 4 (Model of Agricultural Production and its Impacts on the Environment) is a modular open-source framework for modeling global land systems (Dietrich et al 2019) that combines economic and biophysical approaches to simulate spatially explicit global scenarios of land use within the 21st century and the respective interactions with the environment. MAgPIE 4 provides a holistic framework to explore future transformation pathways of the land system, including multiple trade-offs with ecosystem services and sustainable development.

MAgPIE 4 has a flexible spatial resolution at two distinct spatial levels: 1) world regions that can be defined based on any aggregation from countries and 2) spatial clusters characterized by similar local characteristics based on input data on a 0.5°x0.5° spatial grid. MAgPIE 4 takes regional economic conditions, such as demand for agricultural commodities, technological development, and production costs, as well as spatially clustered data on potential crop yields, carbon stocks and water constraints from the global gridded crop, vegetation and hydrology model LPJmL, under current and future climatic conditions into account.

MAgPIE allocates land use to fulfil competing demands for commodities, feed, carbon storage, land conservation and environmental protection. Land use is broadly categorized in cropland, forest plantation, forest land, pasture land, and other natural land. Regional food energy demand is defined for an exogenously given population in 25 food energy categories, based on regional diets. Future trends in food demand are derived from a cross-country regression analysis, based on future scenarios on GDP,

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population growth, demographic structure and anthropometric properties. MAgPIE takes spatially explicit data on potential crop yields, land and water constraints from LPJmL 5 (von Bloh et al 2017) and combines it with information on technological development and production costs. It includes agricultural trade with different levels of regional self-sufficiency constraints. MAgPIE calculates the following AFOLU GHG emissions: CO_2 from land use change (including changes to soil and plant carbon pools), N_2O from fertilizing agricultural soils and manure management, and CH_4 from enteric fermentation, manure management and rice cultivation. It includes a full dynamic and endogenous budget of the agricultural nitrogen cycle.

The model is open-source[3] and documented online[4].

[3] https://github.com/magpiemodel/magpie

[4] https://rse.pik-potsdam.de/doc/magpie/4.1/

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2.4.3. Overview of model differences

Table 3. Overview of main model differences between GLOBIOM and MAgPIE 4 for this report

	GLOBIOM-EU	MAgPIE 4
Model framework	Partial equilibrium, optimization of producer and consumer surplus, recursive dynamic	Cost optimization/Partial equilibrium, recursive dynamic
Sector coverage	Crops: 18 crops globally, 9 additional crops in the EU, pasture Forestry: 5 primary products, 2 processed products Fisheries: marine capture and aquaculture, seafood, fishmeal, and fish oil	19 crops, pasture, 5 livestock products, 1 fish product, 9 secondary products, 2 forestry products
Regional coverage	Global (28 EU Member states + 29 regions)	Global (12 world regions, of which 5 are European and 4 are aggregates of EU Member states)
Resolution on production side	Detailed grid-cell level (>10,000 units worldwide) EU resolution at NUTS2 x AEZ level	59199 grid-cell levels aggregated to 400 homogeneous cluster cells for optimization
Time frame*	2000-2100 (ten-year time step)	2000-2100 (five-year time step, after 2050 ten-year timestep)
Market data source	EUROSTAT and FAOSTAT	FAOSTAT, GTAP
Factor of production explicitly modelled	Land, water, nitrogen, phosphorus	Land, water, nitrogen, feed, seed, investments into technology
Land use change mechanisms	Grid-based. Land conversion possibilities allocated to grid-cells considering biophysical conditions for crop growth and opportunity costs of other land use types, land conversion costs, intensification and trade, protected areas.	Optimization considering biophysical conditions for crop growth and opportunity costs of other land use types, land conversion costs, intensification and trade
Demand side representation	One representative consumer per region and per good, reacting to the price of this good.	Food demand by age-groups, body mass index groups and sex on country level. Price reaction based on real-income elasticity, accounting for the income effect of price shocks. Demand model iterated with MAgPIE for each timestep until equilibrium is reached
GHG accounting	CH_4 and N_2O from crop and livestock, CO_2 from above and below ground living biomass, soil organic carbon, and peatland	CH_4 and N_2O from crop and livestock depending on the pollutant based on IPCC guidelines Tier I, II or III, CO_2 from above and below ground living biomass, soil organic carbon

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2.5. Scenario framework

To build our scenario framework, we combined the different models described above with various scenarios of evolution of climate change, and also socioeconomic developments. These latter are described by the Shared Socioeconomic Pathways (SSPs).

2.5.1. Shared Socioeconomic Pathways (SSPs)

SSPs provide a socio-economic framework and hence do not by itself contain any assumptions on climate change. In economic models, global drivers are combined in different ways to form different SSPs. The main characteristics for each SSP are the following (O'Neill et al., 2014).

- **SSP1 – Sustainability:** Characterized by relatively high levels of GDP growth, lower levels of population growth, high levels of education, international cooperation, fast technological growth, convergence between developed and developing countries, sustainability concerns in consumer behaviour.
- **SSP2 – Middle of the Road:** Representing business as usual development and continuation of currently observed trends.
- **SSP3 – Fragmentation:** Opposite tendencies to SSP1, relatively slow economic growth, sustained population growth, little international coordination, and little progress in reducing resource intensity and fossil fuel dependency.
- **SSP4 – Inequality:** Defined as a highly unequal world both within and across countries, relatively low income and low human capital among the poorer population, ineffective institutions, high population growth in low-income countries, crop yields high in industrial farming but low for small scale farming.
- **SSP5 – Conventional Development**: Characterized as robust economic growth, strong convergence of inter- and intra-regional income distributions, resource intensive consumptions (including inter alia meat rich diets), global population peaks and declines in the 21st century.

The narrative storylines of the SSPs are incorporated in the bio-economic models MAgPIE and GLOBIOM using the following set of quantitative drivers:

- GDP and population growth: Assumptions on population and GDP growth are directly implemented into GLOBIOM/MAgPIE.
- Food demand projections: In GLOBIOM, food demand projections are based on the interaction of three drivers: population growth, income per capita growth, and response to prices. Price effects are endogenously computed while drivers population growth and income per capita are exogenously introduced into the model. Demand increases proportionally with population for each region. GDP per capita changes determine demand variation depending on income elasticity

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values associated to each scenario. The assumptions for the trend of the income elasticity were adapted to match the diet storylines for the different SSPs:
  - SSP1: Future diets are considered to be more sustainable than in the FAO baseline.
  - SSP2: These future diets follow the projections from FAO at the horizon 2050.
  - SSP3: As economic growth is much lower in developing regions, income effects alone lead to a significantly lower demand per capita in these regions. GDP growth decreases much less in developed regions.
  - SSP4: Diets also follow similar patterns as projected for SSP2, in particular consumption of meat remains stable in developed regions.
  - Food consumption around the world converges to Western diet types, with higher intake of meat and milk than in SSP2.
- Technological progress: Semi-quantitative information of the SSPs are converted into crop and livestock productivity growth rates.

2.5.2. Scenario combinations

To be able to disentangle the differences introduced by global climate research projects, climate models, RCPs, crop models, crop model assumptions such as CO_2 fertilization, SSPs, mitigation efforts and economic models, we analyse the full matrix of these elements. This full matrix including that has been run in the bio-economic models GLOBIOM and MAgPIE and can be found in Annex I. In the remainder of this deliverable, we focus on the subset of scenarios laid out in Table 3. With this subset, it is possible to analyse climate change impacts along four axes: First, a comparison along RCPs 2.6, 4.5, 6.0, and 8.5. Second, a comparison along the four GCMs HadGEM2-ES, IPSL-CM5A-LR, NorESM1-M, GFDL-ESM2M. Third, a comparison along the SSP axes of SSP1 through 5. Fourth, a differentiation between a case with and without CO_2 fertilization.

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Table 3. Subset of climate change scenarios analysed

	Scenario Name	SSP	GCM	RCP	Mitigation
1	SSP2_NoCC_NoCC_NoMit	SSP2	NoCC	NoCC	NoMit
2	SSP2_HadGEM2-ES_2p6_NoMit	SSP2	HadGEM2-ES	2p6	NoMit
3	**SSP2_HadGEM2-ES_4p5_NoMit**	**SSP2**	**HadGEM2-ES**	**4p5**	**NoMit**
4	SSP2_HadGEM2-ES_6p0_NoMit	SSP2	HadGEM2-ES	6p0	NoMit
5	SSP2_HadGEM2-ES_8p5_NoMit	SSP2	HadGEM2-ES	8p5	NoMit
6	SSP2_IPSL-CM5A-LR_4p5_NoMit	SSP2	IPSL-CM5A-LR	4p5	NoMit
7	SSP2_NorESM1-M_4p5_NoMit	SSP2	NorESM1-M	4p5	NoMit
8	SSP2_GFDL-ESM2M_4p5_NoMit	SSP2	GFDL-ESM2M	4p5	NoMit
9	SSP1_HadGEM2-ES_4p5_NoMit	SSP1	HadGEM2-ES	4p5	NoMit
10	SSP3_HadGEM2-ES_4p5_NoMit	SSP3	HadGEM2-ES	4p5	NoMit
11	SSP4_HadGEM2-ES_4p5_NoMit	SSP4	HadGEM2-ES	4p5	NoMit
12	SSP5_HadGEM2-ES_4p5_NoMit	SSP5	HadGEM2-ES	4p5	NoMit
13	SSP2_HadGEM2-ES_8p5_NoMit_NoCO$_2$	SSP2	HadGEM2-ES	8p5	NoMit

3. Climate impacts on agriculture from biophysical modelling

3.1. Crop productivity

The biophysical crop model GEPIC estimates the changes in yield, and input use under irrigated and rainfed systems for all GCM and RCP combinations, with and without CO_2 fertilization. To do so, GEPIC makes use of ISIMIP-FastTrack data. The benefit of this is that it gives a world-wide picture and is thereby able to consider the relative impacts of climate change between Europe and the rest of the world. These climate-impacts of the rest of the world can subsequently be considered in the assessment of the economic impacts on agriculture, forestry and fisheries in Chapter 4.

The biophysical crop model EPIC-IIASA uses latest Euro-Cordex data to estimate for all GCMs and the COACCH core-RCPs 2.6 and 4.5 the impacts of climate change on yields and input use for irrigated and rainfed systems. It does so at a very high resolution of 1x1 kilometre. The factor change on yields in 2030, 2050 and 2070 for the crops winter wheat and corn is shown in Figure 5 and Figure 6 below. To disentangle the effects of weather variability from climate, Figure 5 and Figure 6 represent moving averages of yearly factor yield changes around a period of 30 years for the periods 2030, 2050 and 2070. This is consistent with the way the yield and input changes are implemented in GLOBIOM. Figure 5 and Figure 6 highlight two important findings of the biophysical crop modelling for Europe.

First, the magnitude of yield impacts differs highly between crops. Climate impacts on winter wheat are of a much lower magnitude compared to impacts on corn. The reason for these opposite effects among the crops is that corn is a typical C4 crop,

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whereas wheat is a typical C_3 crop. The major trends underlying differences in RCPs and climate change are elevated CO_2 and global warming, and these have opposite effects on crops, depending on whether the crop is a C_4 or a C_3 crop. Elevated CO_2 does little to C4 crops, but generally improves C_3 crops. Winter wheat (Figure 5) indeed shows slightly positive changes of around 10% yield increases in the majority of the European continent thoughout the 2030, 2050 and 2070 time-period. Corn (Figure 6), on the other hand, shows a largely diverging pattern between the North and the South of Europe, with up to 50% yield losses in the South.

Second, albeit of different magnitude, the pattern of changes in crop productivity is consistent between winter wheat and corn. Both show more negative yield changes in the South of Europe, and more positive yield changes in the North of Europe. Especially Southern Spain show negative impacts across crops, an effect that is especially in the case of winter wheat further amplified with time.

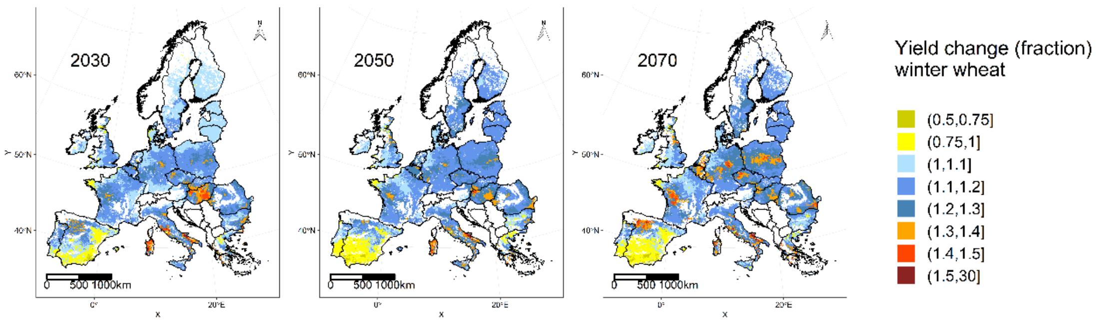

Figure 5. Yield change for winter wheat productivity under RCP4.5, HadGEM-ES.

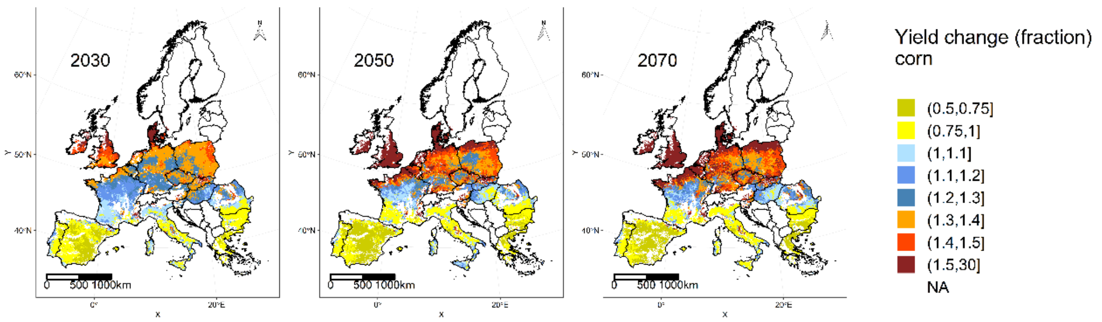

Figure 6. Yield change for corn productivity under RCP4.5, HadGEM-ES.

The global gridded crop, vegetation and hydrology model LPJmL estimates the changes in yield patterns with and without irrigation for all GCM and RCP combinations with and without CO_2 fertilization. Here, the new model version 5 has been for the first time used for an agro-economic assessment. This new model version includes nitrogen dynamics within plants and soils of both natural vegetation and soils. To couple LPJmL 5 and MAgPIE 4 consistently, first a number of tests were carried out to observe how relative yield patterns change under nitrogen limitations. Nitrogen limitations in crop yields do not occur in most farming systems around the world, were N is provided

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rather in excess to avoid yield losses. Limitations however do occur most importantly in Sub-Saharan Africa, where fertilizer prices are relatively high compared to crop value. We therefore set up a sequence of LPJmL runs where N was reduced proportional to plant needs. In such a case, we found that yield levels were reduced, but relative yield patterns were still rather well preserved. We therefore found that under the assumption that farmers distribute the limited nitrogen proportional to yield potentials, the yield patterns of LPJmL without N limitation can be used and scaled proportionally.

Next, we adopted a new calibration method that better accounts for differences between simulated estimates and observed values. If simulated values are very low for areas with high observed values, proportional scaling to observed values can lead to strong overestimation of positive climate impacts when climatic conditions improve: For example, low yields can easily increase by an order of magnitude, which when transferred to high observed yields, resulting in unrealistically high yields. Our new calibration method is based on Heinke et al (2013), and applies absolute shifters in cases where simulated values are far below the observed values, relative shifters were simulated are equal or larger to observed values, and an interpolation in between. This calibration method was applied for the harmonization between yields from GCMs and yields from the observed CRU weather patterns. It was also used to calibrate simulated LPJmL yields to observed FAO yields.

Figure 7 and Figure 8 show exemplary results of the crop model simulations. Here, we show the crop yields in the year 2050 divided by the yields in the year 2010, all before calibration. Before the yields enter the MAgPIE 4 model, they are averaged over a period of 8 years to reduce the effect of weather patterns in the data and to account for farmers expectations in decision making. Please note that these figures do not just represent climate impacts, but also includes weather impacts that are included in the GCMs. We see that Eastern EU tends to benefit in these simulations, while Northern, Western and Southern EU show mixed regional patterns.

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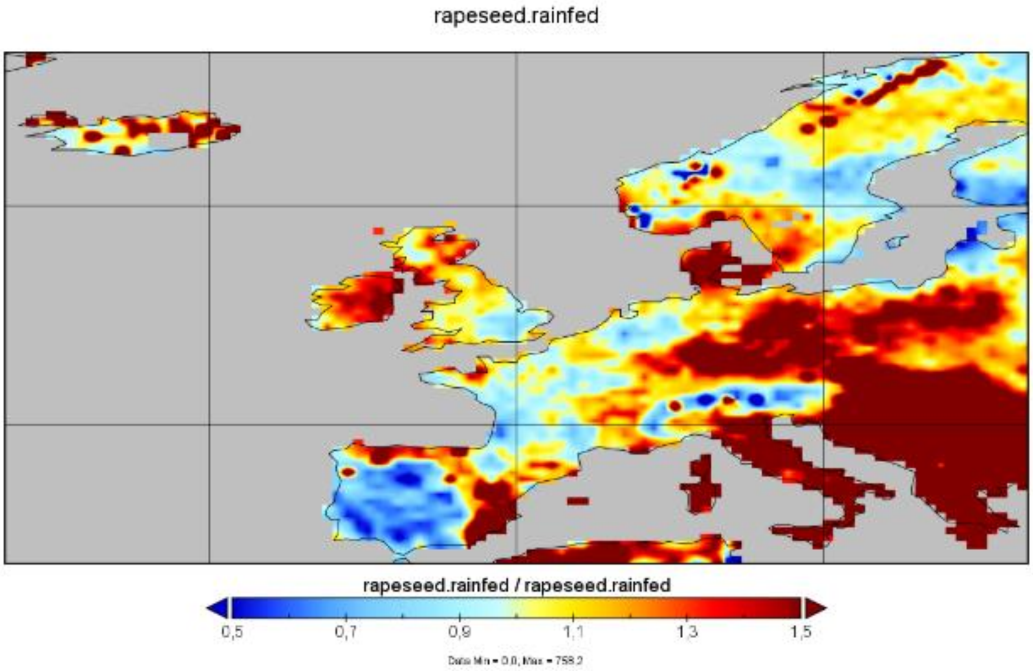

Figure 7. Yield shifters for rapeseed for the year 2050 relative to CRU for the year 2010. Estimates are based on LPJmL5 with rcp4.5 climate forcing from HadGEM-ES and with CO_2 fertilization activated. Estimates are calibrated to meet CRU data in 2010. Estimates exclude technological progress.

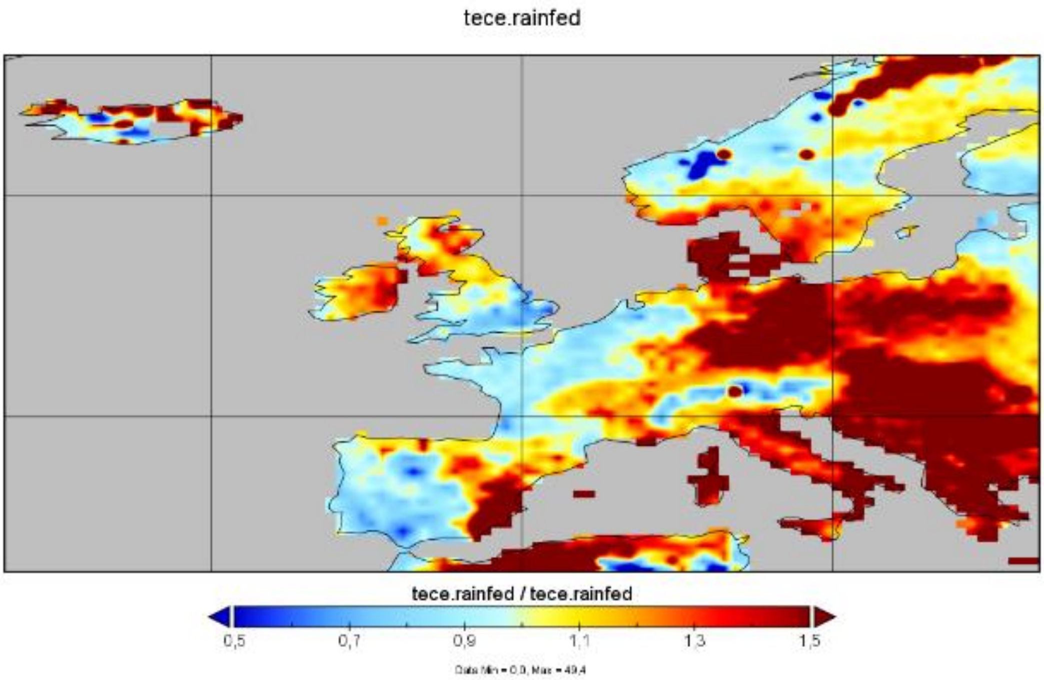

Figure 8. Yield shifters for temperate cereals for the year 2050 relative to CRU for the year 2010. Estimates are based on LPJmL5 with rcp4.5 climate forcing from HadGEM-ES and with CO_2 fertilization

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activated. Estimates are calibrated to meet CRU data in 2010. Estimates exclude technological progress.

