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COACCH

CO-designing the Assessment of Climate CHange costs

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D2.5 Non-market impacts: ecosystems and biodiversity

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Disclaimer

Dissemination Level		
P	Public	X
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Deliverable Summary

Climate change impact assessment are often focusing on market values to derive economic losses. However, a number of non-market ecosystems services can also be impacted by climate change, and require an analysis going beyond market metrics and encompass a broader set of indicators. In this deliverable, several models – GLOBIO, GLOBIOM and MAgPIE – are used to assess the direct and indirect impacts of climate change on biodiversity, land cover change, fertilizer use and greenhouse gas emissions.

Results of GLOBIO, focusing on direct impacts of climate change on plants and vertebrates biodiversity, suggest annual losses for Europe from 15 billion EUR (RCP 2.6 in 2050) to 60 billion EUR (RCP 6.0 in 2100) when a price is given to biodiversity. This cost estimate is a low bound estimate as not all the biodiversity extend could be monetized.

GLOBIOM and MAgPIE identified indirect effects of climate change on biodiversity through the analysis of the effects on land cover, fertilizer use, and greenhouse gas emissions from changes in agricultural and forestry production. Whilst both models report that the results are sensitive to the climate-socio-economic scenario combination analysed, the models agree that land cover changes are more induced due to changes in climatic conditions relative to other regional cultivation areas than to other climatic zones in the world market. For example, GLOBIOM shows that cropland is projected todecrease in parts of Southern Europe but expand in Northern Europe. For both models, this reallocation effect is reflected in matching shifts of fertiliser use that in turn can be expected to affect biodiversity as nitrogen leaches into the local environment. As deforestation is rather limited in Europe, the largest changes in GHG emissions stems from these changes to nitrogen application.

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Table of abbrevations

Abbreviation	*Meaning*
AFOLU	Agriculture, Forestry and Other Land Use
BES-SIM	Biodiversity and Environmental Services – Simulation, modelling and harmonization protocol
GHG	Greenhouse gases
GLOBIO	Global biodiversity model, used by PBL Netherlands Environmental Assessment Agency
GLOBIOM	Global Biosphere Management Model, used by IIASA
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
LPJmL	Lund-Potsdam-Jena managed Land, global vegetation model based mostly at PIK.
MAgPIE	Model of Agricultural Production and its Impact on the Environment, used by PIK.
MSA	Mean Species Abundance – measure of intactness of an ecosystem relative to a natural, undisturbed, state
RCP	Representative Concentration Pathway, set of scenarios used for climate assessment defined by the degree of climate change in 2100.
SSP	Shared Socio-economic Pathway, set of scenarios used for climate assessment, defined by socio-economic circumstances.

1. Introduction

World-wide biodiversity has declined significantly during the last 100 years, driven mostly by an increase in agriculture area at the expense of natural habitats (Sala, van Vuuren, and Zaitsev 2005; IPBES, 2019). In the future it is expected that climate change couldbecome an equally important threat to biodiversity (Sala et al. 2000; van Vuuren, Sala, and Pereira 2006; IPBES, 2019). The impact of climate change could in particular be important for sensitive systems (e.g. mountain systems), in the case of rapid climate change and in thecase of large-scale disruption of existing climate systems (e.g. drying of Amazon regions). In these cases, it might be difficult for ecosystems to adapt to the new climate.

It should be noted that impacts of climate change may not always be direct. First of all, climate change may lead to lower agricultural yields. This may lead to a situation in which more land is needed to feed the global population. But also some climate policy responses could impact biodiversity. For instance, the use of bioenergy could lead to large claims on land leading by itself to negative impacts on biodiversity. The overall impact in that case would depend on the combined impact of bioenergy on limiting climate change and increased land use. Similarly, also other climate mitigation measures requiring land such as afforestation/reforestation strategies and strategies to prevent deforestation could impact biodiversity, in fact both as conservation measureand as threat depending on the exact implementation.

Biodiversity is multi-dimensional in nature and can be defined as the diversity within species, the diversity between species and the diversity of ecosystems. In this study, the focus is on terrestrial biodiversity. Integrated biodiversity models such as GLOBIO can help to explore the biodiversity impacts of integrated climate change scenarios. Here, we present an assessment of climate change impacts for the COACCH project. This is done in 2 ways, first we show the underlying relationships in the GLOBIO model based on available information inthe literature. This relationship presents the pure relation between climate change and biodiversity loss and is defined through the Mean Species Abundance (MSA), giving a measure of intactness of an ecosystem relative to a natural, undisturbed, state.. Second, we show the integrated evaluation of a number of scenarios. These results capture both climate change and land impacts.

In addition, the Global Biosphere Management Model (GLOBIOM) and the Model of Agricultural Production and its Impact on the Environment (MAgPIE) are used toanalyze the competition for land use between agriculture, forestry, and bioenergy, whichare the main land-based production sectors. Indicators of climate change studied in the two models are land cover, fertilizer use and greenhouse gas emissions. These indicators are used to study biodiversity loss, defined as the deviation from the undisturbed pristine situation.

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2. Methodology

2.1. Biodiversity modelling

2.1.1 The GLOBIO model

GLOBIO is a scenario-based gridded global model for biodiversity (Alkemade et al. 2009). The model is used to assess the impact of various drivers and pressures on local biodiversity, including plants and vertebrates. In GLOBIO, the main variable quantifying biodiversity in an ecosystem is the Mean Species Abundance (MSA), which expresses the mean abundance of original species in disturbed conditions relative to their abundance in undisturbed habitat, as an indicator of the degree to which an ecosystem is intact (Alkemade et al. 2009). The MSA index ranges from 0 to 1, where 1 represents a system where the biodiversity is fully intact and 0 means that the original ecosystem is fully destroyed.

In GLOBIO, several pressures, or drivers, reduce the MSA: climate change, land use, roads and fragmentation, atmospheric nitrogen deposition and hunting.

For each of these pressures, a relationship is created from databases designed specifically for this purpose, relating MSA to key variables like global mean temperature, type of land use in a grid cell, proximity to a road etc. GLOBIO combines the pressure–impact relationships with data on past, present or future pressure levels, typically retrieved from the IMAGE model. This results in maps with MSA values corresponding with each pressure. These maps are then combined to obtain overall MSA values, as illustrated in the figure. Next, MSA values are aggregated to larger (user-defined) regions. In addition, the contributions of the different pressures to the losses in MSA are quantified for each region.

GLOBIO also includes a routine to downscale coarse-grained land-use data to more fine-grained maps (currently with a resolution of 10 arc-seconds; ~300 m at the equator). This routine was developed because current global land-use models have a relatively low spatial resolution hence tend to underestimate the spatial heterogeneity of land-use patterns. The downscaling routine requires regional totals or demands (‘claims’) of each land-use type and allocates these to the grid cells within the region in order of decreasing suitability for that land-use type. Based on this, GLOBIO creates estimates of biodiversity loss on a 300m grid resolution. A detailed explanation of the most recent GLOBIO model is available in (Schipper AM 2019).

2.1.2. Scenario choice for biodiversity impact assessment

To assess the impact of both socio-economic and climate related variables, various combinations of Shared Socioeconomic Pathways (SSP) and Representative Concentration Pathways (RCP) scenarios can be used. The socio-economic projections in the model are derived from the SSP scenarios (Riahi et al. 2017), while the RCP scenarios (van Vuuren et al. 2011) are used for climate related variables. An overview of the key properties of each SSP is summarized in Table 1.