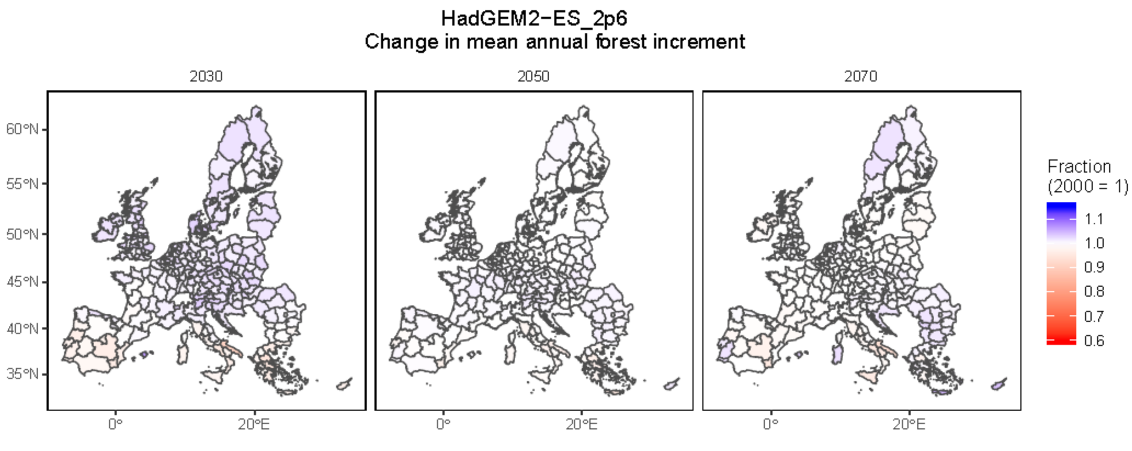
3.2. Forestry

3.2.1. Forest growth impacts

3.2.1.1. G4M

The impact of the different RCPs on forest increments under HadGEM2-ES in the short, medium and long-term is shown in Figure 9. Forest increments gradually move from increases in increments to decreases in increments compared to the situation without climate change under and increasing RCP. Especially in the short-term, the Northern part of Europe benefits by experiencing an increase in the annual increment. This effect remains positive but fades out over the time-horizon. With time, and with an increase in the RCP, the Southern part of Europe is experiencing a decrease of the mean annual increment. The most notable differences are found between RCP2.6 and RCP8.5, with RCP2.6 providing mostly positive impacts on Europe and RCP8.5 providing mostly negative impacts on Europe towards the medium- to long term. Especially striking is also the negative impact on Southern Europe in the short- to long-term under RCP4.5. This is due to the more rapid increase in CO_2 concentration and radiative forcing in RCP4.5 compared to RCP6.0.

One of the main caveats in the calculation of the impact of climate change on the forest increment is that IIASA's forest model G4M did not consider the effects of CO_2 fertilization on the forests, something that is considered for agricultural crops. As a rule of thumb, the effect of CO_2 fertilization on the increment might be up to 25% and around 15% for Europe according to the recent literature (Huntingford et al., 2013; Terrer et al., 2019).



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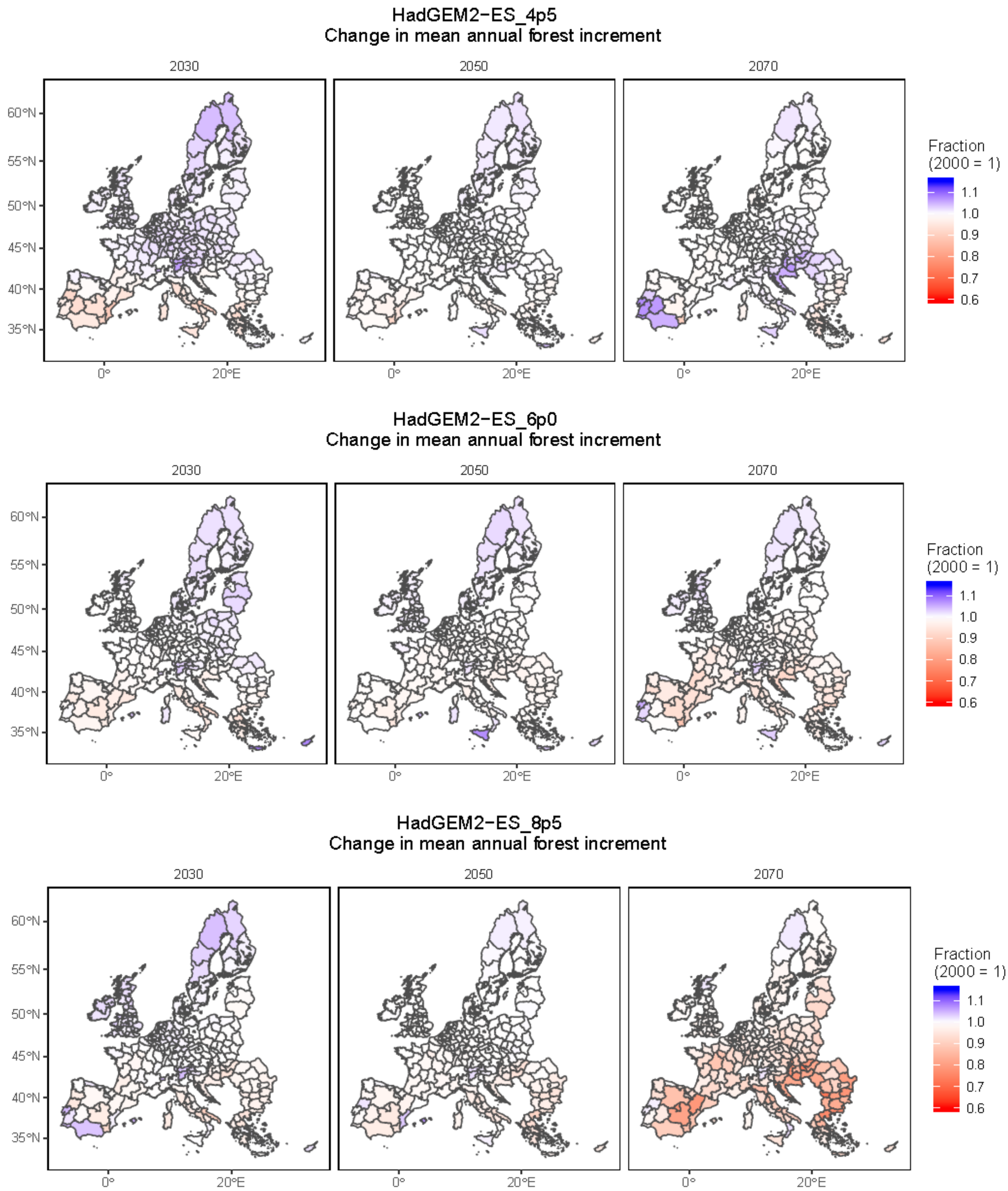

Figure 9. Impact of the different RCPs on shifter of forest increments under HadGEM2-ES in the short, medium and long-term.

3.2.1.2. LPJmL

To estimate forest productivity, we use simulations of aboveground vegetation carbon stocks of LPJmL. LPJmL was run with and without CO_2 fertilization for all combinations of GCMs and RCPs. Figure 11 shows some exemplary results of the relative change in aboveground vegetation carbon of the year 2050 to the year 2010. Globally, carbon stocks tend to increase, but there are also areas where they are declining, most

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notably in Southern Africa, Eastern Europe and Central Asia and Australia (Figure 10). Zooming into Europe, the highest increases in carbon stocks are in Northern latitudes as well as the Southern Mediterranean region, while in particular the eastern part sees a decline in forest carbon stocks. Interestingly, it shows an opposing pattern to crop yields, were the Eastern EU was benefiting. CO_2 fertilization has an impact on forest growth, and does in some regions like northern France even decide upon the sign of the impacts.

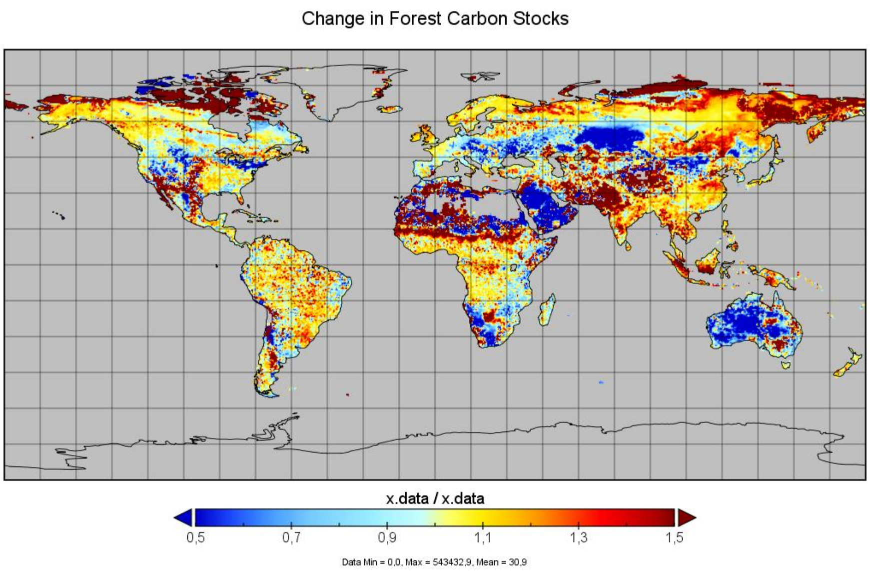
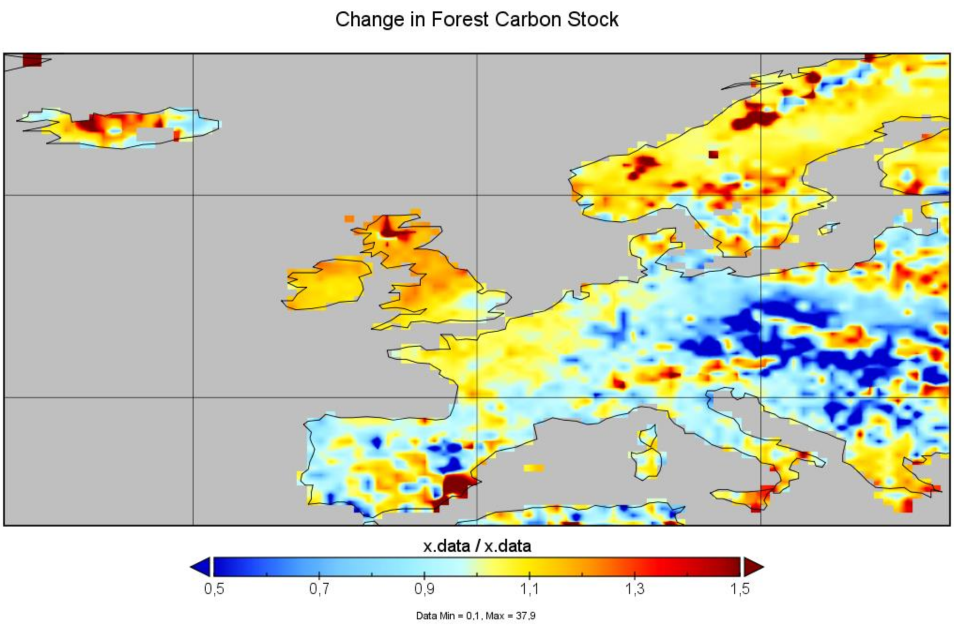


Figure 10. Relative change in potential forest carbon intensities under the climate change scenario HadGEM-ES RCP4.5 simulated by LPJmL 5 with CO_2 fertilization for the year 2050.



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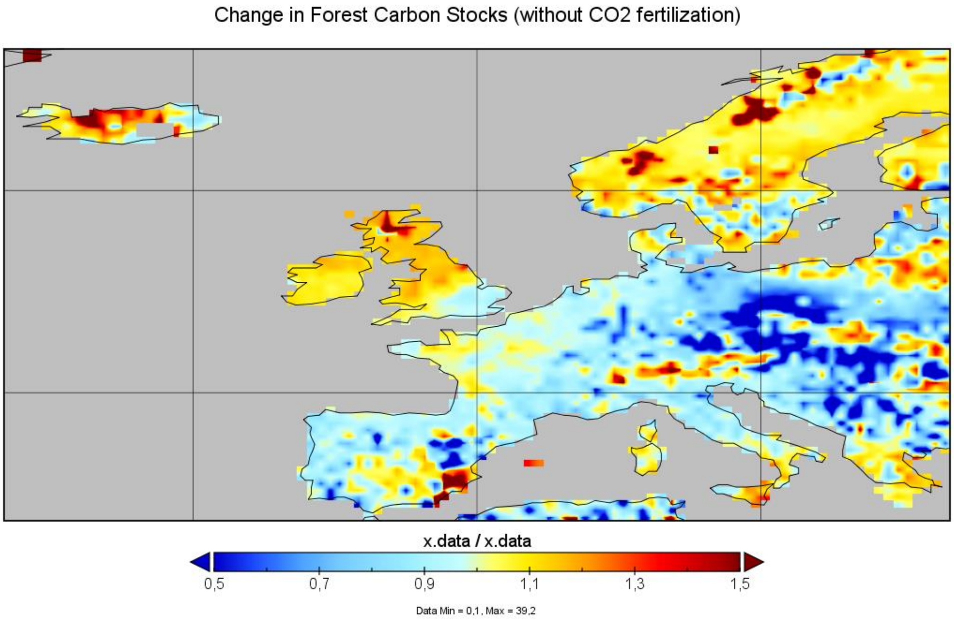

Figure 11. Relative change in potential forest carbon intensities under the climate change scenario HadGEM-ES RCP4.5 simulated by LPJmL 5 with (top) and without (bottom) CO_2 fertilization for the year 2050.

3.2.2. Forest fire occurrence

To estimate the impact of climate change on forest fire occurrence we employed the climate model HadGEM2-ES corresponding to the four RCPs 2.6, 4.5, 6.0 and 8.5. The FLAM modelling results of burned areas of wildfires taking place in the forest are presented in Figure 12 in terms of burned areas for the historical period (2010-2019), and four future periods 2020-2039, 2040-2059, 2060-2079, and 2080-2099. Estimates of the potential increase in average burned areas in Europe under a "no adaptation" scenario compared with 2010–2019 shows that average burned areas can increase by about 150 thousand hectares in 2050 and more than double in hectares by the end of the century in the case of RCP8.5.

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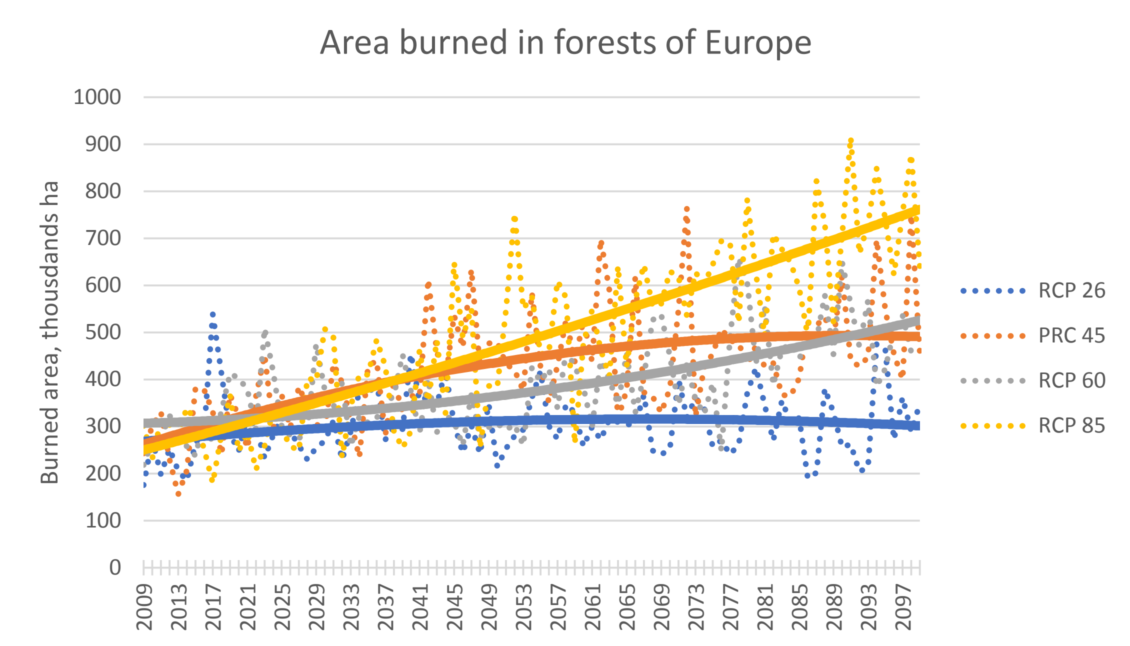

Figure 12. Projected burned areas for European forests and polynomial trends of second order.

Results in terms of relative increase in burned areas are also reported in Table 5. Average percentage increases in burned forest area amount to around 20% by 2020-2039, 65 % by 2040-2059, over 100% by 2040-2059, and 140% by 2080-2099 in the case of RCP 8.5. Furthermore, Figure 12 demonstrates annual dynamics of burned areas modelled by FLAM with corresponding polynomial trends (of order 2). One can see that variability in annual areas with respect to climate is quite high.

Table 4. Average increase in burned areas (percentage) compared to 2009-2018

	2020-2039	2040-2059	2060-2079	2080-2099
RCP 2.6	0%	11%	3%	8%
PRC 4.5	18%	57%	61%	67%
RCP 6.0	19%	14%	41%	63%
RCP 8.5	19%	64%	103%	141%

Figure 13 shows the average burned area of forests at the NUTS2 level for RCP4.5 over the period 2040-2059. The figure shows larger impacts in the South of Europe compared to the Middle and North of the continent. Especially large amounts of burned areas are found in Portugal and Spain.

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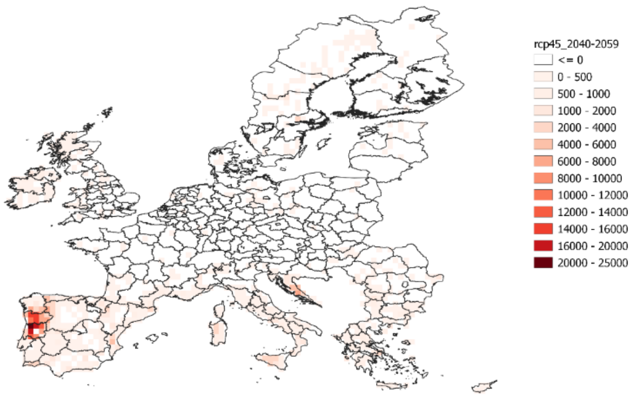

Figure 13. Average burned area in hectares (2040-2059) for RCP 4.5 at the NUTS2 level

3.3. Fisheries

The results from the LMR models show large contrasts between tropical and arctic areas, although the changes in the DBEM model of Cheung et al (2016) are much more contrasted, with marine maximum catch potential in arctic oceans benefiting from global warming, while tropical zones show negative trends under warming (Figure 14 and Figure 15).

For large marine ecosystems close to Europe, Greenland Sea, Barents Sea, Norwegian Sea and Baltic Sea, experience higher productivity under warming, but show declining rates under high warming conditions. Mediterranean, Iberian Coastal, North Sea, And Canary Current see a rather immediate decline in productivity under global warming. According to the two models used, the range of losses in marine catches by mid-century could be for mid-latitude regions around 30% under the most dramatic climate change scenario (RCP8.5). The model appears to be in broad agreement in their assessment of climate change impacts for the European region, although they differ for their impact for the Artic region, however less important here for the scope of our analysis.

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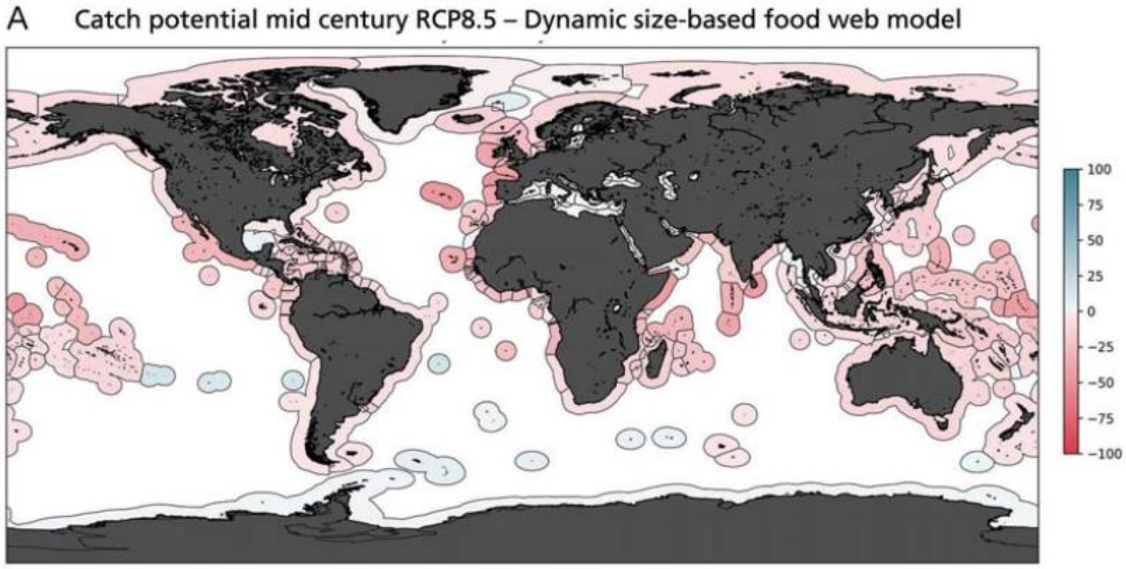

Figure 14. Projected differences in change in maximum catch potential (MCP) in 2050 under RCP8.5 for the DSFM model. Source: Barange et al. 2018.

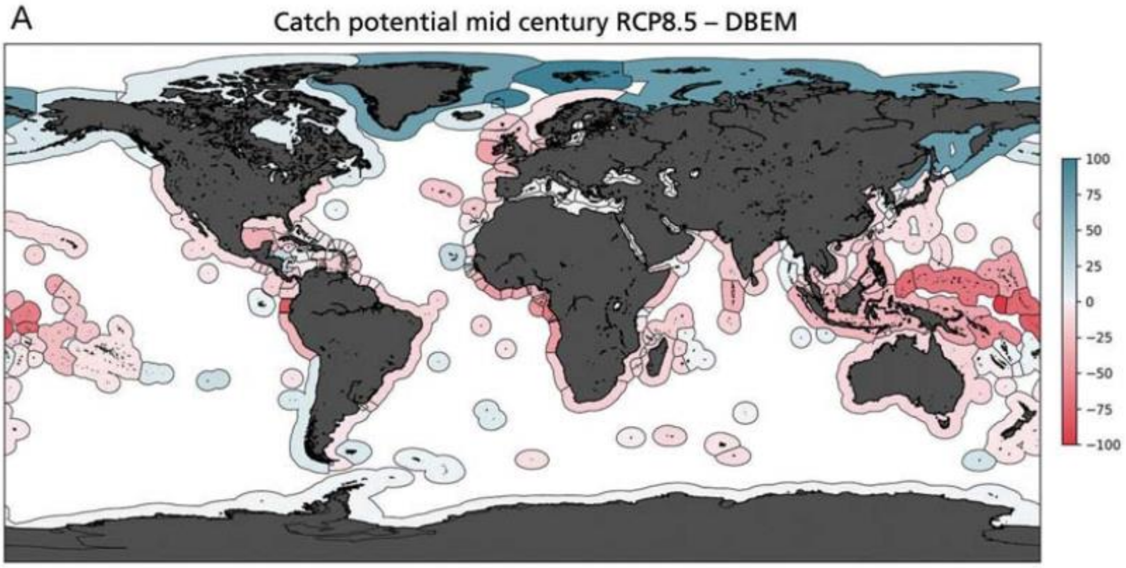

Figure 15. Projected differences in change in maximum catch potential (MCP) in 2050 under RCP8.5 for the DBEM model. Source: Barange et al. 2018.