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Table 1: Characteristics of socio-economic scenarios

	SSP1	SSP2	SSP3	SSP4	SSP5
Storyline	Sustainability: Taking the Green Road	Middle of the Road	Regional Rivalry: A Rocky Road	Inequality: A Road Divided	Fossil-fuelled Development: Taking the Highway
Population from 2050 to 2100	Decline to 7B people	Stabilisation around 9B people	High growth towards 13B people	Stabilisation around 9B people	Decline to 7B people
GDP	Medium-high	Medium-high	Low	Medium-low	High
Land-use	Effective	Limited efforts	No possibility	Limited efforts	Effective

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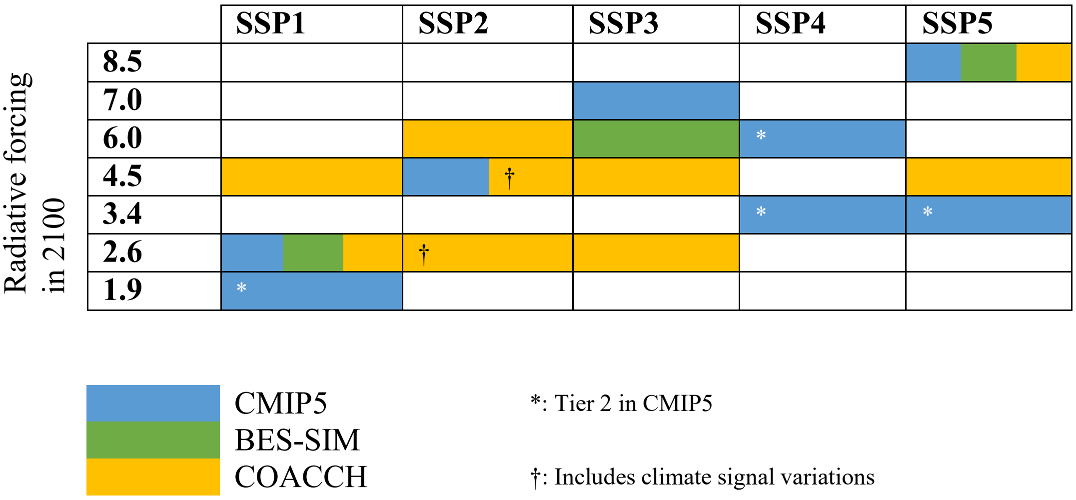
	international cooperation	to curb land-use emissions	to encourage countries to avoid deforestation	to curb land-use emissions	international cooperation

The scenarios for which GLOBIO was used in this deliverable were originally created for the global assessment of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). As part of the IPBES collaboration a modelling and harmonization protocol was developed: BES-SIM. Three SSP/RCP combinations were chosen in BES-SIM to cover the widest range in climate and socio- economic scenarios possible: SSP1-RCP2.6 for a sustainability-oriented scenario with climate mitigation policy, SSP3-RCP6.0 for a regional rivalry baseline scenario and SSP5-RCP8.5 for a fossil-fueled development baseline scenario.

These three scenarios correspond to the three Tier 1 SSP/RCP combinations selected in CMIP5, the climate model inter-comparison project (with some variation on whether the baseline SSP3 run reaches a radiative forcing of 6.0 or 7.0 W/m^2). The COACCH project considers a different set of scenarios, with overlapping SSP1-RCP2.6 and SSP5-RCP8.5 scenarios, as shown in Table 2.

Table 2: Selection of socio-economic scenarios



Radiative forcing in 2100	SSP1	SSP2	SSP3	SSP4	SSP5
8.5					🟦🟩🟨
7.0			🟦		
6.0		🟨	🟩	🟦 *	
4.5	🟨	🟦🟨 †	🟨		🟨
3.4				🟦 *	🟦 *
2.6	🟦🟩🟨	🟨 †	🟨		
1.9	🟦 *				

🟦 CMIP5
🟩 BES-SIM
🟨 COACCH

*: Tier 2 in CMIP5

†: Includes climate signal variations

We selected work done for the BES-SIM scenario analysis to connect IPBES, which has been an authoritative study on biodiversity impacts. For COACCH, the available results were re-interpreted in order to single out climate change as a driver of biodiversity loss. These results can subsequently be used to estimate economic impacts in the COACCH project.

2.2. Agriculture, forestry and land use modelling

2.2.1. The GLOBIOM model

GLOBIOM's analytical process captures the multiple interrelationships between the different systems involved in provision of agricultural and forestry products, for example, population dynamics, ecosystems, technology, and climate.

GLOBIOM is a global, recursively dynamic, and partial equilibrium model (Havlík et al. 2014). It integrates the agricultural, bioenergy, and forestry sectors and draws on comprehensive socioeconomic and geospatial data. It accounts for the 18 most globally important crops, a range of livestock production activities, forestry commodities, first- and second-generation bioenergy, and water. Production is spatially explicit and considers land, management, and weather characteristics.

The market equilibrium is solved by maximizing the sum of producer and consumer surplus subject to resource, technological, and political constraints. Using the year 2000 as the baseline, GLOBIOM simulates demand and supply quantities, bilateral trade flows, and prices for commodities and natural resources at 10-year-step intervals up to 2050. This gives planners a basis for setting future land use and, more importantly, for identifying possible shortfalls in food and biomass supplies.

For the European Union, GLOBIOM has been enhanced to make use of available European datasets (Frank et al. 2015, Frank et al. 2016). A more detailed grid structure 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.

All GLOBIOM scenarios used in this deliverable are a new product of COACCH and are novel in three aspects: First, the currently best-available climate data for Europe (Euro-Cordex) has been used to assess the impacts of climate change on the agricultural sector using a suit of biophysical models. Second, these climate impacts on productivityare integrated into the above-mentioned enhanced version of GLOBIOM that is specifically tailored to Europe. Third, the scenarios are set-up in a way that allows for the separate and integrated impact analysis of the agriculture, forestry and fisheries sector (rather than e.g. only the agricultural sector). The results portrayed in D2.5 build upon the modelling exercise conducted in D2.2 of COACCH. For a more detailed description of GLOBIOM's scenario set-up, we refer the reviewer to D2.2 (Boere et al., 2019).

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2.2.1. The MAgPIE model

MAgPIE 4 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 allocates land use to fulfil competing demands for commodities, feed, carbon storage, land conservation and environmental protection. Land use is broadlycategorized in cropland, forest plantation, forest land, pasture land, and other natural land. MAgPIE takes spatially explicit data on potential crop yields, land and water constraints from LPJmL 5 (von Bloh et al 2018) and combines it with information on technological development and production costs. It includes agricultural trade withdifferent levels of regional self-sufficiency constraints. MAgPIE calculates the following Agriculture Forestry and Other Land Use (AFOLU) Greenhouse gas (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.

In the latest submission of April 2020 the MAgPIE results have been integrated. The MAgPIE analysis follows a similar fashion as the GLOBIOM analysis to allow for inter-model comparison. This new version of the deliverable therefore also includes a discussion section on how the results of the two models compare.

To be able to disentangle the differences introduced by global climate research projects, climate models, RCPs, crop models, crop model assumptions such as CO2 fertilization, SSPs, mitigation efforts and economic models, GLOBIOM and MAgPIE analyse the full matrix of these elements. This matrix of scenarios can be found in Annex I of Deliverable 2.2 of COACCH (Boere et al., 2019).

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3. Results

3.1 Biodiversity impacts from climate change - GLOBIO

GLOBIO uses a variety of MSA-impact relations, each corresponding to a biodiversity pressure/driver. For COACCH, the most relevant driver is climate change. GLOBIO uses a pressure-impact relationship relating MSA to global mean temperature. Direct observations of changes in species richness due to climate change are difficult to obtain, especially for more extreme temperature changes. For this reason, GLOBIO uses data from studies on specialised bioclimatic envelope models. Such models estimate the climatic variables in which a species can thrive or survive. Then, as the climaticvariables change, the spatial distribution and occurrence of the species is changedaccordingly.

In GLOBIO, only climate change effects on global mean temperature increases are considered, ignoring possible impacts from changes in precipitation patterns or regional climate change impact differences. From the different envelope model results, a beta regression analysis is performed to obtain MSA-pressure curves, as shown in Figure 1.