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4. Economic impacts on agriculture, forestry and fisheries

The scenario results on economic variables are the outcome of the interplay between climate change-related biophysical yield shocks on the forestry, fisheries and agriculture sectors in the EU and non-EU countries and the effects and feedbacks on agricultural production, trade, consumption and prices on domestic and international markets. In this chapter, we present the results of the impacts of climate change across the axes of three RCPs (2.6, 4.5, and 6.0), four GCMs (HadGEM2-ES, IPSL-CM5A-LR, NorESM1-M, and GFDL-ESM2M), five SSPs (SSP1-SSP5), and the extreme case of RCP8.5 with and without CO_2 fertilization. Both scenarios are compared to the reference scenario of no climate impacts at a short (2030), medium (2050) and long (2070) timeframe.

4.1. Agriculture

4.1.1. Impact of RCPs

4.1.1.1. GLOBIOM

The impacts of climate change on EU-28 production, area and yield due to climate change in the short, medium and long term under RCP 2.6, 4.6 and 6.0 for GCM HadGEM2-ES under SSP2 are reported in Table 5. For the specific crops corn and wheat, effects are additionally reported in bar-charts in Figure 16. In Table 5, negative impacts compared to the baseline are highlighted with a red gradient that turns darker with increasingly negative impacts. Positive impacts compared to the baseline are highlighted with a green gradient that turns darker with increasingly positive impacts.

Table 5. GLOBIOM results on impact of climate change on EU-28 production, area and yield effects on important food groups due to climate change for RCP 2.6, 4.5 and 6.0 in 2030, 2050 and 2070 for GCM HadGEM2-ES and SSP2.[5]

	RCP2.6			RCP4.5			RCP6.0		
	2030	2050	2070	2030	2050	2070	2030	2050	2070
AREA % difference compared to base									
Agriculture	-0.66	-2.88	-4.00	-1.26	-2.11	-4.01	-2.41	-2.20	-4.35
Crops	-1.28	-5.00	-7.73	-2.59	-3.94	-7.29	-3.79	-3.14	-7.19
Cereals	-1.05	-3.31	-5.15	-2.43	-2.40	-4.84	-3.89	-2.53	-4.45
Oil seeds	-1.49	-5.06	-15.30	-7.19	-9.90	-23.73	-1.77	-2.70	-18.32

[5] Note that in Table 5, the yield effect reported is the biophysical impact on crops that can be directly attributed to changing climate and does not include endogenous adaptation such as a reallocation of crop cultivation or an adoption of different rotation shifters. The yield effect after adaptation can be computed in the table by dividing the production relative change results by the area relative change.

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Sugar	1.24	0.29	-1.67	-2.55	-4.10	-3.07	-1.49	-1.18	-1.32
Corn	1.63	1.94	1.14	8.09	18.17	9.53	-1.46	0.10	1.39
Wheat	-2.05	-3.43	-8.09	-5.36	-7.21	-8.71	-5.09	-5.56	-7.08
PRODUCTION in % difference compared to base									
Agriculture	-1.41	-4.81	-7.55	0.10	0.18	-3.65	0.64	0.98	-3.23
Crops	-1.50	-5.24	-8.33	0.35	0.38	-4.18	0.72	1.09	-3.63
Cereals	-1.20	-4.66	-5.76	-1.86	-1.17	-0.77	-0.72	-0.84	-1.45
Oil seeds	-1.25	-4.12	-21.48	-4.19	-10.69	-32.74	0.18	-3.17	-20.94
Sugar	0.59	0.23	-0.83	0.24	0.25	0.15	0.32	0.31	1.64
Corn	-4.08	-13.20	-18.06	-10.72	-15.94	-20.74	-2.56	-2.86	-5.74
Wheat	1.04	-1.02	-3.03	2.58	3.42	2.96	-0.40	-1.46	-2.56
YIELD effect due to climate change in % difference compared to base									
Crops	-2.35	-2.73	-2.85	-0.45	-2.21	-1.29	2.05	1.70	2.77
Cereals	-2.76	-3.12	-3.49	-1.50	-4.29	-2.65	1.57	0.70	2.99
Oil seeds	-0.61	1.43	0.89	4.77	6.33	6.40	2.17	2.23	4.62
Sugar	-0.60	1.02	2.43	7.30	9.88	9.27	3.42	3.73	8.51
Corn	-10.26	-15.97	-16.01	-23.31	-38.47	-27.41	-0.67	-3.55	0.17
Wheat	0.07	1.48	1.02	5.99	7.62	6.99	2.65	2.51	4.42

Two main patterns can be observed when comparing results across agricultural items in Table 5. First, impacts of climate change are much more contrasted at the level of individual crops than for broader sectoral groups. The agriculture sector as a whole, and the arable sector (crops) report impacts of lower magnitude than the food-groups cereals, oil seeds and sugar crops, and the direction of the results. In turn, these food-groups generally report lower impacts than the individual crops corn and wheat. This indicates that there is a large part of the shocks is buffered by crop switching going on in the agricultural sector. This is further highlighted when looking into the differences between the two crops of in-depth focus, corn and wheat. Corn shows large negative effects of climate change on yields, especially around RCP4.5. Wheat on the other hand, shows an opposite behaviour of positive impacts, especially around RCP4.5. The reason, as explained in section 3.1, for these opposite effects among the crops is that corn is a typical C4 crop, whereas wheat is a typical C_3 crop, a pattern that was also observed in Figure 5 and Figure 6. Elevated CO_2 has limited impact on C4 crop yields, but generally much more subtantial ones on C_3 crops. There are in general more C_3 crops than there are C4 crops in Europe, which could explain why, in RCP6.0 the trends on the composite crops are generally positive, especially towards the long-term.

The second notable effect in the results is that the highest impacts are centered around RCP4.5 and especially around the medium term. This might be in contrast to first expectations, where one would expect larger impacts with higher RCPs. However, up till the 2050-2060 period, CO_2 concentration and radiative forcing are in fact higher under RCP4.5 than it is under RCP6.0. For every decadal period, the yield effect due to climate change is computed over 30-year weighted averaged (e.g. for 2050, this

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implies a weighted average between 2035 and 2065). Moreover, the change in CO_2 concentration and radiative forcing under RCP6.0 is more gradual than that under RCP4.5. These are both reasons for observing higher impacts on area and production changes in the mid-term under RCP4.5.

When we look at the supply effects of the climate impact on yields, we can see that there is very little endogenous adaptation of the corn yields in order to mitigate the negative climate effect. Indeed, across all RCPs, the percentage loss in yields compared to the base remains similar after adaptation (e.g. reallocation of cropland). In the case of wheat, the positive effect gets enlarged due to adaptation and moves from 3-4% increase to 6-10% increase compared to the base for RCP4.5. Furthermore, between corn and wheat opposite effects due to the changes in the yields can be observed. In the case of corn, a decrease in the yield leads to an increase in the area of corn, but not enough to compensate for the loss in production. For wheat, an increase in the yields leads to a decrease in the area of wheat. In the case of RCP2.6 and RCP6.0, this decrease in the area is in fact larger than the increase in the yield. Hence, overall production goes down under these RCPs compared to the base.

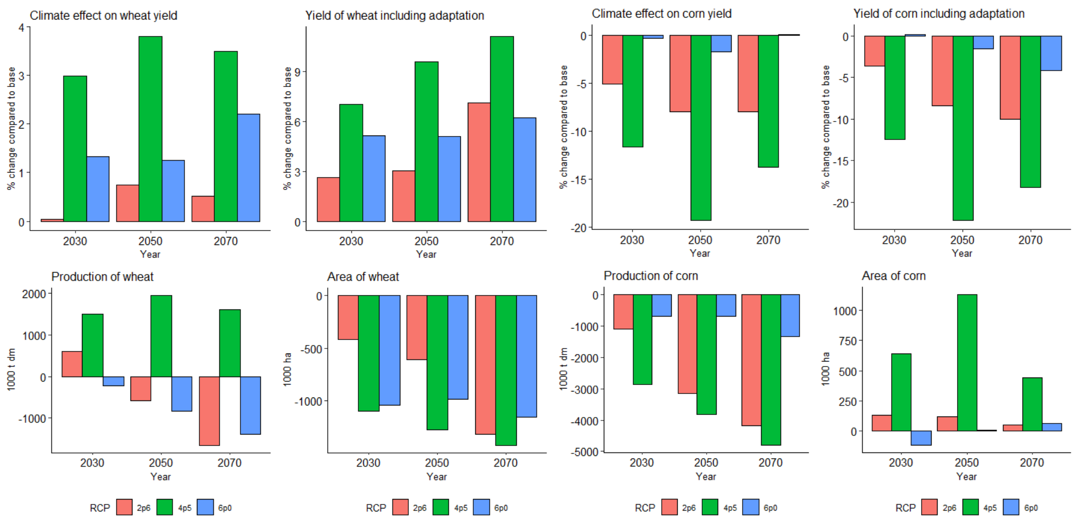

Figure 16. GLOBIOM results on yield, production and area changes of wheat (four left panels) and corn (four right panels) in the EU for HadGEM-ES scenarios.

Figure 17 and Figure 18 show the change in area for wheat and cropland under HadGEM-ES, for RCP4.5 and SSP2. In terms of wheat, losses in area are observed in Southern Spain and the Middle of France and some areas in Eastern Europe. However, we also see some wheat area increases in other regions of the same countries. This pattern is in general replicated for cropland extent, with, for example, decreases in the NUTS2 regions in the South of Spain, and increases in the North of Spain. This reallocation effect within the country may be due to change in profitability of the crop in terms of yields but also additional costs that would be incurred if the crop was cultivated elsewhere. In GLOBIOM-EU, international trade for EU countries is first channeled though a common EU-market, which in terms is connected bilaterally to

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other world regions. At each of these steps (from a country to the EU market and to other world regions), trade costs are incurred. With rather inelastic trade-flows in GLOBIOM-EU, we first see a domestic reallocation before an international reallocation occurs.

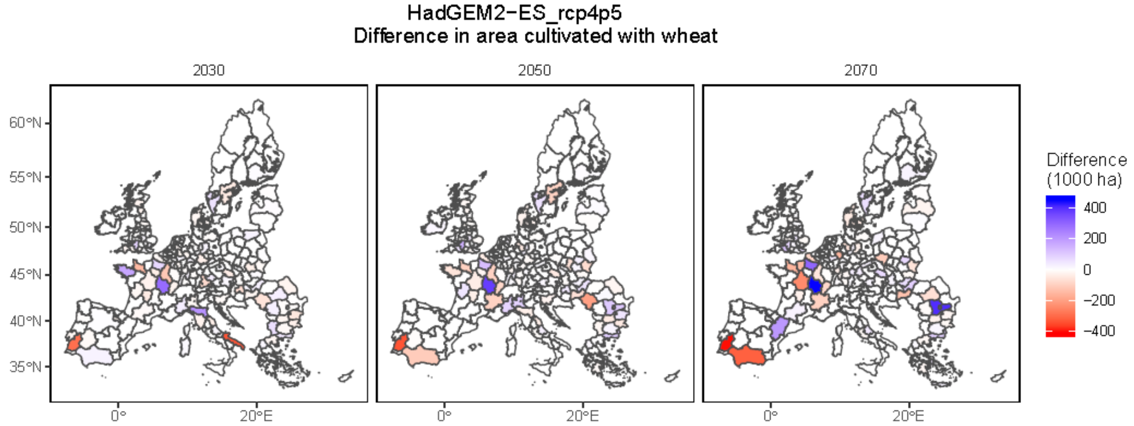

Figure 17. GLOBIOM results on wheat cultivated area changes in the short, medium and long-term in 1000 ha under HadGEM2-ES with RCP4.5 and SSP2.

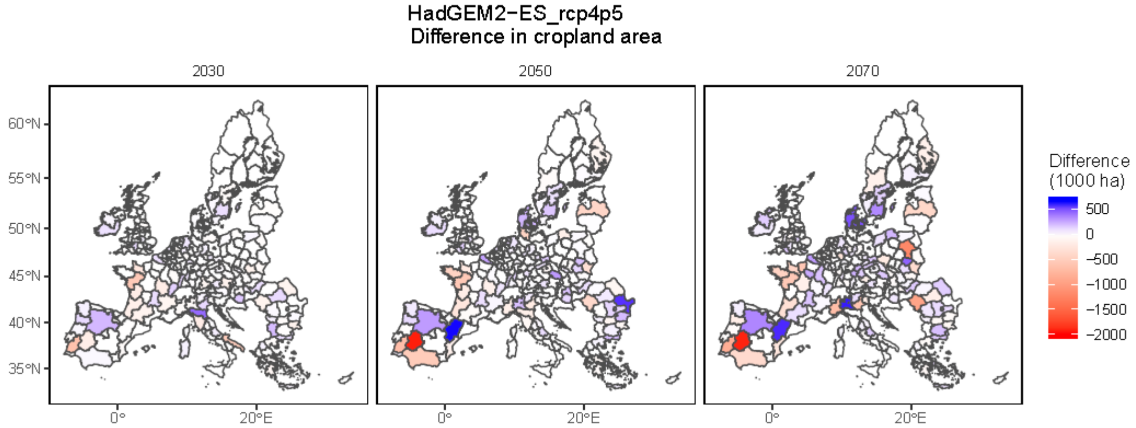

Figure 18. GLOBIOM results on cropland changes (1000 ha) in the short, medium and long-term in 1000 ha under HadGEM-ES with RCP4.5 and SSP2.

However, national effects can be observed as well. Figure 19 shows the percentage change in cropland under RCP4.5 and SSP2 compared to the situation without climate change in 2050. A clear division into four main regions, differentiated by colours can be observed. Largest negative impacts in total cropland area change are observed in Southern Europe, and largest positive impacts are observed in North, West and Central-East. This picture is in line with the biophysical productivity changes due to climate that were observed in Figure 5 and Figure 6. The exception is Luxembourg, which observes a large drop in percentage change in cropland by country, but given the size of the country, this is a small absolute change.

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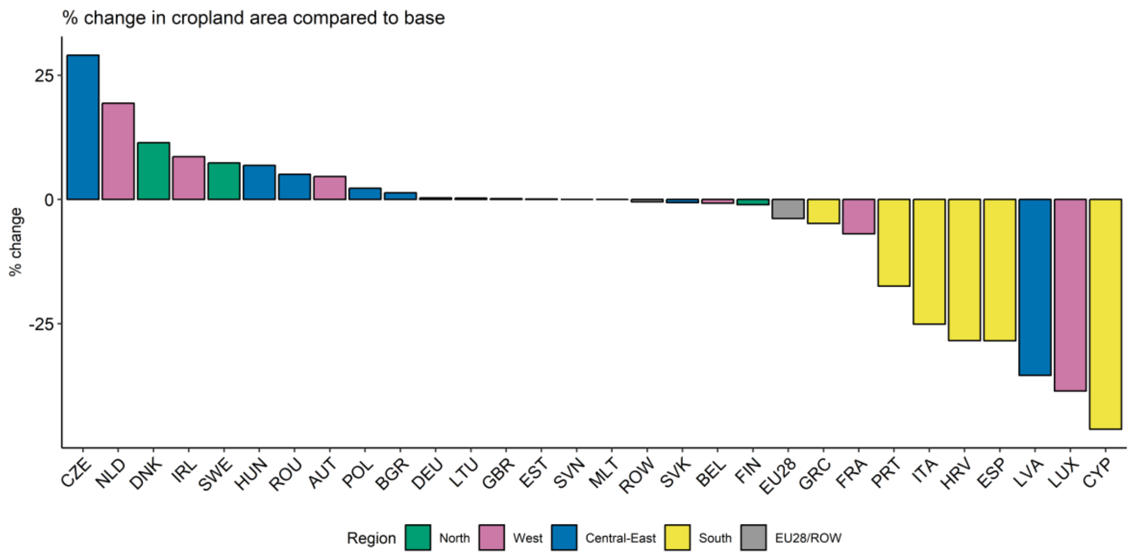

Figure 19. GLOBIOM relative change in cropland area by country under RCP4.5 and SSP2 compared to the situation without climate change in 2050

The decrease in corn production leads to a decrease in corn consumption in almost all RCPs, but especially in the short to medium term and in RCP 2.6 and 4.5. Wheat, on the other hand, shows an increase in consumption due to the increase in production. With the decrease in production of corn, trade increases. Wheat follows the opposite pattern, where for RCP4.5, prices and trade decrease compared to a situation without climate change. Under RCP6.0, wheat as well as other crops are increasingly traded.

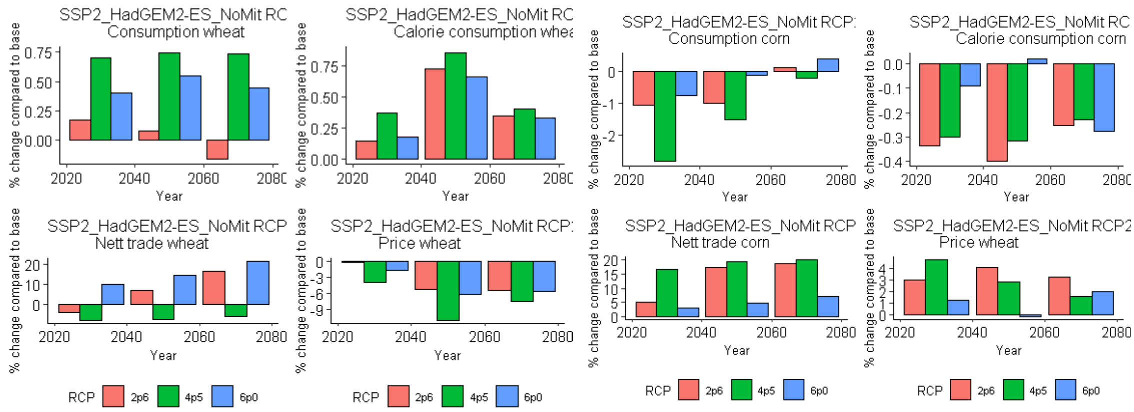

Figure 20. GLOBIOM relative change in consumption, trade and price for wheat (left hand side) and corn (right hand side) under HadGEM2-ES, SSP2, RCP 2.6, 4.5 and 6.0 in 2050

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4.1.1.2. MAgPIE 4

Climate impacts in MAgPIE 4 affect the spatially explicit yield patterns of crops and pastures, the water availability and irrigation water requirements and the carbon stocks of different vegetation types.

Yield shifters from biophysical crop models are often at the upper boundary for the yield impacts estimated by bio-economic models, as the latter models have the potential to adapt to changing climates, for example by changing yield patterns, by changing international trade, by irrigation expansion or by intensifying yields. This is illustrated in Figure 21. The biophysical yield shifters are highest for Eastern Europe. Additionally, the model invests into technological change to further amplify those yield improvements – in reality this could be achieved for example by improved breeds of local varieties. Finally, the model changes the original cultivation patterns to a pattern that is better adapted to the altered growing conditions, further increasing the yields. A different dynamic can be seen in the Western EU, where climate impacts for temperate cereals are less positive. Also there, the areas are further intensified, but at the same time the land use pattern has been changed in a way that other crops than temperate cereals receive the more productive areas, leading to a negative area adaptation.

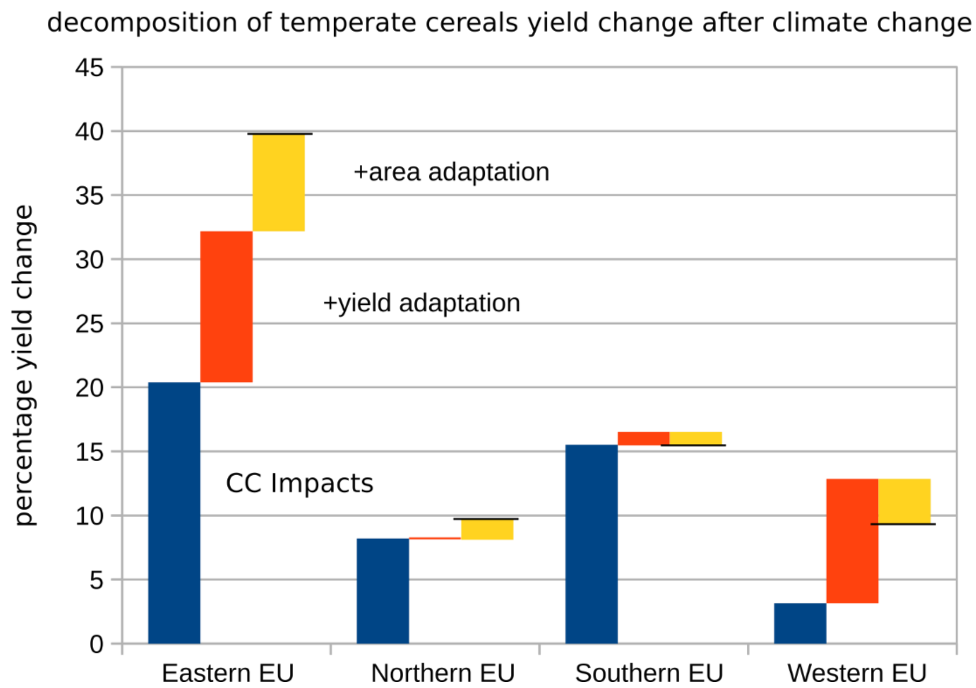

Figure 21. MAgPIE relative changes in crop yields. Changing biophysical yield potentials (blue) lead to adaptation responses of intensification/extensification (orange) or to more cost-optimal land allocation (yellow). Black line indicates the total change in yield levels. This example is from a simulation run with HadGEM-ES RCP4.5 with LPJmL5 with activated yield fertilization. MAgPIE 4 runs are for SSP2 in the year 2050, and the yields shown here are temperate cereals.

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The yields of MAgPIE are therefore always the result of the complex interplay between different relative changes. It can happen, for example, that while the biophysical climate impacts are negative in general, the crops are moved to more productive areas leading to higher yields after adaptation.