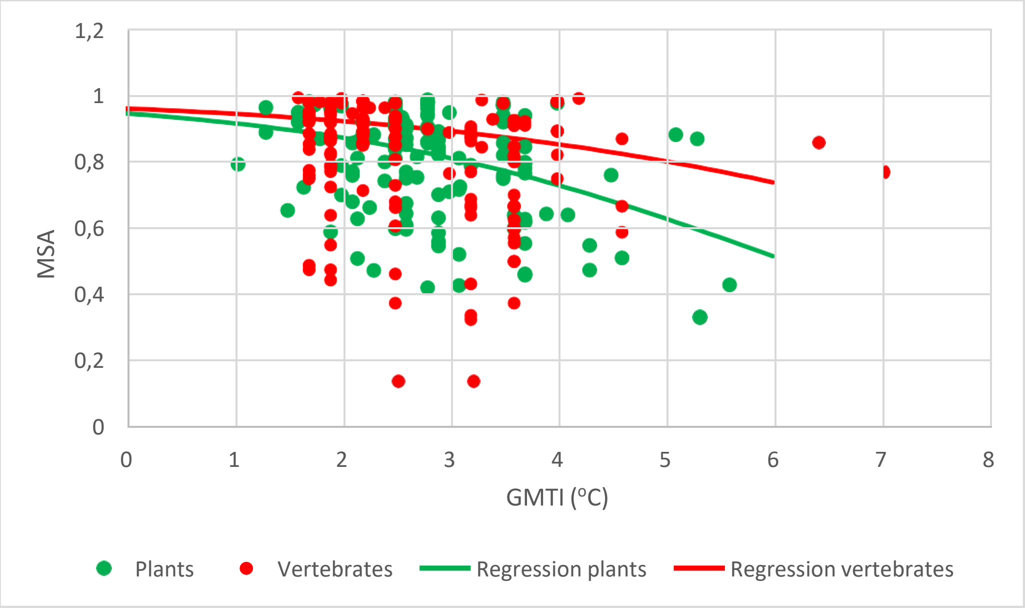

Figure 1 - MSA-pressure curve resulting from envelope model studies for both plants and vertebrates

The results show a resulting negative impact of climate change on biodiversity, although with considerable uncertainty. The results also suggests that plants are more sensitive to climate change than vertebrates, although differences need to be interpreted in the context of the wide uncertainty range shown by the individual observations. However, the suggested difference between plants and vertebrates could be consist with a lower ability to adapt. Clearly, the relationships are beset with uncertainty – with some studies suggesting even strong impacts at 2-3 degrees warming. The “median” regression line suggests 25- 30% decline in plant biodiversity for 4 degrees warming and a 10-20% decline in vertebrate biodiversity.

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3.2 Integrated scenarios - GLOBIO

For the assessment supporting COACCH, we focus on the three available BES-SIM scenarios: SSP1-RCP2.6, SSP3-RCP6.0 and SSP5-RCP8.5. The global MSA is calculated for 2015 as a reference, and then compared to the global MSA in 2050 for each of the three scenarios, as shown in Figure 2. The SSP1-RCP2.6 scenario shows little change in MSA compared to 2015, especiallywhen only plants are considered. The regional rivalry and fossil-fuelled development scenarios show a much stronger impact on biodiversity for plants. Interestingly, the effect on vertebrates is more constant throughout the three future scenarios. The SSP3- RCP6.0 shows a stronger effect on vertebrates MSA than the SSP5-RCP8.5 scenario, even though the former uses a smaller climate change scenario (RCP6.0 vs RCP8.5). It should be noted that the difference in global mean temperature between RCP6.0 and RCP8.5 is still relatively small in 2050, and increases further towards the end of the century. So distilling the impact of global mean temperature increase for COACCH, the MSA difference as function of global mean temperature increase is shown in Figure 3.

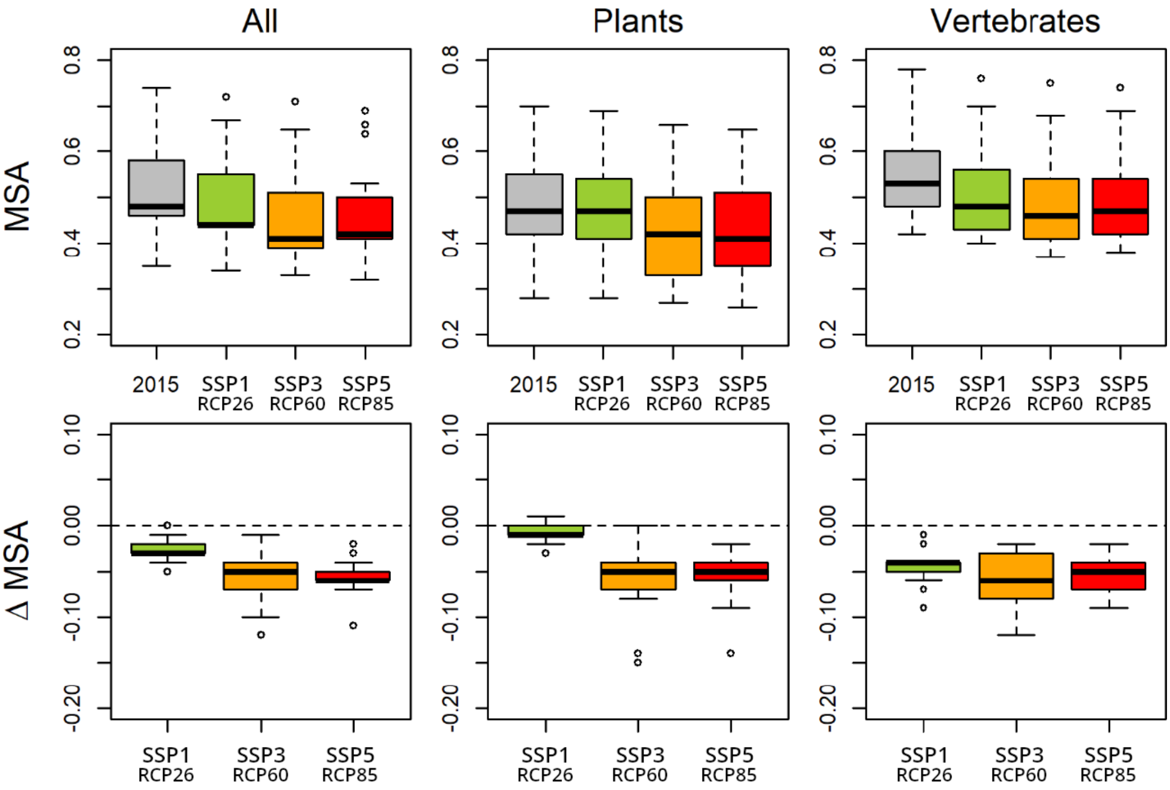

Figure 2 - Global Mean Species Abundance in 2015 compared to the three BES-SIM scenarios: S (Sustainability, SSP1-RCP2.6), RR (Regional rivalry, SSP3-RCP6.0) and FD (Fossil-fuelled development, SSP5-RCP8.5). Bottom row: difference in global MSA compared to 2015 (Schipper AM 2019).