As a consequence of these shifting cropping patterns, also total cropland may be extended or reduced (see Figure 22). In general, we see that increased rates of global warming lead to increased cropland expansion in the world. Within Europe, the picture is more diverse. Climatic conditions in the EU in general improve (see Figure 21), yet at higher rates in the South and East of the EU. This then also leads to increased cropland expansion in these areas, while Western and Northern EU rather show a decline in cropping area. Differences between different RCPs are not very large, as they show very similar patterns until 2050, and even the cropland by 2070 is largely determined by its historical expansion.

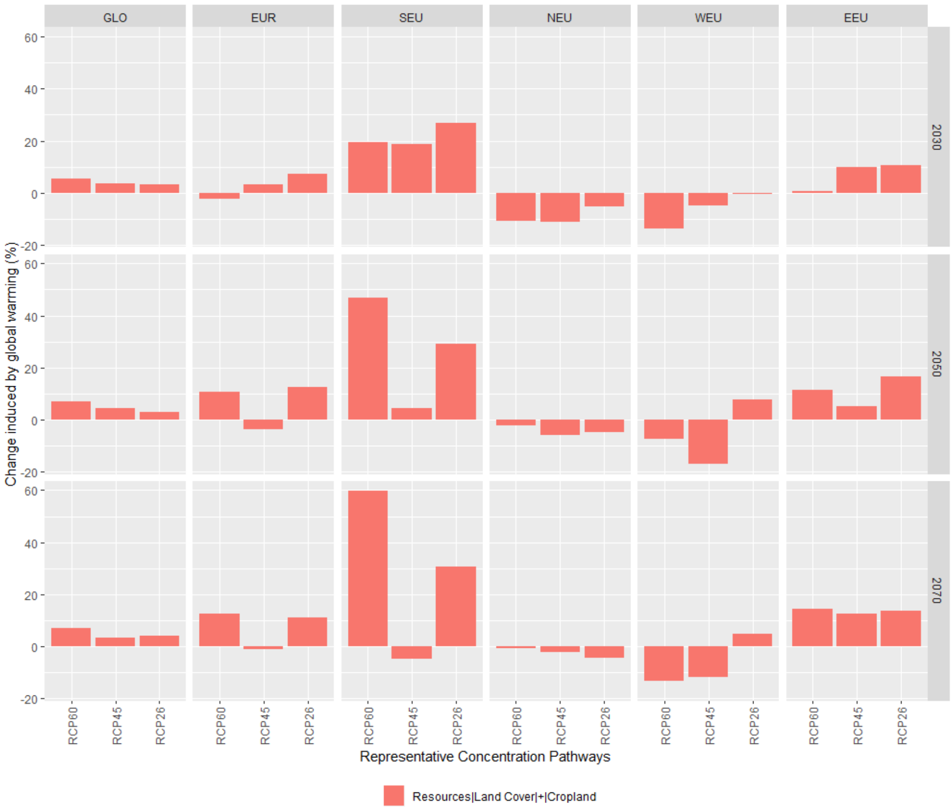

Figure 22. MAgPIE relative change in cropland for the world (GLO), the EU (EUR) as well as 4 European subregions under different levels of mitigation (RCP60-26) for simulations combining HadGEM-ES, LPJmL5 and MAgPIE4.

4.1.2. Impact of SSPs

For the bio-economic modelling within the COACCH project, we analyse the effects of climate change along the SSPs axis.

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4.1.2.1. GLOBIOM

Table 6 shows the GLOBIOM results of impacts of climate change on EU-28 production and area on important food groups due to climate change for SSP1 through SSP5, in 2050, for GCM HadGEM2-ES and RCP4.5. Impacts due to climate change generally show the same direction along the SSPs axis. This direction is generally also consistent with those of the RCPs shown in Table 5. We again observe inter-crop compensation based on the observation that the magnitude of percentage difference decreases with a higher number of agricultural items in a group. Relative differences along the SSPs axis do not diverge as much as along sectors. The strongest effects are found in SSP4, the 'inequality', or 'a road divided' scenario, which is characterized by low challenges to mitigation and high challenges to adaptation (Calvin et al., 2017). This is reflected by the higher changes in production and area adjustment compared to other SSP scenarios.

Table 6. GLOBIOM results on impact of climate change on EU-28 production and area on important food groups for SSP1 through SSP5, in 2050, for GCM HadGEM2-ES and RCP4.5.

	SSP1	**SSP2**	**SSP3**	**SSP4**	**SSP5**
AREA in % difference compared to base					
Agriculture	-1.97	-2.03	-2.01	-1.64	-2.44
Crops	-3.84	-3.70	-3.84	-3.29	-4.64
Cereals	-2.77	-2.42	-1.55	-2.37	-3.10
Oil seeds	-8.09	-9.47	-10.32	-6.67	-5.61
Sugar	-6.44	-4.28	-5.44	-4.24	-3.86
Corn	19.99	18.06	18.13	21.05	15.12
Wheat	-6.74	-7.28	-5.74	-6.76	-4.40
PRODUCTION in % difference compared to base					
Agriculture	0.48	0.34	-0.78	1.63	-1.15
Crops	0.79	0.55	-0.72	1.83	-1.22
Cereals	-2.08	-1.40	0.56	2.11	-1.55
Oil seeds	-8.57	-9.92	-8.05	-10.64	-6.53
Sugar	0.50	0.40	0.62	1.27	3.57
Corn	-12.63	-16.20	-5.81	-15.35	-23.18
Wheat	0.99	3.02	2.09	8.15	4.49

4.1.2.1. MAgPIE

We analyse the impact of climate change over different socioeconomic assumptions by carrying out a sensitivity analysis over the Shared Socioeconomic Pathways (SSPs). We find that climate impacts show a relatively coherent picture across different socioeconomic scenarios. For temperate cereals, the SSP3 scenario, which is characterized by a fragmented world with slow technological progress, shows lower growth rates of yields (Figure 23). The adaptation to changing climatic conditions here is rather realized via expanding cultivation areas than intensifying crop production. For

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maize, differences between SSPs are more diverse and show no clear pattern (Figure 24).

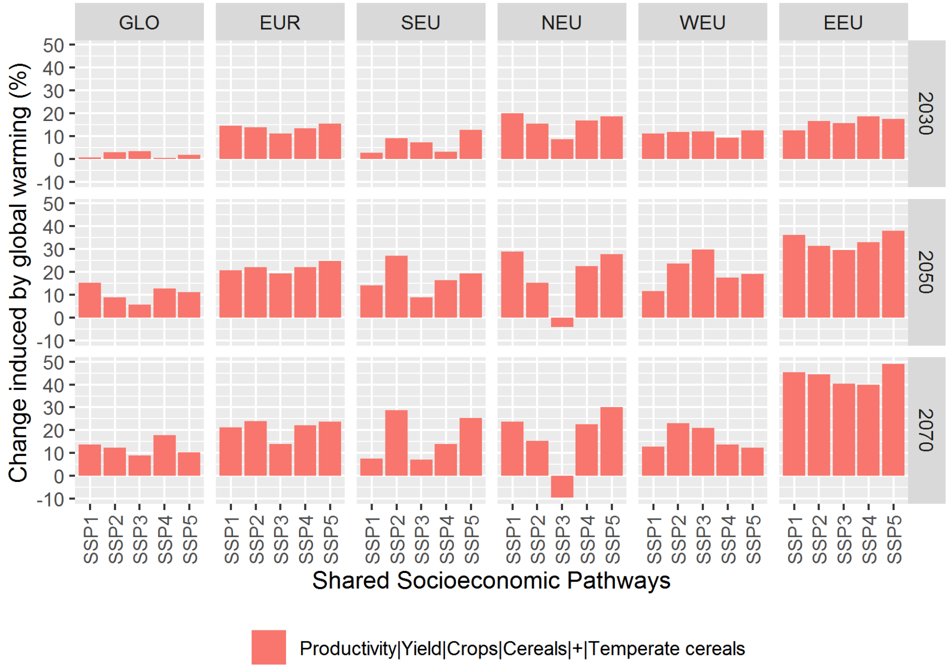

Figure 23. MAgPIE relative change on yield for RCP4.5 with HadGEM-ES across different SSPs

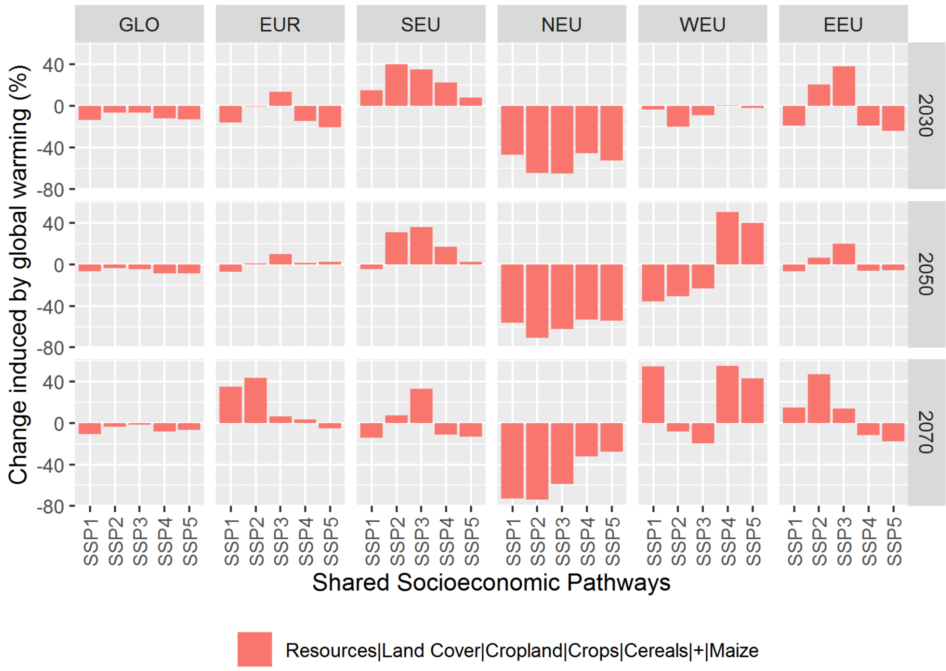

Figure 24. MAgPIE relative change on maize harvested area for RCP4.5 with HadGEM-ES across different SSPs

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4.1.3. Impact of GCMs

4.1.3.1. GLOBIOM

Climate impacts turn out to be quite different across GCMs. The yield effect due to climate change are mostly positive under the GCM GFDL-ESM2M, and mostly negative under the GCM HadGEM2-ES. IPSL-CMA5-LR and NorESM1-M show a more moderate picture with positive yield impacts in Europe.

Warszawski et al. (2014) analyse the average temperature and average annual rainfall between the end of the century and present-day under RCP8.5 between bias-corrected GCMs. Their analysis shows that HadGEM2-ES and IPSL-CMA-LR show much higher average air temperatures compared to NorESM1-M and especially GFDL-ESM2M. In terms of average annual rainfall, especially HadGEM2-ES and IPSL-CMA-LR are dryer. The impact of the lower temperature increases in GFDL-ESM2M, especially compared to HADGEM2-ES, is reflected in Table 7. Here, GFDL-ESM2M shows much higher positive yield effect due to climate change compared to the other GCMs. Furthermore, an outstanding impact is the large negative yield effect observed for corn under HadGEM2-ES, which is likely due to the warmer and dryer predictions of that model. As one of the most important C4 crop in Europe, corn is especially vulnerable to these circumstances. As a consequence, the average impact on cereals, all crops and even total agriculture remain negative impacts in Europe under HadGEM2-ES, whereas impacts are positive under the colder other GCMs.

Table 7. GLOBIOM results on relative change in production, area and yield in the EU for SSP2, RCP4.5, in 2050, across four GCMs.

	GFDL-ESM2M	HadGEM2-ES	IPSL-CM5A-LR	NorESM1-M
AREA % difference compared to base				
Agriculture	-0.17	-2.03	-3.33	-1.85
Crops	0.03	-3.70	-5.15	-2.82
Cereals	-3.43	-2.42	-4.60	-2.86
Oil seeds	-5.33	-9.47	-8.13	-6.06
Sugar	-7.14	-4.28	-3.95	-4.01
Corn	3.65	18.06	-1.67	0.26
Wheat	-8.92	-7.28	-4.96	-3.44
PRODUCTION in % difference compared to base				
Agriculture	6.77	1.03	0.99	2.15
Crops	8.20	1.24	1.18	2.59
Cereals	3.21	-0.69	0.94	1.39
Oil seeds	1.79	-4.98	-1.91	3.17
Sugar	2.12	0.20	0.42	0.58
Corn	-0.11	-8.10	1.45	0.27
Wheat	2.28	1.51	0.66	0.85
YIELD effect due to climate change in % difference compared to base				
Crops	5.61	-1.61	2.63	3.02

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Cereals	6.00	-2.12	2.76	3.12
Oil seeds	8.15	3.15	3.43	4.52
Sugar	10.11	4.94	4.16	5.66
Corn	-2.64	-19.24	1.19	0.24
Wheat	9.57	3.81	3.51	4.17

Figure 25 shows the percentage change in cropland by country and GCM under RCP4.5 and SSP2 compared to the situation without climate change in 2050. In the case of HadGEM2-ES, IPSL-CMA5-LR and NorESM1-M, the countries located in the South of Europe are the ones with the largest relative losses in cropland area. In the case of GFDL-ESM2M, Italy and Croatia experience large relative losses in cropland compared to a no climate change scenario, but this is compensated by large relative increases in cropland in the other Southern European countries Cyprus, Spain and Greece. All GCMs scenarios lead to large cropland losses in the case of Italy and Croatia. With the exception of Luxembourg, we also find robustness among the GCMs in some increases in cropland area in Western Europe, especially in the Netherlands and Ireland.

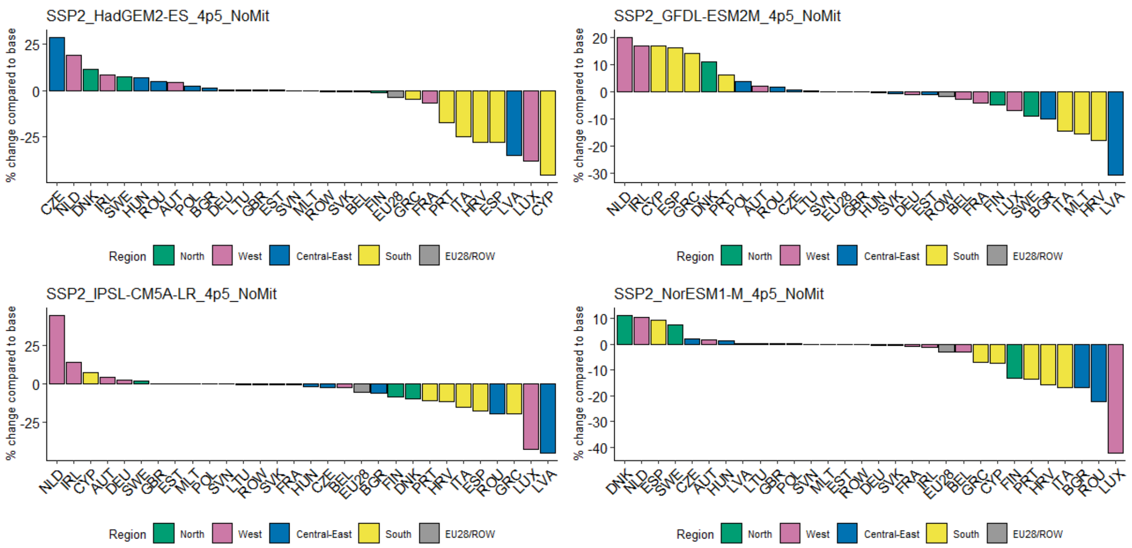

Figure 25. GLOBIOM relative changes in cropland area by country by GCM under RCP4.5 and SSP2 compared to the situation without climate change in 2050

When we take a closer look into the spatial distribution of yield changes for corn and wheat across the GCMs under SSP2, RCP4.5 in 2050, we can indeed see that the negative impacts on yields across the GCMs is particularly visible in HadGEM2-ES in the centre of Europe, and that losses in wheat yields are especially observed in the South for HadGEM2-ES and IPSL-CM5A-LR. High positive impacts, due to the more favourable climate, are especially observed under GFDL-ESM2M in the Mid-West of Europe.

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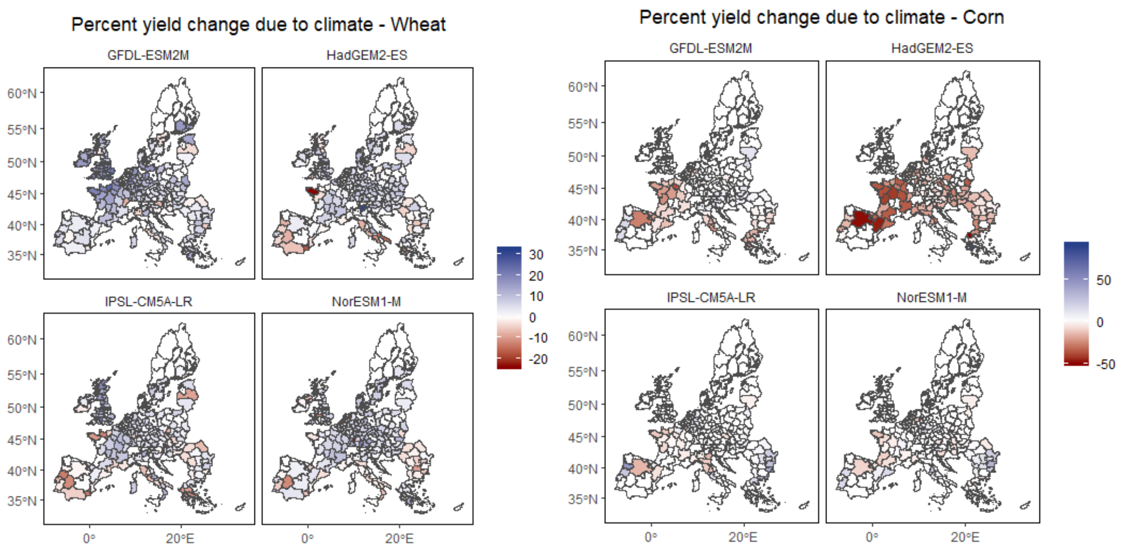

Figure 26. GLOBIOM spatial results on wheat and corn climate-induced yield changes across different GCMs for RCP4.5 in 2050.

4.1.3.2. MAgPIE 4

Sensitivity runs with MAgPIE 4 using the four same GCMs show similarly large variations in regional crop yields, which however lead to more limited changes in EU average and global average yields (Figure 27 and Figure 28). Across GCMs, the change in yield levels of temperate cereals (C_3 crop) and maize (C_4 crop) show for most regions the same sign. Only for maize in the Eastern EU and for temperate cereals in the Northern EU, the selection of GCM has also an impact on the direction of the change.

As explained before (see Figure 21), the change in yields is not solely the outcome of changing biophysical conditions, but also the effect of economic adaptation. Yield increases in Western Europe for maize are not primarily caused by better biophysical conditions; they are caused because Southern and Eastern Europe have negative biophysical climate impacts such that the investments in technological improvements are concentrated on Western EU, and where irrigation is used to support maize yields.

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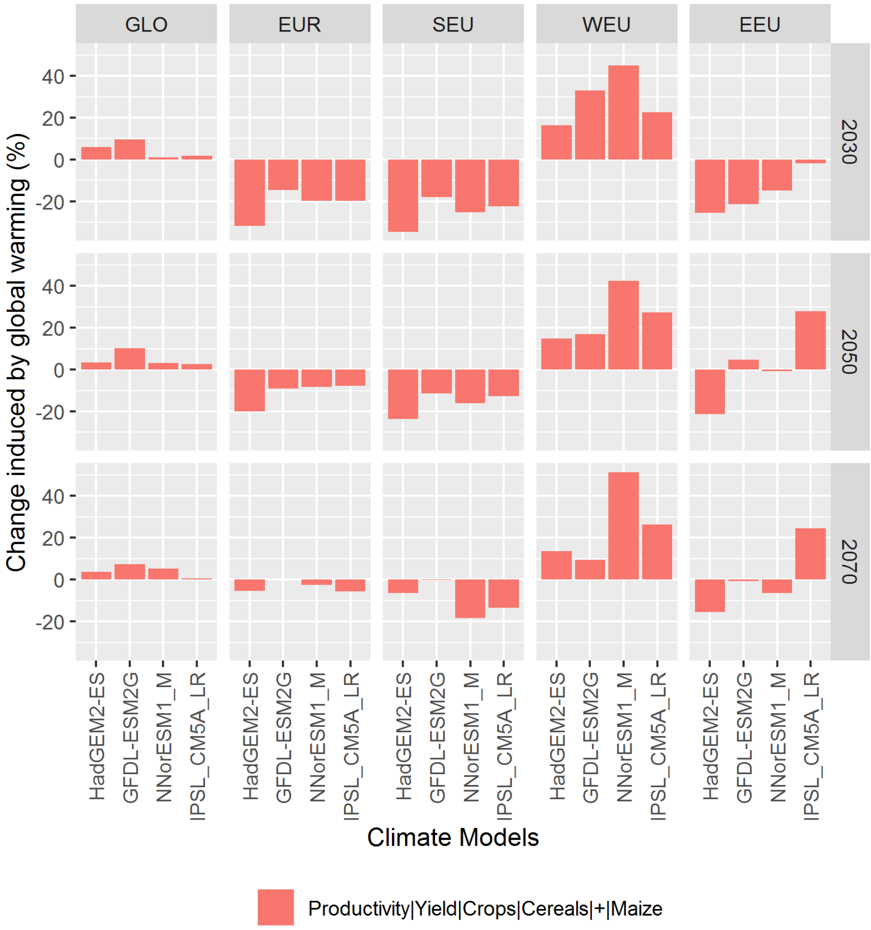

Figure 27. MAgPIE relative change in maize yield due to a climate signal, for the world (GLO), the EU (EUR) as well as 3 European subregions under different GCMs for simulations LPJmL5 and MAgPIE4 with a climate signal from RCP4p5. For maize, the Northern EU region was excluded because yields without climate change are zero or very low.

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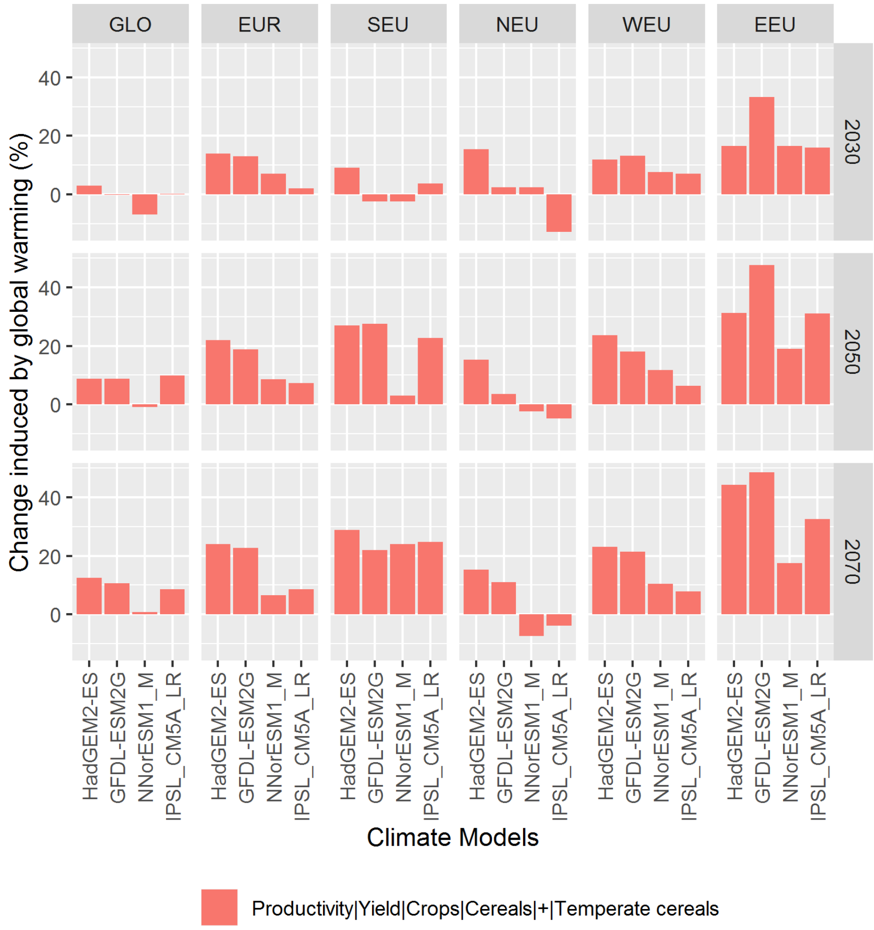

Figure 28. MAgPIE relative change in temperate cereals yield due to a climate signal, for the world (GLO), the EU (EUR) as well as 4 EU subregions under different GCMs for simulations LPJmL5 and MAgPIE4 with a climate signal from RCP4p5.

4.1.4. Impact of CO_2 fertilization

Beside temperature and precipitation changes resulting from GHG radiative forcing, the increase in CO_2 concentration in the atmosphere has also an important impact on the photosynthesis of plants, which could overall lead to an increase in biomass productivity for crops, better known as "CO_2 fertilization" effect. Elevated atmospheric CO_2 concentration also reduces the crop water needs. Thereby, these effects can mitigate the effects of yield losses resulting from the temperature and precipitation changes (Deryng et al. 2016). However, this effect may not be as strong in locations with limiting other factors, such as low temperature, and crops with a C_3 photosynthetic pathway (e.g. wheat) may be much more affected than plants with a C_4 photosynthetic pathway (e.g. corn). Climate change assessments have shown more favourable effect of elevated CO_2 concentration in northern latitudes, compared to tropical and subtropical zones.

Figure 29 and Figure 30 show the comparison of climate change effects on crop yield, production, area, consumption, trade and prices for all crops, wheat and corn with and

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without CO_2 fertilization. For the crop average, for wheat and for corn, the impact of CO_2 fertilization is all positive and is stronger in the medium term compared to the long-term. By 2050, corn yields are 13% higher with than without CO_2 fertilization, whereas the crop average and the corn yields are 6 to 7% higher due to climate change. This leads to a decrease in the area allocated to corn, all crops and wheat of respectively 11%, 4% and 6%. The combined effects of increased yields and decreased areas result in only small increases or decreases in production. However, the increase in yields and reduction in area does lead to change in prices, resulting in an altered trade position for Europe. Exports of wheat go down significantly, but total exports of crops rise by around 7% in 2050 in the case of CO_2 fertilization compared to no- CO_2 fertilization.

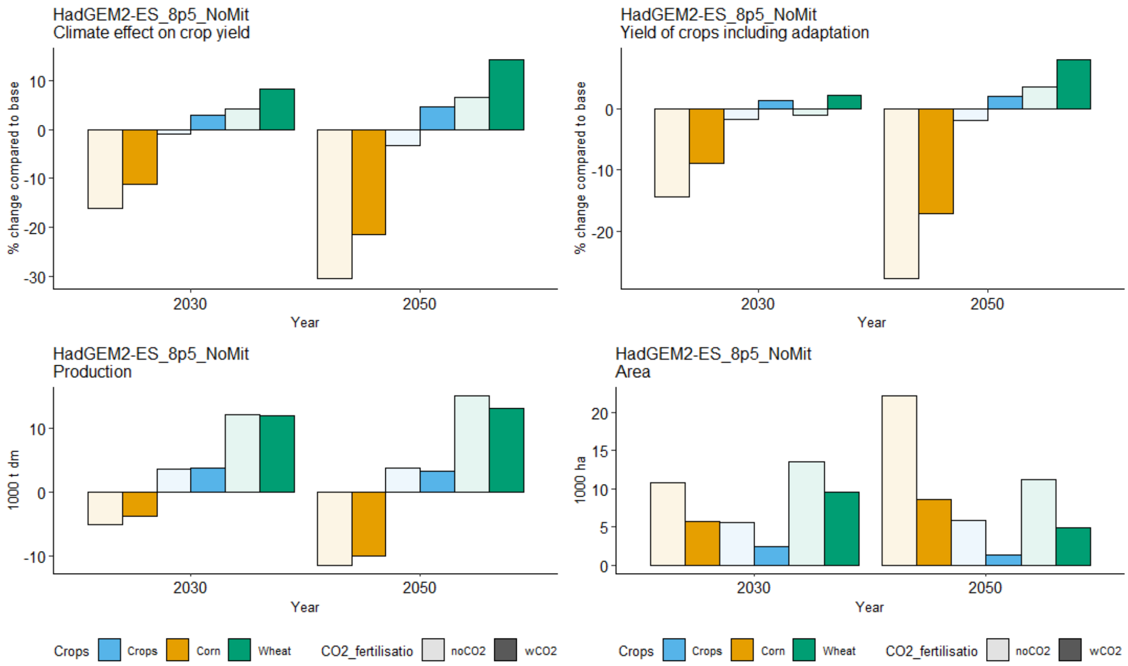

Figure 29. Comparison of yield, production and area for HadGEM2-ES under RCP8.5 with and without CO_2 fertilization.

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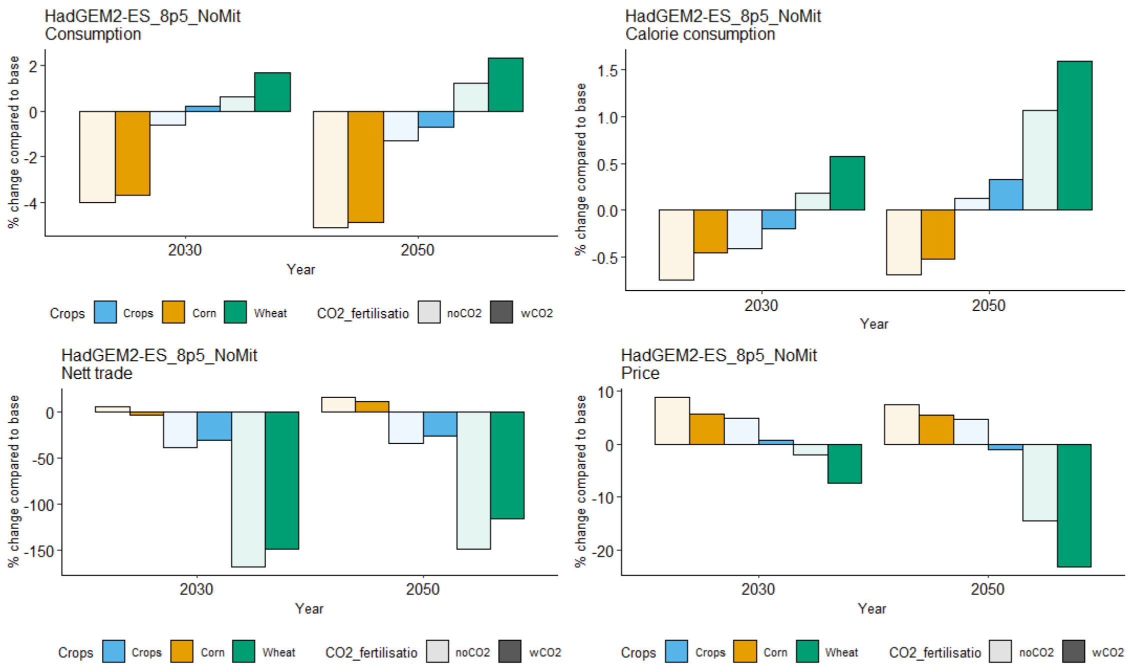

Figure 30. Comparison of consumption, prices and trade for HadGEM2-ES under RCP8.5 with and without CO_2 fertilization.

4.2. Forestry

4.2.1. GLOBIOM

Section 3.2.1 has shown that the climate-induced change on forest increments changes from a positive effect in the short term amongst all RCPs to a negative effect in the long-term, especially for RCP6.0 and RCP8.5. Figure 31 shows the percentage change in managed forest area by country and RCP compared to the situation without climate change in 2050. In 2050, largely positive impacts on forest increments are still reported, especially for countries in the Northern part of Europe. In 2050, the largest negative impacts are observed for RCP4.5 and RCP8.5 in Southern Europe. Figure 31 shows that the larger the positive impact on forest increments, the smaller the relative decrease in logged forest area. In turn, the larger the negative impact on forest increments, the larger the relative increase in logged forest area. Hence, there is a compensation effect in terms of logged forest area.

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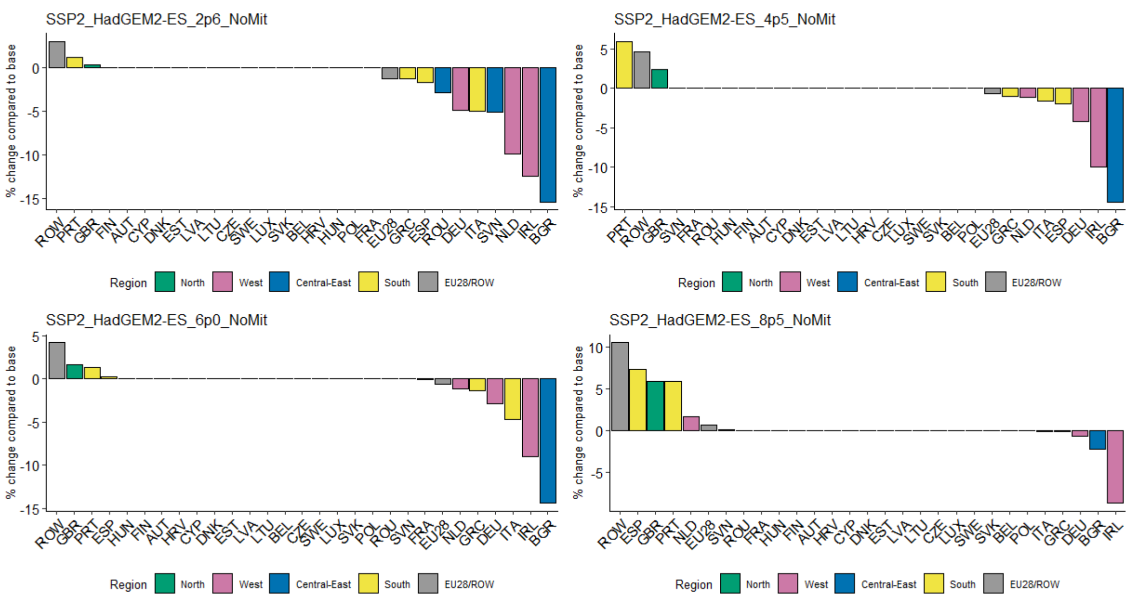

Figure 31. GLOBIOM relative change in managed forest area by country by RCP under HadGEM2-ES and SSP2 compared to the situation without climate change in 2050

This compensation effect is further highlighted in Table 8 which shows the contrast between the managed forest area and the production of sawnwood and woodpulp. The largest negative impacts are observed under RCP8.5 in 2070. Even though managed forest area increases here by 1.73%, total production of sawnwood and woodpulp still decrease by respectively 8.6% and 13%. In the case of RCP2.6 the observed picture has the opposite sign; even though the area of managed forests decreases, sawnwood and woodpulp production still increases due to the increase in yield shifters.

Table 8. GLOBIOM relative change in managed forest area and production of sawnwood and woodpulp for the EU28 in 2050 by RCP under HadGEM2-ES and SSP2 compared to no climate change

	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Land cover for managed forest				
2030	-1.55	-1.51	-1.08	-1.05
2050	-1.22	-0.72	-0.65	0.68
2070	-0.32	0.01	0.42	1.73
Production				
Sawnwood				
2030	0.90	1.00	0.79	0.80
2050	1.31	0.91	1.14	-0.48
2070	2.14	0.89	0.22	-8.55
Woodpulp				
2030	0.87	0.85	0.92	0.80
2050	1.77	1.28	1.68	1.22

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2070	3.07	1.30	0.64	-12.99

4.2.2. MAgPIE 4

The dynamic forestry module in MAgPIE 4 simulates how a given demand for forest products can be satisfied by a combination of plantations, clear-cut and selective logging.

Our estimated changes of global forest cover due to climate change are rather limited in scale and add up to no more than 0.5% of global forest area. The drivers of these changes are direct (from the forest sector) and indirect (from the agricultural sector). The direct effect of climate change is caused by a changed wood harvest from forests, changes of rotation length and changes of the relative contributions from managed forests and harvested unmanaged forests. In general, the estimated impacts of LPJmL 5 on global carbon stocks are positive in most world regions, also due to CO_2 fertilization (see Figure 11 above). For Europe, we see that the Northern regions which benefit a lot from climate change increase their forestry areas, while the temperate zones in Eastern and Western EU marginally reduce their areas.

In terms of indirect effects from agriculture, when cropland and pasture areas expand, primary and secondary forests are reduced. This is visible for Southern EU but also for the world as a whole. Moreover, when forests are cut to make space for this expansion, timber is produced which substitutes production which can possibly come from plantation forests. In our case, managed forests therefore only get harvested later in time, leading to higher areas of managed forests.

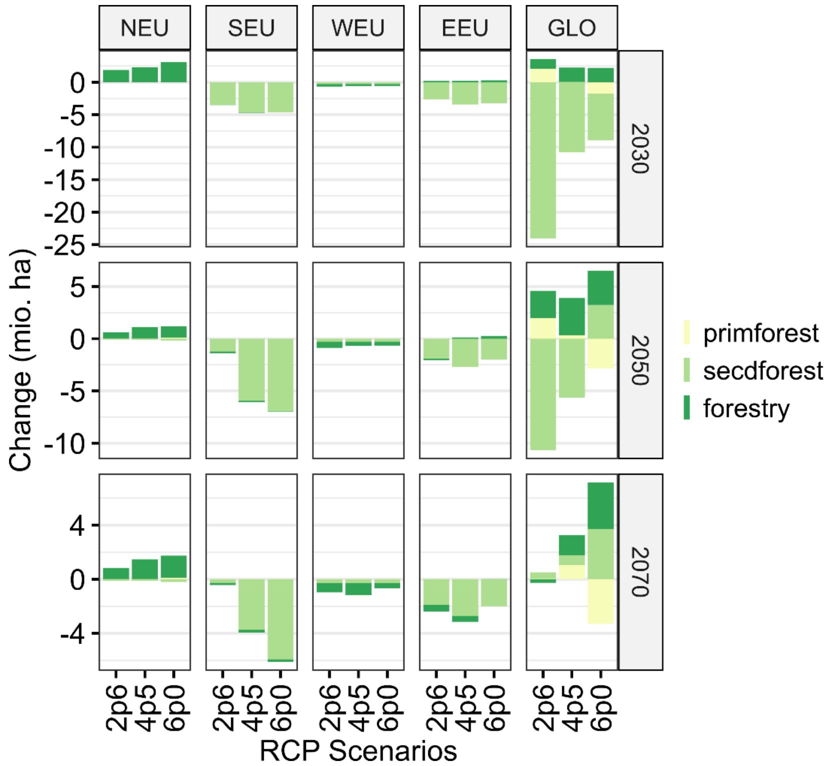

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Figure 32. MAgPIE forest area changes due to climate change, split up into the three categories Primary Forest, Secondary Forests and Managed Forestry for different RCPs, using HadGEM2-ES, LPJmL 5 and MAgPIE4 with a SSP2 scenario.

The current simulations of LPJmL 5 and MAgPIE 4 do however not account for the full range of forestry impacts. LPJmL 5 for example does not account for pests and diseases, nor does it account for more complex ecosystem interactions that may occur when different species adapt to changing climatic conditions. On MAgPIE 4's side, we do not account for demand-side reactions to changing roundwood prices, or for more nuanced management practices for forests that could facilitate adaptation under climate change. Also, as MAgPIE is run in recursive dynamic mode, the model may underestimate the rational anticipation of forest managers in their planning decisions, e.g. for planting new forests.

In general, we can learn from this exercise that the climate-change induced interactions between forestry and agriculture are of rather limited magnitude.

4.3. Fisheries

4.3.1. GLOBIOM

4.3.1.1. Impact on marine catches

The projected mid-century average changes in marine catch potential reported in FAO (2018) are implemented in the GLOBIOM fish model in four alternative scenarios. This is done by gradually changing the exogenous trajectories of capture production through 2050. The estimated changes from the literature are mapped to countries, and unless the data in the FAO reference only pertains to a specific coast or area, all fishing areas for a given country are affected, except for those designated in the fish model database as "Inland". Therefore, freshwater and diadromous species production is largely unaffected by the scenarios. Furthermore, production of the tuna species group is also unaffected, as most tuna catches occur on the open sea while the FAO study only refers to fisheries located in countries' EEZs (370 km off the coast).

Table 9 below shows the mid-century differences in global marine capture between GLOBIOM business as usual scenario, which follows linearly extrapolated historical trends of production and food consumption, and the climate change scenarios.

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Table 9. GLOBIOM projected effects of climate change on marine capture fisheries for the year 2050, based on alternative approaches under alternative RCPs.

	Business as Usual	RCP2.6 DBEM	RCP2.6 DSFM	RCP8.5 DBEM	RCP8.5 DSFM
	(million tons)	Difference from BAU (%)			
Marine capture production affected by climate change	72	-4%	-8%	-10%	-12%
Total production, capture and aquaculture	256	-2%	-4%	-5%	-5%
Food use for human consumption	237	-2%	-4%	-5%	-6%
Fish processing by-product potential	110	-2%	-3%	-4%	-5%
Fishmeal production	5	-2%	-3%	-4%	-4%
Fishmeal aquaculture feed use	3	-3%	-4%	-5%	-4%
Fish oil production	1	-2%	-3%	-4%	-4%
Fish oil aquaculture feed use	1	-3%	-4%	-4%	-4%

All four scenarios consistently indicate a decline in capture production globally, although global figures mask very stark regional differences, where areas near the equator tend to be affected negatively, while higher latitudes are impacted positively. This strong regional differentiation is consistent with the existing literature on climate change in fisheries (Allison et al., 2009; Cheung et al., 2010; Barange et al., 2014).

Table 10 shows the top "winners" and "losers" under each of the four scenarios at the country level, and for the EU28 as a whole. Not a single EU country is projected to see an increase in capture production, except for the territory of Greenland. Non-EU countries such as Norway and Iceland are the biggest winners. While EU countries are not among the most severely negatively affected regions in absolute terms, every EU member is projected to experience a decline in marine productive capacity, with the most serious impacts occurring in Denmark, Spain, France, and the UK.

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Table 10. GLOBIOM projected effects of climate change on marine capture fisheries for the year 2050, based on alternative approaches under alternative RCPs.

DBEM RCP2.6		DSFM RCP2.6		DBEM RCP8.5		DSFM RCP8.5	
Difference from BAU (thousand tons)							
Top Projected Increases in Marine Capture Production							
Russian Federation	2,356	Myanmar	129	Russian Federation	2,972	Chile	46
Iceland	329	Norway	72	Chile	293	Myanmar	22
Norway	203	Iceland	70	Iceland	202	Vanuatu	2
Chile	184	Chile	47	Greenland	194		
Greenland	172	Russian Federation	13	Canada	75		
Canada	56	Vanuatu	6	Norway	70		
Korea, Republic of	40			United States of America	63		
United States of America	28			Korea, Republic of	44		
Top Projected Decreases in Marine Capture Production							
Japan	-137	Philippines	-180	Angola	-178	Morocco	-250
Denmark	-138	United Kingdom	-183	Japan	-215	Mexico	-363
Argentina	-151	France	-258	Ecuador	-234	Russian Federation	-380
Philippines	-162	Spain	-267	Thailand	-319	Philippines	-439
Ecuador	-164	Japan	-314	Malaysia	-424	Cameroon	-452
Malaysia	-207	Peru	-318	Philippines	-446	Viet Nam	-488
India	-421	India	-319	Cameroon	-512	United States of America	-488
Cameroon	-481	United States of America	-340	India	-653	Japan	-505
Viet Nam	-555	Morocco	-357	Viet Nam	-688	Indonesia	-597
Peru	-590	Viet Nam	-448	Indonesia	-1,642	Peru	-598
Indonesia	-743	Cameroon	-458	Peru	-1,959	India	-658
China	-1,488	China	-1,171	China	-2,171	China	-1,249
Global and Regional Net Change in Projected Capture Production							
Global Total	-3,464	Global Total	-6,554	Global Total	-7,831	Global Total	-9,621
EU28	-685	EU28	-1,229	EU28	-776	EU28	-956

The magnitude of the fish population response to climate change is not as dramatic as the environmental parameter changes would have suggested. Fish stocks are highly mobile and therefore able to at least partly mitigate negative changes in the environment. However, the mid-century time horizon considered here is relatively medium-term and the results presented do not reveal the long-term impacts of

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climate change. The estimates for the year 2100 would be significantly more negative, with larger regional differentiation. Another important point regarding the size of the climate change effects is that improvements in fisheries management aimed at reducing fishing effort and fishing at maximum sustainable yield levels have the potential to improve annual production by amounts similar or exceeding those presented here (FAO, 2016; Costello et al., 2016; World Bank, 2017).