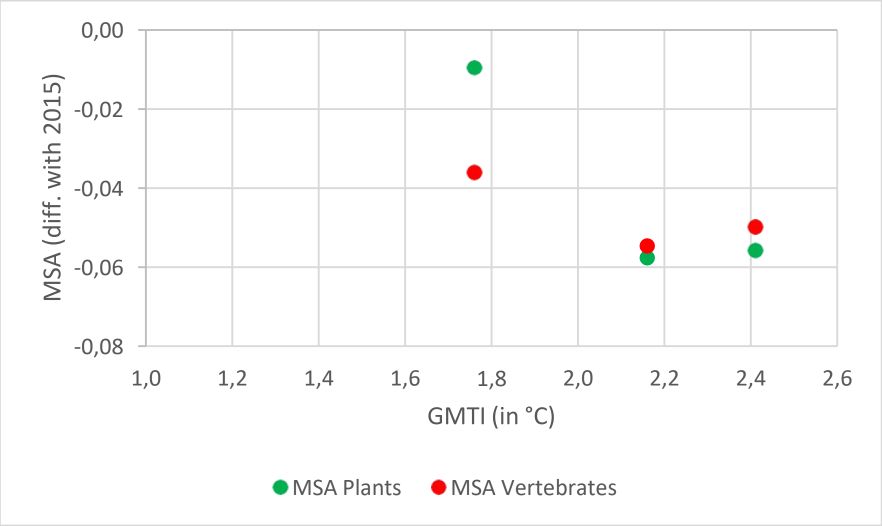

Figure 3 - MSA loss in 2050 for the three different scenarios, as function of Global Mean Temperature increase in 2050.

The results shown in Figure 3 and derived from the previous model runs for COACCH capture both the climate and land use impacts of the scenarios (as function of climate change). It is possible to extract the impact of climate alone as indicated in Table 3, assuming other drivers to be constant. In other words, table 3 summarizes the results for the MSA indicator (globally) singling out the climate change impacts only. Given the definition of MSA (1 indicates pristine condition, 0 indicates a fully destroyed ecosystem), the loss of MSA as calculated on the basis of the average decline worldwide can also be expressed in terms of an equivalent amount ofloss of pristine nature area (see Schippers et al., 2019). This is done in the subsequent column.

Table 3: Summary of global biodiversity loss (both plants and vertebrates) based on MSA calculations for climate change only

Time Period	Scenario	Temp. Change	MSA	Eq. Loss
		Deg C	-	Gha
2015		0.99	0.480	
2050	SSP2_2.6	1.77	0.467	-0.17
	SSP2_3.4	1.92	0.464	-0.21
	SSP2_4.5	2.04	0.462	-0.24
	SSP2_6.0	2.10	0.460	-0.25
2100	SSP2_2.6	1.76	0.467	-0.16
	SSP2_3.4	2.17	0.459	-0.27
	SSP2_4.5	2.70	0.446	-0.44
	SSP2_6.0	3.32	0.429	-0.66

In a subsequent step, we have expressed the hectarage losses in monetary terms. We make monetary estimates of the loss by following the methods first developed by Costanza et al (1997), and subsequently in de Groot (2012) and Costanza et al (2014), applying them in the European context. The monetary values were derived by synthesising unit values available in the academic literature. In the first instance, the database compiled by de

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Groot et al (2012) and applied in Costanza et al. (2014) was utilised by identifying all studies listed as being undertaken in a European country. These studies were disaggregated according to the biome and ecosystem service(s) for which they derived Willingness To Pay (WTP) values. We then reviewed the literature published subsequent to 2012 in which WTP values were derived for European biomes. The identified values were added to those previously extracted from the de Groot database and updated mean representative values were estimated. In the case of three biome types – Fresh water, Crop and Urban –ecosystem service values are not available for the EU and so totals have been estimated from the global total values given in Costanza et al. (2014) on a value transfer basis.The resulting representative values – disaggregated by ecosystem service - are presentedin Table 4.

Table 4. Unit values (Euro/hectare/annum) for Ecosystem Services in European Biomes

	Inland Wetlands	Fresh water (rivers/lakes)	Temperate forest	Woodlands	Grasslands	Crop	Urban
Provisioning services	970	-	1044	336	31	-	-
Regulating services	3436	-	-	449	238	-	-
Habitat services	7040	-	-	-	2428	-	-
Cultural services	6996	-	562	86	198	-	-
Total	**18,442**	**8028**	**1,606**	**851**	**2,895**	**3572**	**4274**

The representative value for each biome was then multiplied by the appropriate biome hectarage in Europe. Biome areas within Europe were taken from EEA (2015). The global climate change-induced changes in biome hectare-equivalents given in Table 3 were then scaled to the European land area to give the results presented in Table 5. It was assumed that the global percentage changes apply at the European scale. The resultsshow annual damage costs in 2050 to range between about Euro 15 billion and Euro 22 billion under SSP2-RCP2.6 and SSP2-RCP6.0 scenario combinations, respectively, whilst for 2100 the range of annual damage costs are Euro 14 billion to Euro 58 billion.

Table 5. Climate Change-induced damage costs in Europe

Time Period	Scenario	Euro (bn, 2018 prices, annual)
2050	SSP2_2.6	14.862
	SSP2_3.4	18.359
	SSP2_4.5	20.982
	SSP2_6.0	21.856
2100	SSP2_2.6	13.988
	SSP2_3.4	23.605
	SSP2_4.5	38.467
	SSP2_6.0	57.700

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Discussion

We have expressed the possible impact of climate change induced damage in Europe on the basis of the GLOBIO results and the monetarisation method introduced by Constanza et al and de Groot et al. Clearly, it should be noted that there is considerable uncertainty in these numbers.

- The GLOBIO relationship uses a direct relationship between temperature change and global impacts on biodiversity based on more detailed models. The reason to use model input is that sufficient emperical studies are lacking. Moreover, even for the model outcomes there is considerable spread as shown in Figure 1
- More detailed approaches could look into local circumstances. This would, instance, allow to assess the interplay between different presures on biodiversity such as fragmentation and biodiversity (reducing the ability for species to adapt).
- As part of the assessment, we also did not look into the uncertainties resulting from different climate system representation (e.g. depending of the model different SSP/RCP combination can lead to different levels of warming).
- For the translation to monetary numbers single representative numbers per hectare were used. Clearly, there is an uncertainty while also the numbers differ per ecossytem. Given current data, however, more refined methods could not be applied.

This means that the results should be interpreted as indicative.At the same time, however, not so much work has been done in this area and the insights provide an useful insight in the order of magnitude of this set on non-market damages and their relationship with temperature change.

3.3 Non-market impacts from climate change – GLOBIOM and MagPIE

We present in this section the impacts of different climate change scenarios on non-market indicators related to land use and agricultural markets impacts in the GLOBIOM and MAgPIE models. These impacts are indirect impacts, in the sense that they result from the adaptation response of agriculture and forestry to the climate change through shifts in management practices, production reallocation and land use change.

Three different indicators are scrutinized, reflecting different ecosystem services and hidden costs to the environment: land cover change, fertilizer use, and greenhouse gas emissions.

3.3.1 Land cover

Climate change is expected to impact crop yield and affect cropland needs, as change in harvested area is part of the adaptation response that farmers adopt in response to yield changes. Two effects can be expected: as yields decrease, farmers can expand their harvested area to compensate for a part of their losses, in particular if prices on the markets increase. But in case some substitution across crops is possible, farmers may also adopt

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alternative crops providing them more profit opportunities or abandon the land to grow crops in other regions with more favorable conditions. Non-market impacts on the other hand receive no price or no complete price in the optimization algorithm. In the case of land expansion, the optimization only considers the land- expansion costs but not for the environmental damage of removing the natural vegetation.