An indirect effect of climate change can also be found in the link between capture fisheries and aquaculture, which operates via the feed markets. Capture fisheries are the sole source of whole fish destined for reduction, and capture fisheries are therefore the primary source of fishmeal and fish oil. Both are key ingredients in the diets of farmed fish, especially those that would otherwise be carnivorous predators in the wild, such as salmon, trout, eels, etc. As can be seen in Figure 35 and Figure 36, total fish production in the scenarios declines by more than just the difference in marine capture. The drop in catches of demersal, pelagic, and other marine fish results in a decrease in the production of fishmeal and fish oil; the latter one projected to become especially scarce by 2050, the total amount of aquaculture production which can be supported in the scenarios also decreases. A second, weaker feedback effect also comes into play. About a quarter of world's fishmeal and fish oil does not come from the reduction of whole fish, but from the reduction of by-products of seafood processing, canning, and packaging. The source of these by-products can be either marine capture or aquaculture, therefore a decrease in aquaculture production in certain regions and sectors results in a further decrease of fishmeal and fish oil availability. As a result of all of these factors, we can see that while the effect of the scenarios ranges between a 3 to 9 million tonnes drop in annual catches, the projected decrease in seafood availability is larger, between 5 and 15 million tonnes annually; the indirect effect on the aquaculture sector is therefore almost as large as the initial shock itself.

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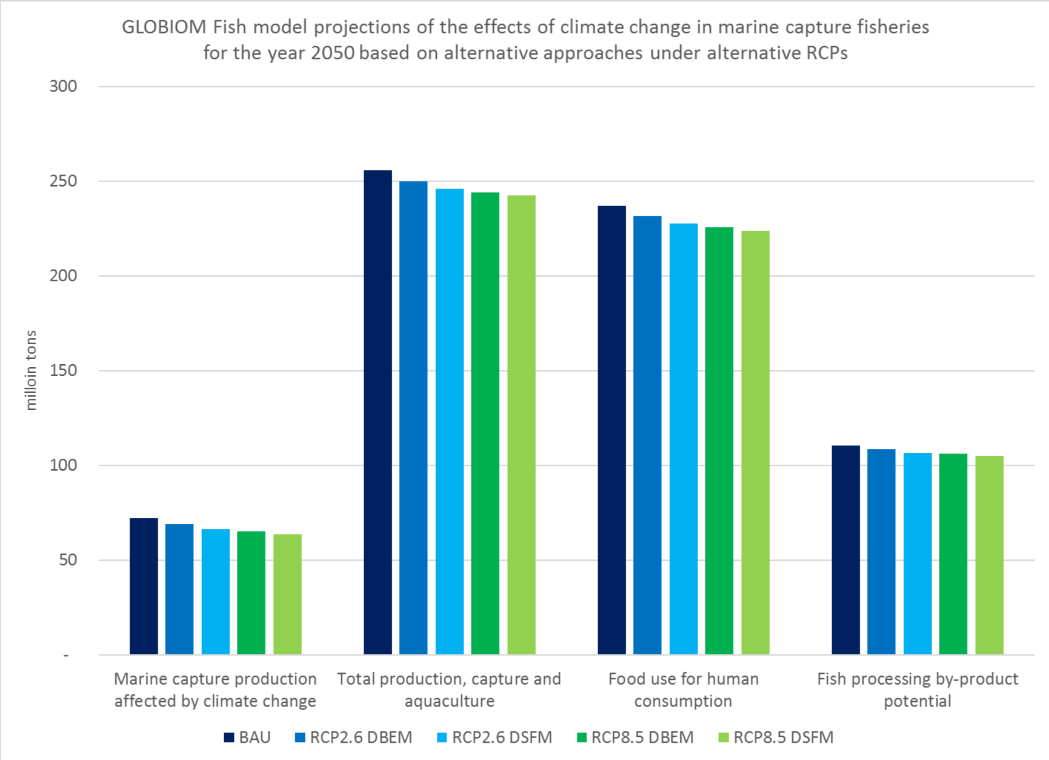

Figure 33. GLOBIOM model projections of the effects of climate change on capture fish production and consumption by 2050 in SSP2

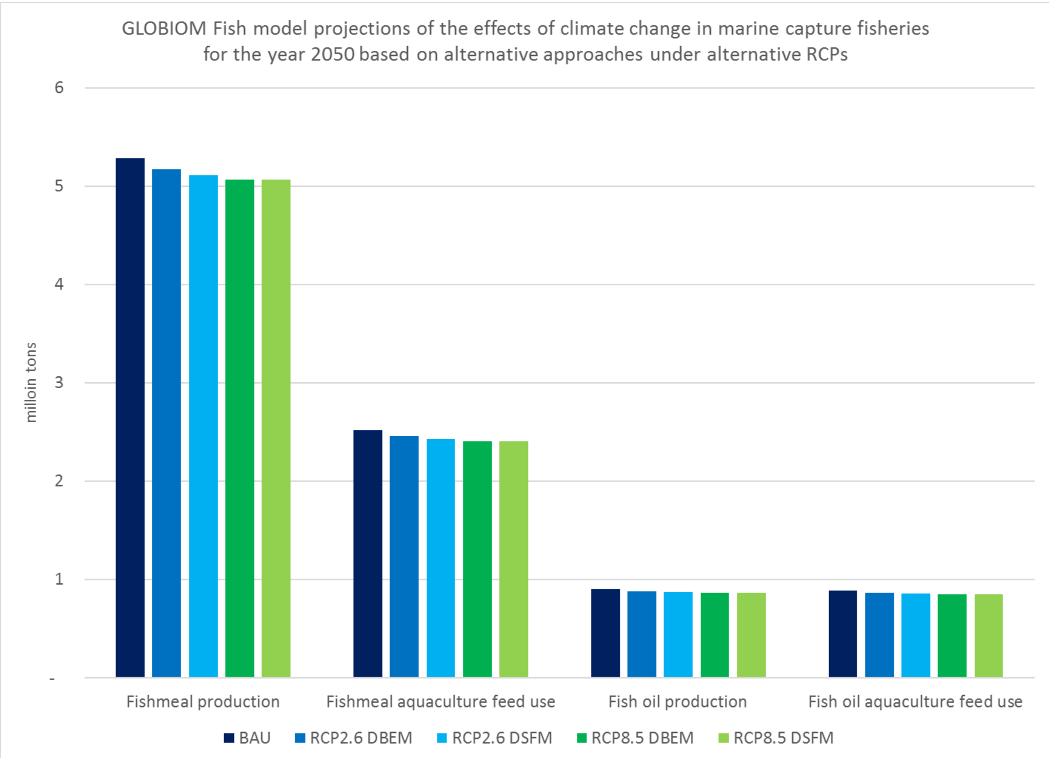

Figure 34. GLOBIOM model projections of the effects of climate change on fish meal and fish oil production and use by 2050 in SSP2

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Table 11 illustrates the potential economic impacts of the capture fisheries climate scenarios by expressing the physical quantities into economic value using the average unit values of EU capture and aquaculture production respectively. The current average unit value of EU aquaculture production is 3,237 EUR per tonne of live-weight versus 1,356 EUR per tonne of capture production, according to EUROSTAT data.[6] According to our projections, the combined EU28 capture and aquaculture sector stands to incur production losses of 1-2 billion EUR. The losses in the aquaculture sector are projected to be much smaller, but still significant, due to the much higher average value of the typical EU aquaculture product.

Table 11. GLOBIOM projected effects of climate change on marine capture and marine aquaculture for the year 2050, based on alternative approaches under alternative RCPs.

	Business as Usual	DBEM RCP2.6	DSFM RCP2.6	DBEM RCP8.5	DSFM RCP8.5
Volume (tonnes)					
Capture	5,706,737	-685,426	-1,229,060	-775,863	-955,534
Aquaculture	1,658,508	-22,183	-31,549	-39,436	-38,450
Value (million EUR)					
Capture	7,738	-929	-1,667	-1,052	-1,296
Aquaculture	5,369	-72	-102	-128	-124

The results presented here come with certain limitations. First of all, there is considerable uncertainty in the estimates of catch potentials in the reference literature itself. Secondly, the effect of climate variability could turn out to be very significant but is not taken into account here (Merino et al., 2012). Also, the changes in catch potentials, estimated on country EEZs, were applied in the GLOBIOM model onto larger areas of the ocean; on the other hand, most catches occur close to the shore, so this effect is likely not decisive. A major source of uncertainty is the effect of climate change on individual fish species and species groups. The estimates from the reference were applied in the GLOBIOM model uniformly across all the relevant species. But if in reality the effects were different across species, the results could be slightly different, not only directly, but also indirectly, since different fish species groups in the model produce varying amounts of fish oil, and would therefore expand or contract the amount of feasible aquaculture production differently.

4.3.1.1. Impact on marine aquaculture

Froehlich et al. (2018) modelled and mapped the effects of warming ocean conditions on finfish and bivalves in terms of the areas suitable for marine aquaculture

[6] Source: Eurostat variables “fish_aq2a”, “fish_ca_main”, and “fish_ld_main”. Averages over 5 and 3 years around the year 2015 were used.

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production as well as the growth performance of marine aquaculture species. Their mid-century RCP8.5 estimates have been mapped to the countries contained in the GLOBIOM fish model and applied on the corresponding species groups and the aquaculture production designated by the FAO as taking place in a marine environment. The resulting GLOBIOM fish model projections are for a 6% increase in marine finfish aquaculture production and a 26% decrease in bivalve production in 2050 relative to the business-as-usual scenario. Since marine aquaculture is projected to continue to account for only a relatively small portion of total seafood production, the combined effects result in a 3% drop in total global seafood production.

As the GLOBIOM model assumes that aquaculture products would never be used for whole for reduction into fishmeal and fish oil (FM/FO), the first consequence of the change in production is that the entire difference in production is reflected in a 3% decrease in seafood use. The second consequence is that there is no change in the amount of whole fish utilized for FM/FO production; the only change is in the amount of fish processing by-products that are potentially available for reduction. Because of the different rates of by-product utilization and different FM/FO yields across different countries, the scenario projection is for a 5% decrease in the by-product potential, but a 1% increase in the utilization of that potential, a small increase in fishmeal production, and a small decrease in fish oil production globally. Because of the increase in marine aquaculture production, which is quite FM/FO-intensive, the GLOBIOM model projects a small increase in the amount of FM/FO required to sustain that level of production. Such increases in FM/FO aquaculture feed use might be difficult in an already stretched feed market in the business-as-usual case, but they might be extremely difficult under climate change, given the effects on marine capture discussed in the previous section.

Table 12. GLOBIOM projected effects of climate change on marine aquaculture for the year 2050.

	Business as Usual	**RCP8.5**
	(million tonnes)	Difference from BAU (%)
Marine finfish aquaculture production affected by climate change	10	6%
Marine bivalve aquaculture production affected by climate change	29	-26%
Total production, capture and aquaculture	256	-3%
Food use for human consumption	237	-3%
Fish processing by-product potential	110	-5%
Fish processing by-product utilization	11	1%
Fishmeal production	5.3	1%
Fishmeal aquaculture feed use	2.5	1%
Fish oil production	0.9	0%
Fish oil aquaculture feed use	0.9	3%

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The country-level and regional results presented in Table 13 below again point to very strong regional differentiation, but perhaps with a slightly less unambiguous dichotomy between low- and high-latitude regions. The single largest beneficiaries are, however, projected to be Norway and the Russian Federation due to their adjacency to the Arctic Ocean. The list of the most severely negatively impacted regions is influenced by the existing level of aquaculture production, which is quite concentrated; the large producers in East, Southeast, and South Asia would appear to suffer the greatest losses in production under climate change. The EU as a whole is affected neither extremely positively nor negatively; the profile of the changes follows the global total in that marine finfish would potentially suffer while bivalves would potentially benefit. Among EU28 members, Finland and Spain are projected to see an increase in finfish and bivalve production respectively, while the United Kingdom and Denmark are projected to see their output shrink.

Table 13. GLOBIOM projected effects of RCP8.5 on marine aquaculture for the year 2050, for finfish and bivalves respectively.

Finfish			Bivalves	
Difference from BAU (tonnes)				
Top Projected Increases in Marine Aquaculture Production			**Top Projected Increases in Marine Aquaculture Production**	
Norway	366,603		Russian Federation	1,133,274
Russian Federation	166,021		New Zealand	300,399
China	53,823		United States of America	251,261
India	34,651		Chile	148,952
Tunisia	7,486		Canada	16,571
Canada	6,947		India	10,909
Finland	6,101		Australia	7,323
Japan	5,418		Spain	2,778
Greece	5,365		**Top Projected Decreases in Marine Aquaculture Production**	
Viet Nam	3,525		Cambodia	-1,192
Mexico	3,249		Costa Rica	-1,305
Taiwan Province of China	2,749		Denmark	-3,200
Iceland	2,654		United Kingdom	-7,021
Algeria	1,021		Thailand	-11,084
Top Projected Decreases in Marine Aquaculture Production			Netherlands	-15,305
United Kingdom	-1,457		Brazil	-16,654
Turkey	-1,475		Korea, Republic of	-215,851
Philippines	-2,348		Viet Nam	-268,393
Malaysia	-5,648		China	-8,997,743
Indonesia	-16,624			

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Global and Regional Net Change in Projected Aquaculture Production				
EU 28	12,602		EU 28	-23,733
Global Total	639,838		Global Total	-7,666,546

The economic effects of the aquaculture climate change scenario were once again quantified using the corresponding average unit value of EU finfish and bivalve marine aquaculture respectively. Typical EU finfish products being nearly three times as expensive as a typical bivalve product (4,505 EUR vs. 1,596 EUR per tonne of live-weight), the projected economic losses and gains very nearly cancel each other out, even though the physical quantities are far apart.

Table 14. GLOBIOM projected effects of climate change on marine aquaculture for the year 2050, under RCP8.5.

	Business as Usual	RCP8.5
Volume (tonnes)		
Finfish	1,020,720	12,602
Bivalves	637,222	-23,733
Value (million EUR)		
Finfish	4,598	57
Bivalves	1,017	-38

4.3.2. MAgPIE 4

MAgPIE estimates the effects that climate impacts on marine systems may have on capture fisheries, as well as the effect which the substitution of capture fish by chicken meat may have on the agricultural markets.

Applying the climate impacts of Cheung et al (2016) to FAO FishStat production results in a modest reduction of global marine fish catches of just 2% under 1.5° warming and 10% under 3.5° warming. However, there are large regional differences in fish impacts that largely balance out. In general, tropical countries have reduced fish catches, while countries with temperate and polar fish habitats benefit from warming (see Figure 35). Within the EU, the Mediterranean countries have negative impacts from climate change, while the Northern countries substantially benefit from warming oceans. Baltic countries (Lithuania and Latvia) will face negative consequences since those countries capture fish in long distance fishing vessels within tropical fishing areas as well. Considering that a substantial share also comes from inland fisheries and aquaculture, the impact of climate change and total fish production is somewhat lower (see Table 15).

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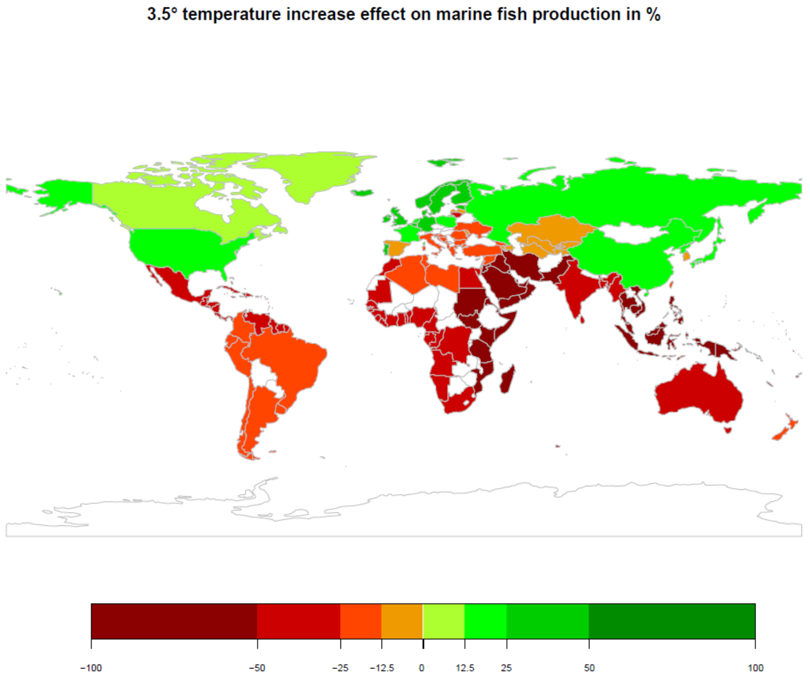

Figure 35. MAgPIE percentage changes in marine fish catches due to climate change in a scenario of 3.5° warming (approximately RCP8.5 in the year 2070), calculated back from fishing grounds to fish capture by country.

Table 15. MAgPIE change in total fish production in European Union and the World under three levels of global warming. Only climate impacts on marine capture fisheries are accounted for here.

		+1.5°	+2.5°	+3.5°
Northern EU	NEU	1.09	1.26	1.3
Southern EU	SEU	0.97	1.03	0.97
Western EU	WEU	1.06	1.2	1.19
Eastern EU	EEU	0.99	1.07	1.1
World	GLO	0.98	0.99	0.9

In order to estimate a high-end scenario of climate change impacts, we assumed a pathway in which the world will warm by 2.5° until 2050 and by 3.5° until 2100 – a scenario that is in between RCP6.0 and RCP8.5. We then assumed that the reduction of marine fish catches will be substituted by increased consumption of chicken meat. A substitution by aquaculture fish may be even more likely due to the similar properties of the products, but would have similar consequences on agricultural markets, as also aquaculture receives farmed feed.

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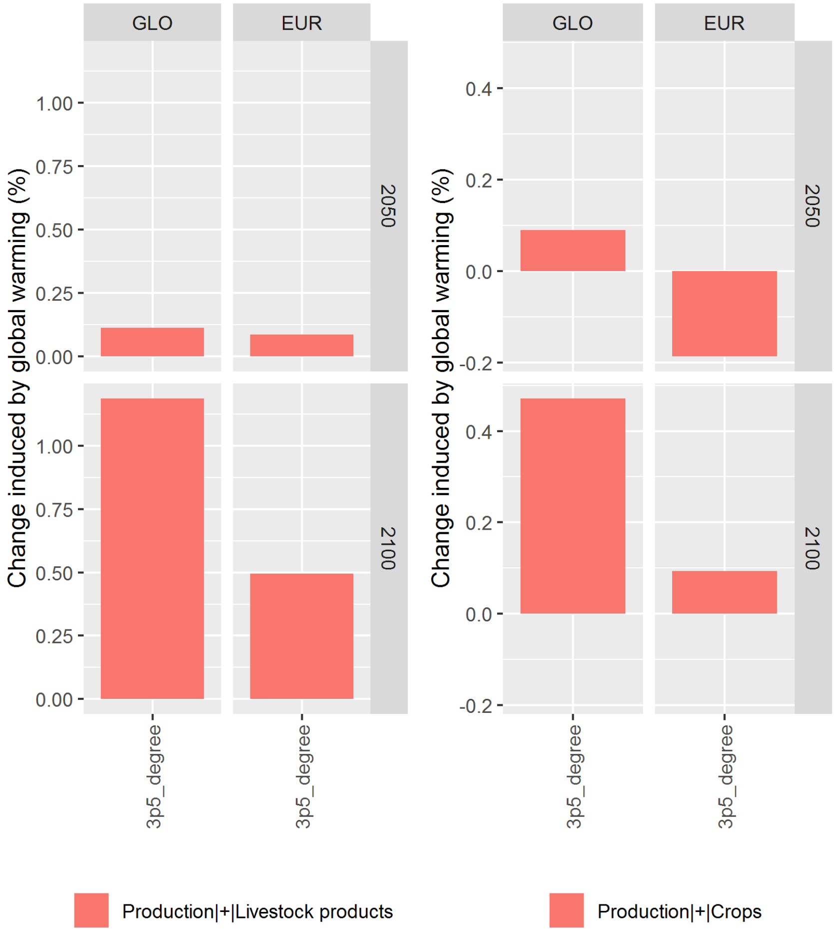

Figure 36. MAgPIE relative change in chicken meat and crop production illustrating the substitution effect from marine fish catches on the terrestrial livestock and crop production.

As shown in Figure 36, the substitution of fish by chicken has only a very limited consequences on the terrestrial land system. This has different reasons: Firstly, the quantity of fish within human diets is (with regional exceptions) relatively low compared to livestock products. Secondly, our scenario only reduced marine fish catches while aquaculture and inland fish catches were held constant, as they are much less affected by climate change. Thirdly, our model does not yet account for the role of fish in livestock feeding. A substitution of fish meal (often from marine fish catches) by comparable protein (e.g. soybean) would lead to higher impacts. On the other hand, our scenario may also overstate the impacts for various reasons. Foremost, our assumption that the relative shares of capture and aquaculture fisheries, as well as marine and inland fisheries remain constant may lead to an overestimation of climate impacts. Most marine fishery production systems are already today at the limit of sustainable catch potentials, and marine fish capture has stabilized in recent decades. In contrast, additional production growth came almost exclusively from an extension of aquaculture. It is therefore likely that the share of marine capture fisheries in total production further declines, and the climate change impacts on marine fish catches has an even lower impact on global fish markets.

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4.4. Economic costs of climate change

4.4.1. GLOBIOM

Previous subsections of Section 4 have analysed so far the climate effects of agriculture, forestry and fisheries on production, consumption and trade that stem from productivity changes. These changes can be added together to compose the total costs of climate change. To measure the costs of climate change, we separately define the costs for the consumers and the costs for the producers. The costs for the consumer are defined as the consumer equivalent variation. The consumer equivalent variation is calculated as the consumption multiplied by fixed calibration prices and reported in current million Euro. Consumption is defined as the consumption of products for food, biofuels and other uses. Similarly, the cost for the producer is computed as the change in production volume expressed as the production of agricultural and forest products multiplied by calibration prices and reported in current million Euros. Table 16 shows an overview of these costs by sector and a breakdown within the category crops and agriculture by main item. It is important to note that these costs do not sum up, as they look at the same variations, simply taking a different perspective. Producers losses will only be partly reflected in the consumer losses in our partial equilibrium framework, because these are also able to import from other world regions if needed. Similarly, producers may also be affected through their exports, which will not directly impact the EU consumers.

The economic costs of agriculture show that for the producer, 1.7 billion Euros of losses are found under the central case of RCP4.5 in 2050. Costs for the producers are mostly negative, but may vary a lot with warming potentials, and, for example, whether CO_2 fertilization is included in the construction of the costs. Furthermore, impacts are largely differentiated between the crops. Section 3 and 4 have shown that especially corn is vulnerable to climate change. This is reflected in the costs. Corn production could represent up to a third of the agricultural losses and up to two billion Euros without farmers adaptation. These costs constitute here a low bound because GLOBIOM does not cover all crops produced in the EU, notably fruits and vegetables.

Losses in fisheries increase with time and along the RCPs. In the worst-case scenario of RCP8.5 in 2050, producer losses can amount to 1.3 billion Euros. For Europe, these losses are mostly related to a decrease in capture production.

Losses in the forestry sector are most profound under RCP8.5 as well. In 2050, losses amount to 63 million Euros for the producer side and 670 million Euros for the consumer side. Both the losses for the producer and the consumer side increase largely in the long term of 2070. Furthermore, under RCP8.5, fire protection efforts could more than double compared to the current day. Forest damages are currently estimated to amount to 1.5 billion EUR for the EU (San-Miguel-Ayanz et al, 2010). Increase in fire occurrence could escalate these costs, potentially by 1-2 billion EUR more if costs are assumed proportional for forest fire occurrences.

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Table 16 GLOBIOM changes in producer and consumer costs in SSP2 compared to no climate change

	HadGEM2-ES RCP2.6			HadGEM2-ES RCP4.5			HadGEM2-ES RCP6.0			HadGEM2-ES RCP8.5		
	2030	2050	2070	2030	2050	2070	2030	2050	2070	2030	2050	2070
Consumer equivalent variation												
Agriculture	38	11	-80	-265	516	514	223	732	167	163	854	823
Forestry	798	1453	2849	876	908	232	784	1234	-583	700	-670	-12260
Fisheries	-252	-2003	-1754							-502	-1718	-2934
Crops	311	419	172	132	608	131	110	338	69	360	836	523
Cereals	7	47	19	23	62	31	13	54	20	19	62	48
Oil seeds	131	247	160	-220	232	94	-22	231	117	165	538	691
Sugar	7	9	-24	-8	6	33	1	12	63	-3	44	29
Corn	-3	-5	-2	-5	-5	-2	-2	-1	-4	-2	-3	0
Wheat	13	54	24	29	62	25	15	48	28	22	61	39
Producer equivalent variation												
Agriculture	-551	-1710	-2495	-1407	-1717	-1052	340	267	-865	-289	-831	-631
Forestry	833	1503	2745	902	1106	1201	782	1380	423	763	-63	-11154
Fisheries	-424	-1385	-2346							-401	-1338	-2275
Crops	-191	-953	-1861	-901	-1517	-1454	103	-278	-938	-159	-906	-959
Cereals	16	-264	-643	-40	-120	-226	-112	-39	-9	-15	27	-144
Oil seeds	-9	-141	-572	-118	-312	-798	8	-105	-478	95	28	-386
Sugar	74	71	15	37	-33	45	-38	-26	104	-25	10	98
Corn	41	33	-282	-107	-327	-580	35	48	6	-27	6	-66
Wheat	50	-136	-367	144	139	86	-86	-150	-159	34	-2	-328

Besides the overall picture in Europe, winners and losers of climate change can be identified as well. Figure 37 highlights the variation in benefits and costs of climate change for producers perceived by country. For our central case, HadGEM2-ES, RCP 4.5 in 2050 (top right graph), the Southern part of Europe (yellow bars) show the largest losses. This is consistent with the picture of the biophysical losses and production losses observed in the Southern European countries. Largest gains on the other hand are observed for the Northern and Central-Eastern countries. These regions benefit through a reallocation of agricultural activities that is induced by a change in relative profitability. Moreover, due to CO_2 fertilization effects, increases in productivity are sometimes observed in these regions.

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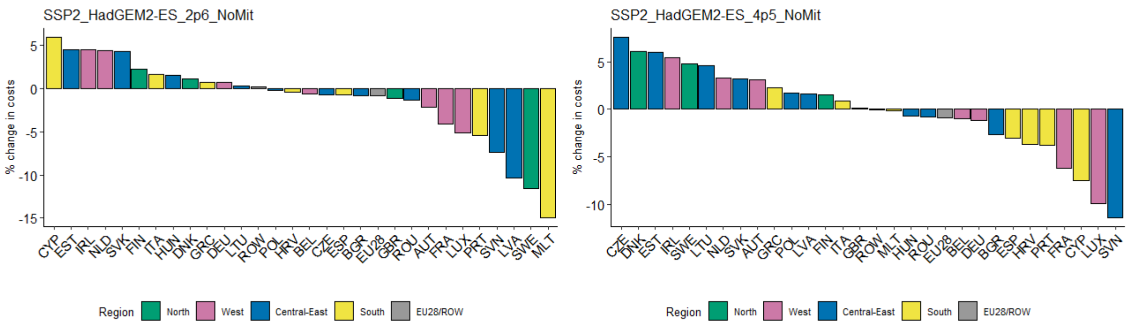

Figure 37: GLOBIOM results breakdown across countries for relative change in production and consumption for agriculture products due to climate change for RCP2.6 and RCP4.5 in 2050.

4.4.2. MAgPIE 4

MAgPIE estimates the costs of production to fulfil a specific food demand. Comparing a scenario with climate change (CC) impacts and a scenario without CC impacts allows to estimate the costs and benefits of climate change for the agricultural sector (see Figure 38).

MAgPIE results, using the climate simulations of the HadGEM2-ES model show that until 2030, CC and increased CO_2 concentration actually has on average positive effects on agriculture on the global scale. Similar positive effects can also be seen with different GCMs – only in the NorESM1-M model, costs increase slightly already in 2030.

These positive effects are most pronounced if the warming is moderate, i.e. in the RCP2.6 scenario. In this mitigation scenario, CC impacts may also be continuously positive for the year 2050 and 2070, if production costs around the world are summed up. In the GCM GDFL-ESM2G case, these are even positive for the RCP4.5 scenario. All the other GCMs however project less favourable conditions for agricultural production, so that production costs increase in RCP4.5 and RCP6.0. Surprisingly, the RCP4.5 shows higher impacts than the RCP6.0. This could be connected to the temporal development of global warming. RCP4.5 projects higher temperatures in 2050 than RCP6.0. RCP6.0 only becomes warmer in the second half of the century. The fact that MAgPIE also projects higher production costs in 2070 may be explained by path-dependent outcomes of agricultural development.

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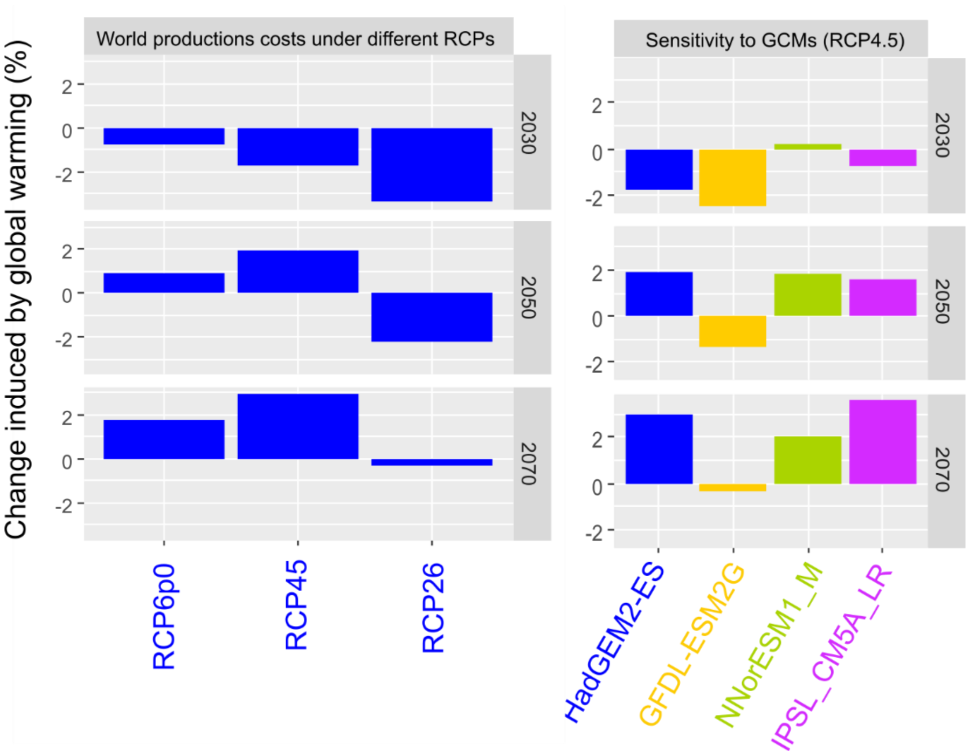

Figure 38. MAgPIE relative change in global costs of agricultural production under different RCPs and using different GCMs. Left: Simulations for different RCPs using the HadGEM2-ES model. RIght: Simulations with different GCMs using the forcing of RCP4p5.

Looking at the impacts of climate change on the EU, we see that the different sub-regions react differently. Comparing exemplarily the impacts of a RCP4.5 scenario calculated by HadGEM2-ES with a scenario with stable climate (Figure 39), we see that the value of agricultural products (calculated as production volume variation as described above for GLOBIOM) increases in the Northern, Eastern and Southern EU, while the Western EU is rather negatively affected. Net benefits for the EU remain positive and indicate a relative advantage of EU production under climate change compared to other world regions.

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Figure 39. MAgPIE relative change in agricultural production value under SSP2 and RCP4.5 scenario simulated by HadGEM2-ES relative to a SSP2 scenario with constant climate.

The MAgPIE 4 simulations reflect rather optimistic assumptions in respect to climate change adaptation. They for example assume that farmers change their production as soon as climatic conditions become more favourable for the new crop. Actually, rigidities in adaptation may be considerable and include sunk capital stocks in agriculture, lost experience of farmers under changing climatic conditions, and non-adaptive supply chains with regional specialisation. Moreover, the model chain does not account for extreme events, impacts of climate change on labour productivity, impacts on pests and diseases or impacts of climate on livestock production. Climate change impacts may therefore be considerably higher.

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5. Conclusion

Climate change has the potential to affect the agriculture, forestry and fisheries sector, both negatively (e.g. from lower rainfall, increasing variability, extreme heat) and positively (e.g. from CO_2 fertilization, extended seasons). These effects will arise from gradual climate change and extreme events that will directly affect production, but also from indirect effects, e.g. changes in prevalence of pests and diseases. These will affect productivity and, in turn, production, consumption, prices, trade and decisions on land-use.

This study analyses the impacts of slow-onset climate change on the agriculture, forestry and fisheries sector. To do so, this study developed new estimates, using a suite of models and assumptions to quantify the costs of climate change on the agriculture, forestry and fisheries sector. This uses a range of GCMs, three crop models (EPIC, GEPIC and LPJmL 5), and two bio-economic models (MAgPIE 4 and GLOBIOM) covering the agricultural, forestry and fisheries sector. The impact of additional factors that impact uncertainty, such as CO_2 fertilization, have been quantified.

5.1. Main findings

To be able to disentangle the differences introduced by climate models, RCPs, crop models, CO_2 fertilization, SSPs and economic models, this study analysed the full matrix of these elements on the agriculture, forestry and fisheries sector.

This study finds that the magnitude of climate induced yield impacts highly differs between crops. Climate impacts on winter wheat, oilseeds and sugar crops are of a much lower magnitude compared to impacts on corn. This is reflected throughout the entire modelling chain, where corn productivity losses induce large area reallocations from the South to the North of Europe and may comprise up to a third of the total agricultural losses in monetary value from crop production. Compensation effects within Europe dampen the negative effects found in the agricultural system, a sector which is typically defined by large socio-economic trends such as population and income growth, dietary trends or trade policies. Still, the relative change of climate impacts stayed relatively invariant across socio-economic storylines.

Furthermore, the change in relative competitiveness under climate change induces a reallocation of agricultural practices between European countries. Here the results of the agro-economic models differ. GLOBIOM estimates that cropland area especially reduces in the South of Europe, whereas it increases in the North, West and Central-Eastern countries. In contrast, MAgPIE estimates that cropland expands in the Southern EU and in Eastern EU, while it contracts in the Western and Northern EU. The model results comparison did not allow to identify robust regional land use patterns, but these differences are most likely to be attributed to the upstream crop model disagreements. For forestry, both models estimate that Northern parts of Europe benefit from climate change and increase their forestry areas. Climate-induced

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interactions between the agriculture and forestry sectors are however of limited magnitude.

Forestry is a sector with long production cycles, and thus high vulnerability to climate change. As with agriculture, forest growth may be enhanced by some processes but impacted by others, with the latter including changes in water availability, extremes (droughts, wind storms) and pests and diseases. Additional impacts can arise from changes in forest ecosystem health, and from increasing forest fires, affecting managed and natural forests.

Climate change affects the forest sector in two ways; first, through the impact on forest increments and harvest potentials, and second, through the enhanced risk of forest fires. The biophysical forest model G4M estimates that increased temperature and decreased precipitation cause a reduction in the biomass and growth rate of forests in Southern Europe, especially towards 2070 under RCP8.5. In the short-term, smaller gains on biomass growth can be expected mostly in Northern Europe.

For forestry, the Wildfire Climate Impacts and Adaptation Model (FLAM) is used to capture impacts of climate, population, and fuel availability on burned areas along with IIASA's global forestry model G4M. Forest fires damages in Europe currently amount to €1.5 billion (San-Miguel-Ayanz et al, 2010). The new analysis in COACCH estimates that the potential burned area in Europe will increase significantly in Europe especially under the RCP8.5 scenario, where burned areas could more than double compared to present-day, which could increase associated costs accordingly. The regions with the highest shares of burned areas are found in Portugal, Spain, South of France and Greece.

Fisheries will also be impacted by climate change, with changes in abiotic (sea temperature, acidification, etc.) and biotic conditions (primary production, food webs, etc), affecting reproductive success and growth, as well as the distribution of species. Similar risks exist for freshwater fisheries and aquaculture. While human fishing activities are the dominant factor for commercial fisheries, climate change will add additional pressure.

For capture fisheries, the analysis in COACCH indicates that under all scenarios, there is a decline in capture production globally, although there are strong regional differences. Fish stocks are highly mobile and can partly mitigate negative changes: this means that fisheries near the equator are affected more negatively and may migrate to Northern latitudes that may gain. In GLOBIOM, all EU Member States are projected to experience declines in marine productive capacity, with the most serious impacts occurring in Denmark, Spain, France, and the UK. Based on two Living Marine Resource models, GLOBIOM estimates that for the EU28, a reduction of 3 to 9 million tonnes in annual catches can be expected at the horizon 2050. It is noted that these estimates do not consider additional impacts from marine extremes and ocean acidification. MAgPIE simulations, based on only one of the two models used by GLOBIOM, come to different findings. Here, oceans in the arctic zones increase in productivity under climate change, while the tropical oceans, but also the Mediterranean suffers from declining productivity. Nevertheless, as the EU capture

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fisheries obtain their fish from several large marine ecosystems, the EU as a whole benefits from climate change and even has a relative advantage, as total global capture fishery potentials decline. A decline in total marine fish catches would probably have limited effects on the land system, as fish demand – and in particular marine capture fish – represents only a small share of total animal calories consumed worldwide. It must be noted that this does not consider the effects of aquaculture, however.

5.2. Limitations

Despite these important findings, our results also highlight some relatively large uncertainties and some caveats in the analysis.

The results show high uncertainties that accumulate over the impact chain. Climate models show considerable differences in temperature and precipitation patterns. The yield effect due to climate change are most positive under the GCM GFDL-ESM2M, and most negative under the GCM HadGEM2-ES. IPSL-CMA5-LR and NorESM1-M show a more moderate picture with positive yield impacts in Europe. Furthermore, the selected crop models show considerable differences in their reaction to RCP scenarios. The degree to which CO_2 fertilization will impact agricultural potentials plays a crucial role here. Biophysical models could be expanded by accounting for other climate induced effects such as pests and diseases. Also in the fisheries sector, there is considerable uncertainty in the estimates of catch potentials. The fisheries sector could in general benefit from a closer assessment of the climate effects on various species.

The bio-economic models GLOBIOM and MAgPIE reveal that large parts of the dynamics are not driven by absolute change in climatic conditions, but by relative changes compared to other competing production sites, world regions and cultivation options. For example, a region in which temperate cereal crops are affected positively by climate change may still cease production as other world regions become even more attractive, or as another crop type is favoured if its relative profitability increases. Regional climate impact estimates are therefore of very high uncertainty as their outcome is not affected by local climate change only, but in times of international agricultural trade by the relative competitiveness within the local region and the world market. GLOBIOM and MAgPIE are both run in a recursive-dynamic fashion, implying that they may underestimate the foresight of producers in their planning decisions, something that is especially relevant for the forest sector. Furthermore, both GLOBIOM and MAgPIE are partial-equilibrium models that do not consider the impacts of the agriculture, forestry and fisheries sector on other sectors.

Two important impacts are not considered in this study. First, this study does not yet consider the impacts of extreme events such as hail or storm, or the changing climatic conditions for pests and diseases. There is a growing evidence that both the frequency and intensity of weather extremes has increased due to climate change (IPCC 2013; Schleussner et al. 2016). About a decade ago, the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) anticipated that "projected

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changes in the frequency and severity of extreme climate events will have more serious consequences for food and forestry production, and food insecurity, than will changes in projected means of temperature and precipitation” (IPCC 2007). Recently, the World Economic Forum considered extreme weather events amongst the top risks facing the world (World Economic Forum 2018). Considering the increased variability and likelihood of extreme events caused by climate change is therefore of crucial importance to arrive with more comprehensive climate impact estimates for both the agriculture and forestry sector. This will be considered in work package 3 of COACCH.

Second, the degree to which producers can adapt to climate change needs to be further researched. This study found that the biophysical yield impacts indicate an upper limit to biophysical impacts as shifting cultivation patterns allow for adaptation. How rapid and at which costs farming systems can adapt to new climatic conditions, and for example change between crop types and cultivars is a topic that requires further attention and interdisciplinary research. Economic constraints such as sunk capital costs, but also cultural constraints or misinformed expectations may hinder adaptation and thereby increase the costs of climate change. This adaptation, and the degree to which policies can help producers to adapt against climate change, and towards which direction, will be further researched in work package 4 of COACCH.

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6. References

Adams, R. M., Rosenzweig, C., Peart, R. M., Ritchie, J. T., McCarl, B. A., Glyer, J. D., ... & Allen Jr, L. H. (1990). Global climate change and US agriculture. Nature, 345(6272), 219.

Allison, E. H., Perry, A. L., Badjeck, M. , Neil Adger, W. , Brown, K. , Conway, D. , Halls, A. S., Pilling, G. M., Reynolds, J. D., Andrew, N. L. and Dulvy, N. K. (2009), Vulnerability of national economies to the impacts of climate change on fisheries. *Fish and Fisheries*, 10: 173-196. doi:10.1111/j.1467-2979.2008.00310.x

Allison, Edward H., Allison L. Perry, Marie-Caroline Badjeck, W. Neil Adger, Katrina Brown, Declan Conway, Ashley S. Halls, et al. (2009). 'Vulnerability of National Economies to the Impacts of Climate Change on Fisheries'. *Fish and Fisheries* 10 (2): 173–96. https://doi.org/10.1111/j.1467-2979.2008.00310.x.

Asseng, S., Ewert, F., Rosenzweig, C., Jones, J. W., Hatfield, J. L., Ruane, A. C., ... & Brisson, N. (2013). Uncertainty in simulating wheat yields under climate change. Nature climate change, 3(9), 827.

Balkovic, J., R. Skalsky, et al. (2009). D2100 of the cc-tame project: Database and data strategy report. Technical report.: 24.

Barange, Manuel & Merino, Gorka & Blanchard, Julia & Scholtens, Joeri & Harle, James & Allison, Edward & Allen, Icarus & Holt, J. & Jennings, Simon. (2014). Impacts of climate change on marine ecosystem production in societies dependent on fisheries. Nature Climate Change. 4. 10.1038/nclimate2119.

Barange, M., Bahri, T., Beveridge, M.C.M., Cochrane, K.L., Funge-Smith, S. & Poulain, F., eds. (2018). Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. FAO Fisheries and Aquaculture Technical Paper No. 627. Rome, FAO. 628 pp.

Blanchard, J. L., Jennings, S., Holmes, R., Harle, J., Merino, G., Allen, J. I., ... & Barange, M. (2012). Potential consequences of climate change for primary production and fish production in large marine ecosystems. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *367*(1605), 2979-2989.

Bloh, W. von, S. Schaphoff, C. Müller, S. Rolinski, K. Waha, and S. Zaehle. (2017). 'Implementing the Nitrogen Cycle into the Dynamic Global Vegetation, Hydrology and Crop Growth Model LPJmL (Version 5)'. *Geosci. Model Dev. Discuss.* 2017 (October): 1–35. https://doi.org/10.5194/gmd-2017-228.

Calvin, K., Bond-Lamberty, B., Clarke, L., Edmonds, J., Eom, J., Hartin, C., Kim, S., Kyle, P., Link, R., Moss, R., McJeon, H., Patel, P., Smith, S., Waldhoff, S., Wise, M. (2017). The SSP4: A world of deepening inequality. *Global Environmental Change*. 42: 284-296.

César Terrer, C., Jackson, R., Prentice, I., Keenan, T., Kaiser, C., Vicca, S., Fisher, J., Reich, P., Stocker, B., Hungate, B., Peñuelas, J., McCallum, I., Soudzilovskaia, N., Cernusak, L., Talhelm,

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

A., Van Sundert, K., Piao, S., Newton, P., Hovenden, M., Blumenthal, D., Liu, Y., Müller, C., Winter, K., Field, C., Viechtbauer, W., Van Lissa, C., Hoosbeek, M., Watanabe, M., Koike, T., Leshyk, V., Polley, H., Franklin, O. (2019). Nitrogen and phosphorus constrain the CO_2 fertilization of global plant biomass. *Nature Climate Change*. (9):684–689

Challinor, A. J., Watson, J., Lobell, D. B., Howden, S. M., Smith, D. R., & Chhetri, N. (2014). A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change*, *4*(4), 287.

Chen, C. C., McCarl, B. A., & Schimmelpfennig, D. E. (2004). Yield variability as influenced by climate: A statistical investigation. *Climatic Change*, *66*(1-2), 239-261.

Cheung, William & Lam, Vicky & SARMIENTO, JORGE & Kearney, Kelly & Watson, Reg & Zeller, Dirk & PAULY, DANIEL. (2010). Large-scale Redistribution of Maximum Fisheries Catch Potential in the Global Ocean under Climate Change. *Global Change Biology.* 16. 24 - 35. 10.1111/j.1365-2486.2009.01995.x.