GLOBIOM

The way the different effects counterbalance can be observed in Figure 4 below. For instance, the figure shows that areas like the South of Spain respond to climate change with significant decrease of cropland, whereas others expand in the North of the same country. This is a reallocation effect due to the relatively more favourable conditions for crop cultivation in the North, compared to the South of Spain, something that is shown in Figure 5. Here, yields of winter wheat somewhat increase in the North-West of Spain but largely decrease in the South of Spain. However, the most general trend due to climate change remains a decrease in cropland in the EU, due to the yield increase associated with CO_2 fertilisation, in particular for crops like wheat that are already benefitting from the climate change. By 2050, for three out of the four Global Circulation Models (GCMs), EU cropland decreases by 2 to 5 Mha, and in 2070, the decrease of cropland area can reach 6.5 Mha (HadGEM-ES RCP4.5). Change in pasture area is less significant in our scenarios (less than 0.5 Mha increase to compensate for concentrate feed higher prices), also because we ignore the effect of CO_2 fertilisation on grass productivity. As a consequence, land area devoted to nature significantly increases, in a range of 2.5-5 Mha by 2050, except for the GFDL-ESM2M scenario where EU cropland remains

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relatively stable (see Figure 4 and Figure 6**Errore. L'origine riferimento non è stata trovata.**).

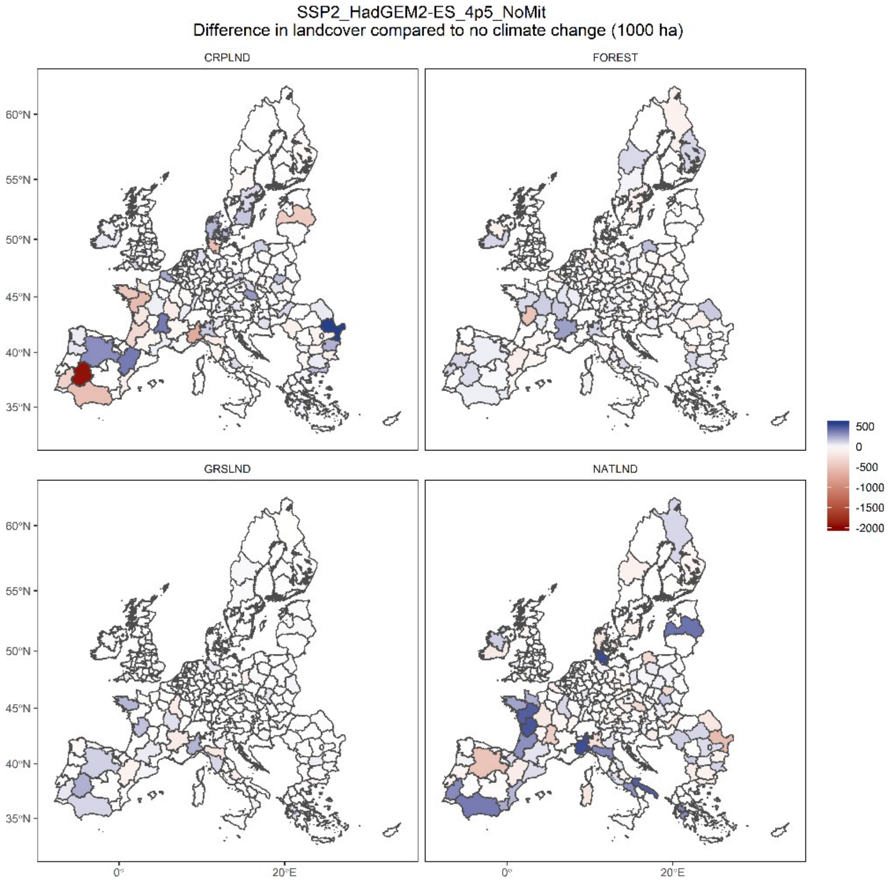

Figure 4: Impacts of RCP4.5, HadGEM2-ES, in 2050 on land cover change.

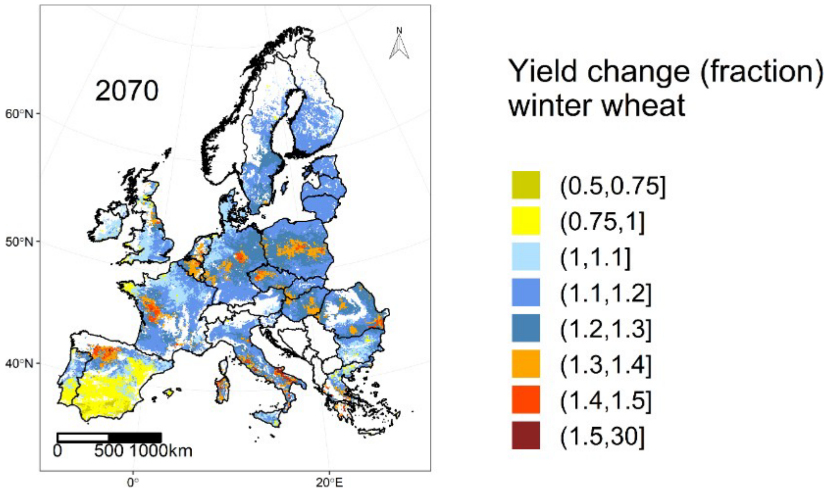

Figure 5: Impact of climate change on winter wheat yield by 2070 in Europe for HadGEM-ES2 under RCP4.5

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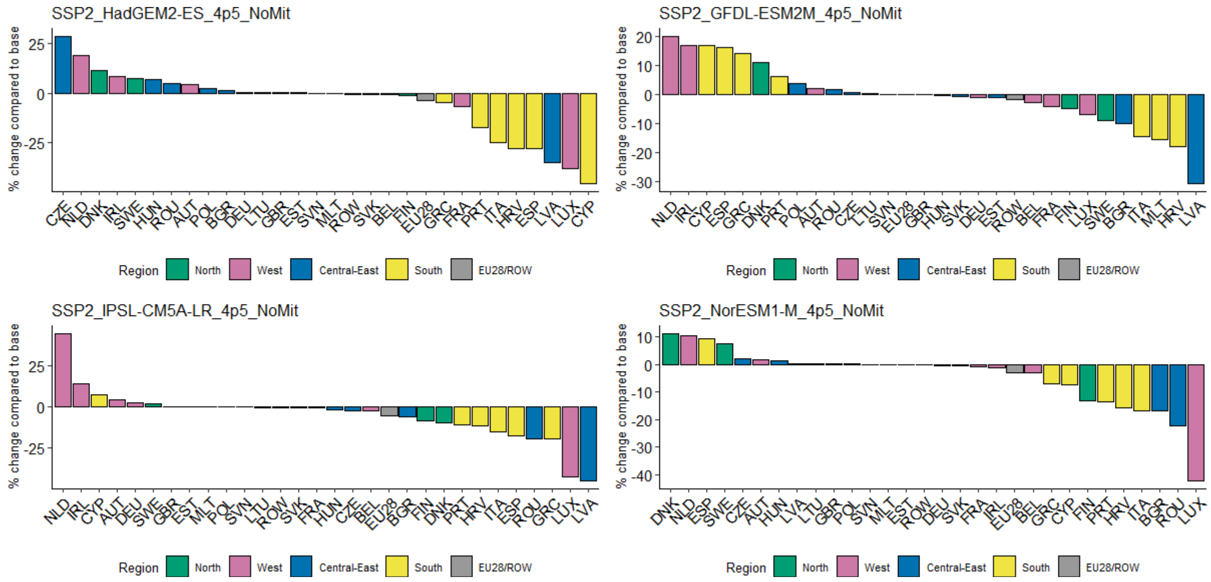

Figure 6: Percentage change in cropland by country by GCM under RCP4.5 and SSP2 compared to the situation without climate change in 2050

MAgPIE

Land cover changes due to climate change in MAgPIE are driven mainly by three dynamics: (a) changed absolute land productivity, leading to changing land expansion, (b) change in relative competitiveness, resulting in a re-location of production, and (c) climate-impact-induced change in demand. The change in relative competitiveness has in our simulations the largest impacts on the land expansion, while the change in demand is negligible.

It is also for this reason that the patterns of land cover do not necessarily increase with the strength of global warming (see figures 7 and 8). It is more important how the climatic conditions change relative to other regional cultivation areas and relative to other climatic zones in the world market.

Impacts on forest land cover are not very large (Figure 7), as most forest areas in Europe are under productive usage or protected areas. Figure 8 shows, that most changes occur in the land cover type “other land”, which is defined as land which is neither under agricultural usage, nor built-up area, nor classified as forests (mostly due to yet insufficient biomass to classify as forests). The signal of climate change on this “other land” is not clearly directed. Taking the Southern EU in RCP 2.6 as example, the change between expansion and reduction of “other land” is the net effect of a declining pastureland, an increasing cropland and an increasing forest area.

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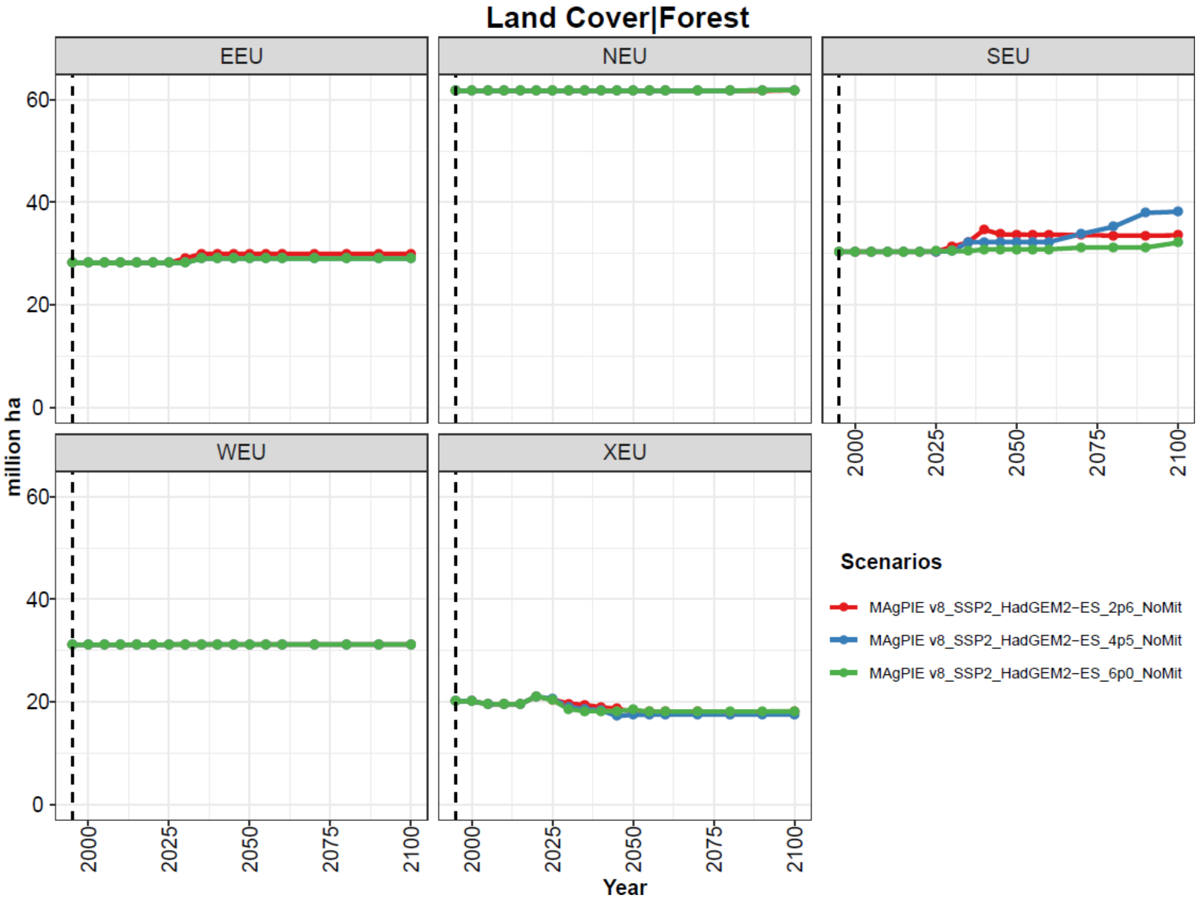

Figure 7: Change in forest land cover (including forestry) for three scenarios with climate impacts from LPJmL, driven by simulations with HadGEM2-ES for three different degrees of climate forcing (RCPs 2p6, 4p5 and 6p0). The regions are Eastern EU (EEU), Northern EU (NEU), Southern EU (SEU), Western EU (WEU), and non-EU Europe (XEU).

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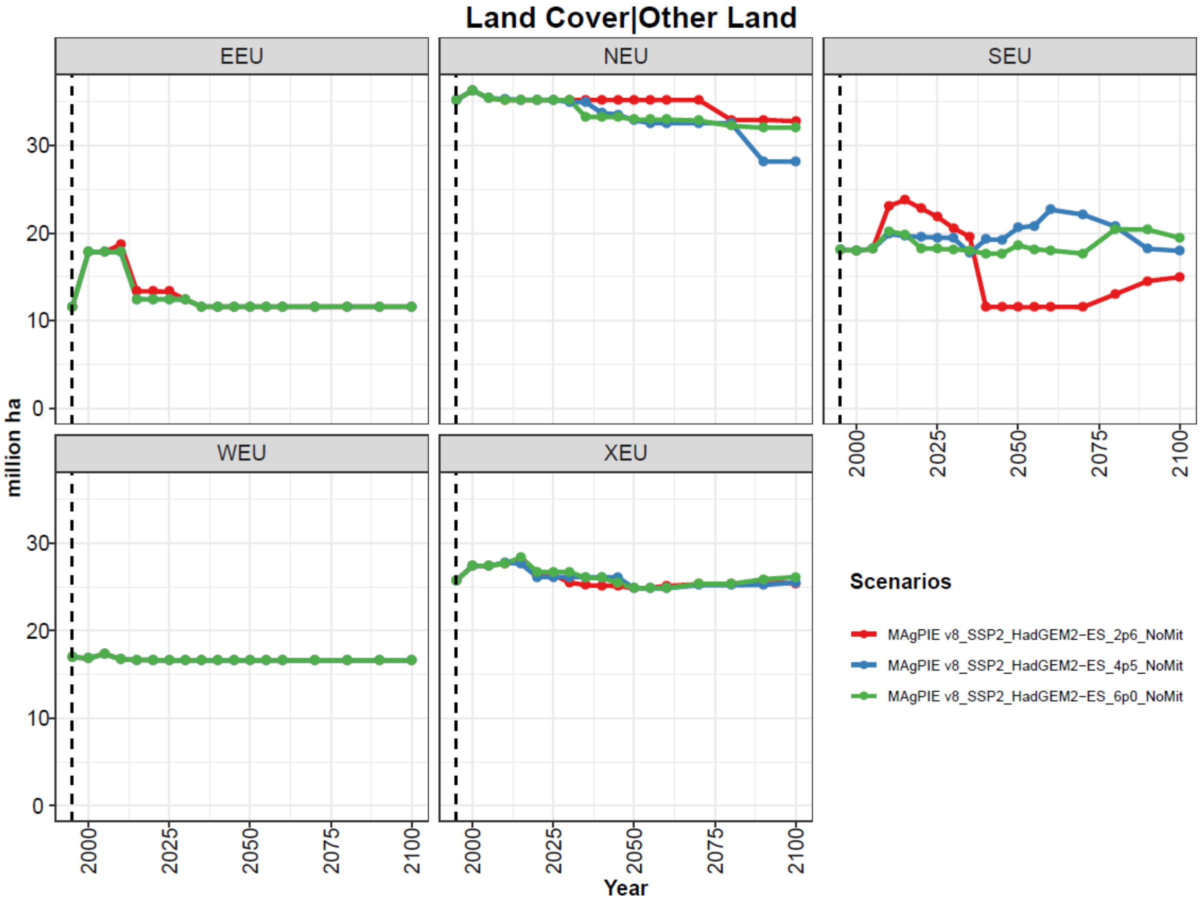

Figure 8: Change in "other land" (land cover which neither classifies as agricultural land, nor as forest, nor as built-up area) for three scenarios with climate impacts from LPJmL, driven by simulations with HadGEM2-ES for three different degrees of climate forcing (RCPs 2p6, 4p5 and 6p0). The regions are Eastern EU (EEU), Northern EU (NEU), Southern EU (SEU), Western EU (WEU), and non-EU Europe (XEU).