Cheung, William W. L., Gabriel Reygondeau, and Thomas L. Frölicher. 2016. 'Large Benefits to Marine Fisheries of Meeting the 1.5°C Global Warming Target'. *Science* 354 (6319): 1591–94. https://doi.org/10.1126/science.aag2331.

Ciscar, J.C., D. Ibarreta, A. Soria, A. Dosio, A.Toreti, A. Ceglar, D. Fumagalli, F. Dentener, R. Lecerf, A. Zucchini, L. Panarello, S. Niemeyer, I. Pérez-Domínguez, T. Fellmann, A. Kitous, J. Després, A. Christodoulou, H. Demirel, L. Alfieri, F. Dottori, M.I. Vousdoukas, L. Mentaschi, E. Voukouvalas, C. Cammalleri, P. Barbosa, F. Micale, J.V. Vogt, J.I. Barredo, G. Caudullo, A. Mauri, D. de Rigo, G. Libertà, T. Houston Durrant, T. Artés Vivancos, J. San-Miguel-Ayanz, S.N. Gosling, J. Zaherpour, A. De Roo, B. Bisselink, J. Bernhard, L., Bianchi, M. Rozsai, W. Szewczyk, I. Mongelli and L. Feyen (2018), Climate impacts in Europe: Final report of the JRC PESETA III project, EUR 29427 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-79-97218-8, doi:10.2760/93257, JRC112769. https://ec.europa.eu/jrc/en/peseta-iii

Claussen, M., Mysak, L., Weaver, A., Crucifix, M., Fichefet, T., Loutre, M. F., ... & Calov, R. (2002). Earth system models of intermediate complexity: closing the gap in the spectrum of climate system models. *Climate dynamics*, *18*(7), 579-586.

Costello, Christopher & Ovando, Daniel & Clavelle, Tyler & Strauss, C. & Hilborn, Ray & Melnychuk, Michael & Branch, Trevor & Gaines, Steven & Szuwalski, Cody & Cabral, Reniel & Rader, Douglas & Leland, Amanda. (2016). Global fishery prospects under contrasting management regimes. *Proceedings of the National Academy of Sciences.* 113. 201520420. 10.1073/pnas.1520420113.

Deryng, D., Elliott, J., Folberth, C., Müller, C., Pugh, T., Boote, K., Conway, D., Ruane, A., Gerten, D., Jones, J., Khabarov, N., Olin, S., Schaphoff, S., Schmid, E., Yang, H., Rosenzweig, C., Regional disparities in the beneficial effects of rising CO_2 concentrations on crop water productivity. *Nature Climate Change*. 6:786.

Dietrich, Jan Philipp, Benjamin Leon Bodirsky, Florian Humpenöder, Isabelle Weindl, Miodrag Stevanović, Kristine Karstens, Ulrich Kreidenweis, et al. 2019. 'MAgPIE 4 – a Modular Open-

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

Source Framework for Modeling Global Land Systems'. *Geoscientific Model Development* 12 (4): 1299–1317. https://doi.org/10.5194/gmd-12-1299-2019.

Dubrovský, M., Hayes, M., Duce, P., Trnka, M., Svoboda, M., & Zara, P. (2014). Multi-GCM projections of future drought and climate variability indicators for the Mediterranean region. *Regional Environmental Change*, *14*(5), 1907-1919.

FAO. 2016.The State of World Fisheries and Aquaculture 2016.Contributing to food security and nutrition for all. Rome. 200 pp.

FAO (2015), 'Global Forest Resources Assessment', Technical report, Food and Agriculture Organization of the United Nations.

Folberth, C., Gaiser, T., Abbaspour, K. C., Schulin, R., Yang, H. (2012) Regionalization of a Large-Scale Crop Growth Model for Sub-Saharan Africa: Model Setup, Evaluation, and Estimation of Maize Yields. *Agriculture, Ecosystems and Environment*, *151*, 21–33. https://doi.org/10.1016/j.agee.2012.01.026

Frank, S., E. Schmid, et al. (2015). "The dynamic soil organic carbon mitigation potential of European cropland." *Global Environmental Change* **35**: 269-278.

Frank, S., H. Böttcher, et al. (2016). "Dynamics of the land use, land use change, and forestry sink in the European Union: the impacts of energy and climate targets for 2030." *Climatic Change*: 1-14.

Frieler, K., Warszawski, L., & Zhao, F. (2017, April). Assessing the impacts of 1.5° C of global warming-The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) approach. In EGU General Assembly Conference Abstracts (Vol. 19, p. 19403).

Gerten, D. et al. (2004) 'Terrestrial vegetation and water balance. Hydrological evaluation of a dynamic global vegetation model.', *Journal of Hydrology*, 286, pp. 249–270.

Gorka Merino, Manuel Barange, Julia L. Blanchard, James Harle, Robert Holmes, Icarus Allen, Edward H. Allison, Marie Caroline Badjeck, Nicholas K. Dulvy, Jason Holt, Simon Jennings, Christian Mullon, Lynda D. Rodwell (2012) Can marine fisheries and aquaculture meet fish demand from a growing human population in a changing climate?, *Global Environmental Change*, Volume 22, Issue 4, Pages 795-806, ISSN 0959-3780, https://doi.org/10.1016/j.gloenvcha.2012.03.003.

Gusti, M. (2010). "An algorithm for simulation of forest management decisions in the global forest model." *Artificial Intelligence*, N4:45-49.

Hasegawa, T.; Fujimori, S.; Havlk, P.; Valin, H.; Bodirsky, B. L.; Doelman, J. C.; Fellmann, T.; Kyle, P.; Koopman, J. F. L.; Lotze-Campen, H.; Mason-D'Croz, D.; Ochi, Y.; Domnguez, I. P.; Stehfest, E.; Sulser, T. B.; Tabeau, A.; Takahashi, K.; Takakura, J.; van Meijl, H.; van Zeist, W.-J.; Wiebe, K. & Witzke, P. (2018), 'Risk of increased food insecurity under stringent global climate change mitigation policy', *Nature Climate Change* **8**(8), 699--703.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

Hatfield, J. L., Boote, K. J., Kimball, B. A., Ziska, L. H., Izaurralde, R. C., Ort, D., ... & Wolfe, D. (2011). Climate impacts on agriculture: implications for crop production. *Agronomy journal*, *103*(2), 351-370.

Havlík, P., H. Valin, et al. (2014). "Climate change mitigation through livestock system transitions." *Proceedings of the National Academy of Sciences of the United States of America* 111(10): 3709-3714.

Heinke, J., S. Ostberg, S. Schaphoff, K. Frieler, C. Müller, D. Gerten, M. Meinshausen, and W. Lucht. 2013. 'A New Climate Dataset for Systematic Assessments of Climate Change Impacts as a Function of Global Warming'. *Geoscientific Model Development* 6 (5): 1689–1703. https://doi.org/10.5194/gmd-6-1689-2013.

Herrero, M., P. Havlík, et al. (2013). "Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems." P*roceedings of the National Academy of Sciences* 110(52): 20888-20893.

Huntingford, C., Zelazowski, P., Galbraith, D., Mercado, L., Sitch, S., Fisher, R., Lomas, M., Walker, A., Jones, C., Booth, B., Malhi, Y., Hemming, D., Kay, G., Good, P., Lewis, S., Phillips, O., Atkin, O., Lloyd, J., Gloor, E., Zaragoza-Castell, J., Meir, P., Betts, R., Harris, P., Nobre, C., Marngo, J., Cox, P. (2013). Simulated resilience of tropical rainforests to CO_2-induced climate change. *Nature Geocscience.* (6):268-273.

Izaurralde, R. C.; Williams, J. R.; McGill, W. B.; Rosenberg, N. J. & Jakas, M. C. (2006), 'Simulating soil C dynamics with EPIC: Model description and testing against long-term data', *Ecological Modelling* **192**(3-4), 362--384.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B., Bouwer, L. M.et al. (2014). EURO-CORDEX: new high-resolution climate change projections for European impact research. *Regional environmental change*, 14(2), 563-578.

Josephson, A. L., Ricker-Gilbert, J., & Florax, R. J. (2014). How does population density influence agricultural intensification and productivity? Evidence from Ethiopia. *Food Policy*, *48*, 142-152.

Kindermann, G. E., I. McCallum, et al. (2008). "A global forest growing stock, biomass and carbon map based on FAO statistics." *Silva Fennica* 42(3): 387-396.

Lauri, P., P. Havlík, et al. (2014). "Woody biomass energy potential in 2050." *Energy Policy* 66(0): 19-31.

Leclère, D.; Havlík, P.; Fuss, S.; Schmid, E.; Mosnier, A.; Walsh, B.; Valin, H.; Herrero, M.; Khabarov, N. & Obersteiner, M. (2014), 'Climate change induced transformations of agricultural systems: insights from a global model', *Environmental Research Letters* **9**(12), 124018.

Liu, J., Williams, J. R., Zehnder, A. J. B. & Yang, H. (2007), 'GEPIC modelling wheat yield and crop water productivity with high resolution on a global scale', *Agricultural Systems* **94**(2), 478--493.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

Lobell, D. & Burke, M., ed. (2010), *Climate Change and Food Security: Adapting Agriculture to a Warmer Word*, Vol. 37, Springer, London New-York.

Moss, R. H.; Edmonds, J. A.; Hibbard, K. A.; Manning, M. R.; Rose, S. K.; Van Vuuren, D. P.; Carter, T. R.; Emori, S.; Kainuma, M.; Kram, T. & others (2010), 'The next generation of scenarios for climate change research and assessment', *Nature* **463**(7282), 747--756.

Nelson, G. C.; Valin, H.; Sands, R. D.; Havlík, P.; Ahammad, H.; Deryng, D.; Elliott, J.; Fujimori, S.; Hasegawa, T.; Heyhoe, E.; Kyle, P.; von Lampe, M.; Lotze-Campen, H.; Mason D'Croz, D.; van Meijl, H.; van der Mensbrugghe, D.; Müller, C.; Popp, A.; Robertson, R.; Robinson, S.; Schmid, E.; Schmitz, C.; Tabeau, A. & Willenbockel, D. (2014), 'Climate change effects on agriculture: Economic responses to biophysical shocks', *Proceedings of the National Academy of Sciences* **111**(9), 3274--3279.

O'Neill, B., E. Kriegler, K. Riahi, K. Ebi, S. Hallegatte, T. Carter, R. Mathur and D. Vuuren (2014). A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic Change* **122**(3): 387-400.

Pathak, H., & Wassmann, R. (2009). Quantitative evaluation of climatic variability and risks for wheat yield in India. *Climatic change*, 93(1-2), 157.

Pérez Domínguez, I.and Fellmann,T.(2018):PESETA III: Agro-economic analysis of climate change impacts in Europe, JRC Technical Reports, EUR29431EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-79-97220-1, doi:10.2760/179780.

Rajczak, J., & Schär, C. (2017). Projections of future precipitation extremes over Europe: A multimodel assessment of climate simulations. *Journal of Geophysical Research: Atmospheres*, *122*(20), 10-773.

Randall, D. A., Wood, R. A., Bony, S., Colman, R., Fichefet, T., Fyfe, J., ... & Stouffer, R. J. (2007). Climate models and their evaluation. In *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC (FAR)* (pp. 589-662). Cambridge University Press.

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A. C., Müller, C., Arneth, A., Boote, K. J., Folberth, C., Glotter, M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T. A. M., Schmid, E., Stehfest, E., Yang, H. & Jones, J. W. (2014), 'Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison', *Proceedings of the National Academy of Sciences* **111**(9), 3268-3273.

San-Miguel-Ayanz, J., Camia, A., 2010. Forest Fires, in Mapping the Impacts of Natural Hazards and Technological Accidents in Europe: An Overview of the Last Decade. EEA Technical Report N13/2010, pp. 47–53.

Schaphoff, Sibyll, Werner von Bloh, Anja Rammig, Kirsten Thonicke, Hester Biemans, Matthias Forkel, Dieter Gerten, et al. (2018). 'LPJmL4 – a Dynamic Global Vegetation Model with Managed Land – Part 1: Model Description'. *Geoscientific Model Development* 11 (4): 1343–75. https://doi.org/10.5194/gmd-11-1343-2018.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

Scoccimarro, E., Fogli, P. G., & Gualdi, S. (2017). The role of humidity in determining scenarios of perceived temperature extremes in Europe. Environmental Research Letters, 12(11), 114029.

Scoccimarro, E., Gualdi, S., Bellucci, A., Zampieri, M., & Navarra, A. (2016). Heavy precipitation events over the Euro-Mediterranean region in a warmer climate: results from CMIP5 models. *Regional environmental change*, *16*(3), 595-602.

Sherman K, Aquarone MC and Adams S (2007) Global applications of the Large Marine Ecosystem concept. *NOAA Technical Memorandum NMFS NE*, 208, 72 p.

Skalský, R., Z. Tarasovičová, et al. (2008). GEO-BENE global database for bio-physical modeling v. 1.0 - concepts, methodologies and data. The GEO-BENE database report., International Institute for Applied Systems Analysis (IIASA), Austria: 58.

Sunyer, M. A., Madsen, H., & Ang, P. H. (2012). A comparison of different regional climate models and statistical downscaling methods for extreme rainfall estimation under climate change. *Atmospheric Research*, *103*, 119-128.

Vautard, R., Gobiet, A., Sobolowski, S., Kjellström, E., Stegehuis, A., Watkiss, P., ... & Jacob, D. (2014). The European climate under a 2 C global warming. Environmental Research Letters, 9(3), 034006.

Vuuren, D. P.; Edmonds, J.; Kainuma, M.; Riahi, K.; Thomson, A.; Hibbard, K.; Hurtt, G. C.; Kram, T.; Krey, V.; Lamarque, J.-F.; Masui, T.; Meinshausen, M.; Nakicenovic, N.; Smith, S. & Rose, S. K. (2011), 'The representative concentration pathways: an overview', *Climatic Change* **109**, 5-31.

Williams, J. R. (1995). The EPIC Model. Computer Models of Watershed Hydrology. V. P. Singh, *Water Resources Publications*, Highlands Ranch, Colorado: 909-1000.

Wolf, J., Kanellopoulos, A., Kros, J., Webber, H., Zhao, G., Britz, W., ... & de Vries, W. (2015). Combined analysis of climate, technological and price changes on future arable farming systems in Europe. *Agricultural Systems*, *140*, 56-73.

World Bank. (2017). The Sunken Billions Revisited : Progress and Challenges in Global Marine Fisheries. Environment and Development;. Washington, DC: World Bank. © World Bank. https://openknowledge.worldbank.org/handle/10986/24056 License: CC BY 3.0 IGO.

Worm, B., & Lotze, H. K. (2016). Marine biodiversity and climate change. *Climate Change*, 195-212.

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

Annex I: List of COACCH scenarios run in bio-economic models GLOBIOM and MAgPIE

#	Scenario Name	SSP	GCM	RCP	Miti-gation
1	SSP2_NoCC_NoCC_NoMit	SSP2	NoCC	NoCC	NoMit
2	SSP2_HadGEM2-ES_2p6_NoMit	SSP2	HadGEM2-ES	2p6	NoMit
3	SSP2_HadGEM2-ES_4p5_NoMit	SSP2	HadGEM2-ES	4p5	NoMit
4	SSP2_HadGEM2-ES_6p0_NoMit	SSP2	HadGEM2-ES	6p0	NoMit
5	SSP2_IPSL-CM5A-LR_2p6_NoMit	SSP2	IPSL-CM5A-LR	2p6	NoMit
6	SSP2_IPSL-CM5A-LR_4p5_NoMit	SSP2	IPSL-CM5A-LR	4p5	NoMit
7	SSP2_IPSL-CM5A-LR_6p0_NoMit	SSP2	IPSL-CM5A-LR	6p0	NoMit
8	SSP2_NorESM1-M_2p6_NoMit	SSP2	NorESM1-M	2p6	NoMit
9	SSP2_NorESM1-M_4p5_NoMit	SSP2	NorESM1-M	4p5	NoMit
10	SSP2_NorESM1-M_6p0_NoMit	SSP2	NorESM1-M	6p0	NoMit
11	SSP2_GFDL-ESM2M_2p6_NoMit	SSP2	GFDL-ESM2M	2p6	NoMit
12	SSP2_GFDL-ESM2M_4p5_NoMit	SSP2	GFDL-ESM2M	4p5	NoMit
13	SSP2_GFDL-ESM2M_6p0_NoMit	SSP2	GFDL-ESM2M	6p0	NoMit
14	SSP1_NoCC_NoCC_NoMit	SSP1	NoCC	NoCC	NoMit
15	SSP1_HadGEM2-ES_2p6_NoMit	SSP1	HadGEM2-ES	2p6	NoMit
16	SSP1_HadGEM2-ES_4p5_NoMit	SSP1	HadGEM2-ES	4p5	NoMit
17	SSP1_HadGEM2-ES_6p0_NoMit	SSP1	HadGEM2-ES	6p0	NoMit
18	SSP3_NoCC_NoCC_NoMit	SSP3	NoCC	NoCC	NoMit
19	SSP3_HadGEM2-ES_4p5_NoMit	SSP3	HadGEM2-ES	4p5	NoMit
20	SSP3_HadGEM2-ES_6p0_NoMit	SSP3	HadGEM2-ES	6p0	NoMit
21	SSP4_NoCC_NoCC_NoMit	SSP4	NoCC	NoCC	NoMit
22	SSP4_HadGEM2-ES_2p6_NoMit	SSP4	HadGEM2-ES	2p6	NoMit
23	SSP4_HadGEM2-ES_4p5_NoMit	SSP4	HadGEM2-ES	4p5	NoMit
24	SSP4_HadGEM2-ES_6p0_NoMit	SSP4	HadGEM2-ES	6p0	NoMit
25	SSP5_NoCC_NoCC_NoMit	SSP5	NoCC	NoCC	NoMit
26	SSP5_HadGEM2-ES_2p6_NoMit	SSP5	HadGEM2-ES	2p6	NoMit
27	SSP5_HadGEM2-ES_4p5_NoMit	SSP5	HadGEM2-ES	4p5	NoMit
28	SSP5_HadGEM2-ES_6p0_NoMit	SSP5	HadGEM2-ES	6p0	NoMit
29	SSP5_HadGEM2-ES_8p5_NoMit	SSP5	HadGEM2-ES	8p5	NoMit
30	SSP5_HadGEM2-ES_8p5_NoMit	SSP5	HadGEM2-ES	8p5	NoMit
31	SSP2_HadGEM2-ES_2p6_4p5	SSP2	HadGEM2-ES	2p6	4p5
32	SSP2_HadGEM2-ES_4p5_4p5	SSP2	HadGEM2-ES	4p5	4p5
33	SSP2_HadGEM2-ES_6p0_4p5	SSP2	HadGEM2-ES	6p0	4p5
34	SSP2_IPSL-CM5A-LR_2p6_4p5	SSP2	IPSL-CM5A-LR	2p6	4p5
35	SSP2_IPSL-CM5A-LR_4p5_4p5	SSP2	IPSL-CM5A-LR	4p5	4p5
36	SSP2_IPSL-CM5A-LR_6p0_4p5	SSP2	IPSL-CM5A-LR	6p0	4p5

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37	SSP2_NorESM1-M_2p6_4p5	SSP2	NorESM1-M	2p6	4p5
38	SSP2_NorESM1-M_4p5_4p5	SSP2	NorESM1-M	4p5	4p5
39	SSP2_NorESM1-M_6p0_4p5	SSP2	NorESM1-M	6p0	4p5
40	SSP2_GFDL-ESM2M_2p6_4p5	SSP2	GFDL-ESM2M	2p6	4p5
41	SSP2_GFDL-ESM2M_4p5_4p5	SSP2	GFDL-ESM2M	4p5	4p5
42	SSP2_GFDL-ESM2M_6p0_4p5	SSP2	GFDL-ESM2M	6p0	4p5
43	SSP2_HadGEM2-ES_2p6_2p6	SSP2	HadGEM2-ES	2p6	2p6
44	SSP2_HadGEM2-ES_4p5_2p6	SSP2	HadGEM2-ES	4p5	2p6
45	SSP2_HadGEM2-ES_6p0_2p6	SSP2	HadGEM2-ES	6p0	2p6
46	SSP2_IPSL-CM5A-LR_2p6_2p6	SSP2	IPSL-CM5A-LR	2p6	2p6
47	SSP2_IPSL-CM5A-LR_4p5_2p6	SSP2	IPSL-CM5A-LR	4p5	2p6
48	SSP2_IPSL-CM5A-LR_6p0_2p6	SSP2	IPSL-CM5A-LR	6p0	2p6
49	SSP2_NorESM1-M_2p6_2p6	SSP2	NorESM1-M	2p6	2p6
50	SSP2_NorESM1-M_4p5_2p6	SSP2	NorESM1-M	4p5	2p6
51	SSP2_NorESM1-M_6p0_2p6	SSP2	NorESM1-M	6p0	2p6
52	SSP2_GFDL-ESM2M_2p6_2p6	SSP2	GFDL-ESM2M	2p6	2p6
53	SSP2_GFDL-ESM2M_4p5_2p6	SSP2	GFDL-ESM2M	4p5	2p6
54	SSP2_GFDL-ESM2M_6p0_2p6	SSP2	GFDL-ESM2M	6p0	2p6
55	SSP2_SMHI-RCA4_HadGEM2-ES_4p5_NoMit	SSP2	SMHI-RCA4_HadGEM2-ES	4p5	NoMit
56	SSP2_IPSL_WRF33_CM5A_4p5_NoMit	SSP2	IPSL_WRF33_CM5A	4p5	NoMit
57	SSP2_CSC_REMO2009_MPI-ESM-LR_2p6_NoMit	SSP2	CSC_REMO2009_MPI-ESM-LR	2p6	NoMit
58	SSP2_CSC_REMO2009_MPI-ESM-LR_4p5_NoMit	SSP2	CSC_REMO2009_MPI-ESM-LR	4p5	NoMit
59	SSP2_SMHI_RCA4_EC-EARTH_2p6_NoMit	SSP2	SMHI_RCA4_EC-EARTH	2p6	NoMit
60	SSP2_SMHI_RCA4_EC-EARTH_4p5_NoMit	SSP2	SMHI_RCA4_EC-EARTH	4p5	NoMit
61	SSP2_KNMI_RACMO22E_EC-EARTH_4p5_NoMit	SSP2	KNMI_RACMO22E_EC-EARTH	4p5	NoMit

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