3.3.2 Fertilizer use

Fertilizer application generates greenhouse emissions through N_2O but also generates adverse impacts in case of leaching and run-off in river streams, including eutrophication in water pools. Nitrogen pollution thereby includes most importantly nitrate leaching to groundwater and surface waters, air pollution by ammonia and nitrous oxide as greenhouse gas (the latter will be discussed in the section on climate change). As climate change affects crop productivity, farmers will need to adapt their practices to accommodate or compensate for the effects on yields.

GLOBIOM

The analysis from GLOBIOM reveals that the impact on fertilizer use will likely follow the direction of crop yield changes, as farmers provide the nutrient requested by crops for the growth in their new environmental conditions.

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Figure 9 below illustrates the extent of variation of nitrogen fertilizer in the face of different climate change scenarios, and at different time periods. Results are strongly influenced by the climate model chosen. When changes are expected to be positive to crop growth, like in the GFDL-ESM2M or the NorESM1-M case, fertilizer consumption increases, and the level of extra use can exceed 500,000 tonnes for Europe after 2050 in the case of GFDL (all RCPs). But for the HadGEM scenario, the prospect is the reverse, as crop yield losses lead farmers to decrease their application. The strongest impacts are however observed in RCP2.6 and RCP4.5 as CO_2 fertilizationtend to compensate for the yield losses for RCP6.0.

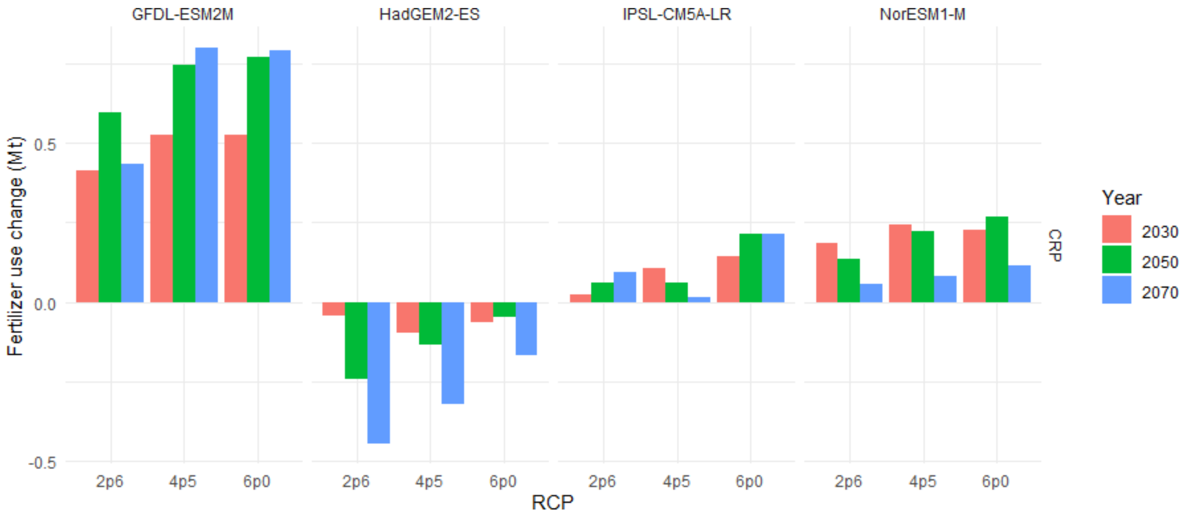

Figure 9: Change in nitrogen fertilizer consumption in the European Union for different RCPs (x-axis) and different time periods (color of the bars), compared to the baseline without climate change.

MAgPIE

As a proxy for nitrogen pollution, MAgPIE includes the inorganic fertilizer usage(Figure 10) and the nitrogen surplus (Figure 11). The latter is defined as the difference between all nitrogen inputs (fertilizer, manure, crop residues, atmospheric deposition etc) and all nitrogen harvest (harvested grains and crop residues). The surplus is a more precise indicator than nitrogen fertilizer application, as it also incorporates the organic nutrients and the beneficial impacts of high nitrogen use efficiency.

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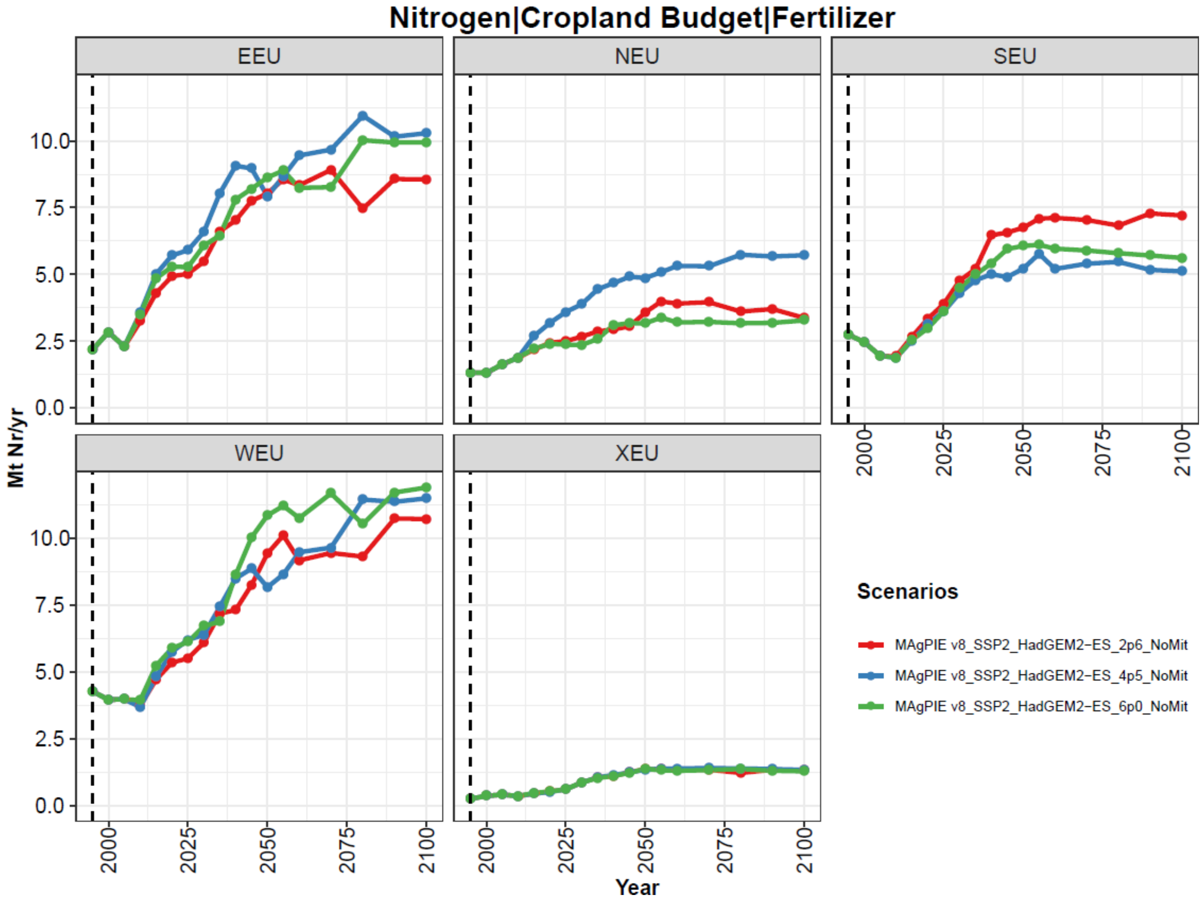

Figure 10: Change in inorganic fertilizer application for three scenarios with climate impacts from LPJmL, driven by simulations with HadGEM2-ES for three different degrees of climate forcing (RCPs 2p6, 4p5 and 6p0). The regions are Eastern EU (EEU), Northern EU (NEU), Southern EU (SEU), Western EU (WEU), and non-EU Europe (XEU).

In general our SSP2 scenarios see a trend of increasing nitrogen fertilizer application, as production further increases and nitrogen use efficiency does not improve substantially. The impact of climate change on nitrogen pollution in MAgPIE 4 stems mainly from changing production quantities and crop yields. The impact of changing precipitation on the leaching fraction, or the impact of rising temperature on ammonia emissions are not considered in this analysis. The change in nitrogen pollution therefore mostly follows the change in production quantities, yet affected by the nitrogen content of the particular crops. For example, oilcrops like rapeseed have a higher impact on nitrogen pollution than cereals, and their spatial relocation has a higher impact on nitrogen budgets.Nitrogen fertilizer application and nitrogen surplus show similar, yet not identical patterns. The reason for this is that in our simulations, climate change had a much stronger impact on the location of crops than on the location of livestock production systems (also due to the limitation that MAgPIE 4 does not include climate change impacts on livestock systems such as heat stress). A shift in livestock productionsystems would have also led to a relocation of organic nutrients and to differing patternsbetween fertilizer application and nitrogen surplus.

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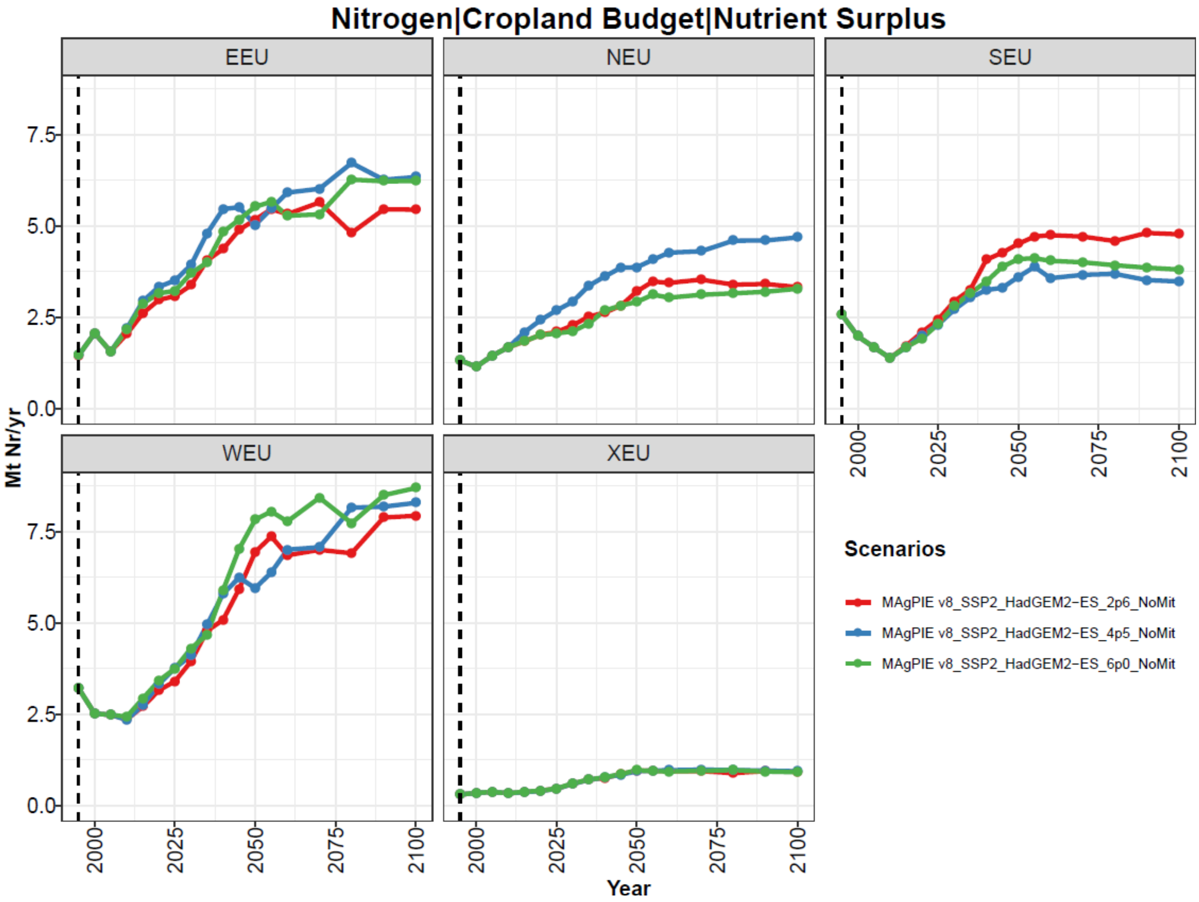

Figure 11: Change in Nitrogen surpluses on croplands for three scenarios with climate impacts from LPJmL, driven by simulations with HadGEM2-ES for three different degrees of climate forcing (RCPs 2p6, 4p5 and 6p0). The regions are Eastern EU (EEU), Northern EU (NEU), Southern EU (SEU), Western EU (WEU), and non-EU Europe (XEU).

3.3.3. Greenhouse gas emissions

Change in the land use system in response to climate change will impact in return greenhouse gases emissions through different channels. Some of these channels are direct, for instance, forest fires or melting of the permafrost can release GHG emissions into the atmosphere. Some other effects are indirect, such as those related to emissions from land cover changes or management response to climate following adaptation in theagriculture or forestry activities.

Agriculture causes direct emissions of the non- CO_2 greenhouse gases N_2O and CH_4, as well as indirect CO_2 emissions from land-use change. These emissions sources are included in GLOBIOM and MAgPIE 4 as far as they are allocated to the agricultural sector according to IPCC accounting. For example, emissions connected to agricultural transport and storage are usually accounted for in the transport sector, while emissions by the chemical industry to produce fertilizers and pesticides are accounted for in the industry sector.

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GLOBIOM

The first important indirect response in the agricultural sector is adaptation by farmers through change in nitrogen application to reflect their newly attainable crop yields and intensify their production where possible. Figure 12 shows how this effect (green bar) represent the largest source of GHG emission variation in the EU. The magnitude and direction of these emissions is however highly dependent on the GCM used and the climate scenario, as previously observed for the fertilizer application case. GFDL is the model for which the response is the highest and most positive, because farmers apply more fertilizers in that scenario, and this degrades the GHG balance of the EU. This comes in contrast with the HadGEM results, where production and fertilizer application tend to decrease. Other adjustments also occur in the EU through the livestock sector, and changes in land cover (mostly conversion of grassland and other natural areas, as deforestation is considered restricted). These latter sources play however a much minor role in the final emission variation for the EU.

Overall, EU emissions vary by a relatively small amount, less than 5 $MtCO_2$/year for all the scenarios. This corresponds to less than 1% of the AFOLU emissions of the EU. However, as observed in the case of yields and related land use impacts, the impacts are very uneven throughout the EU. Some Member States see their agricultural emissions increase by up to 12% in the case of the HadGEM scenario RCP4.5, whereas some other see a decline of up to 8% (**Figure** 13). Emissions generally follow the same pattern as land cover change, with especially the areas in the South of Europe decreasing their emissions.

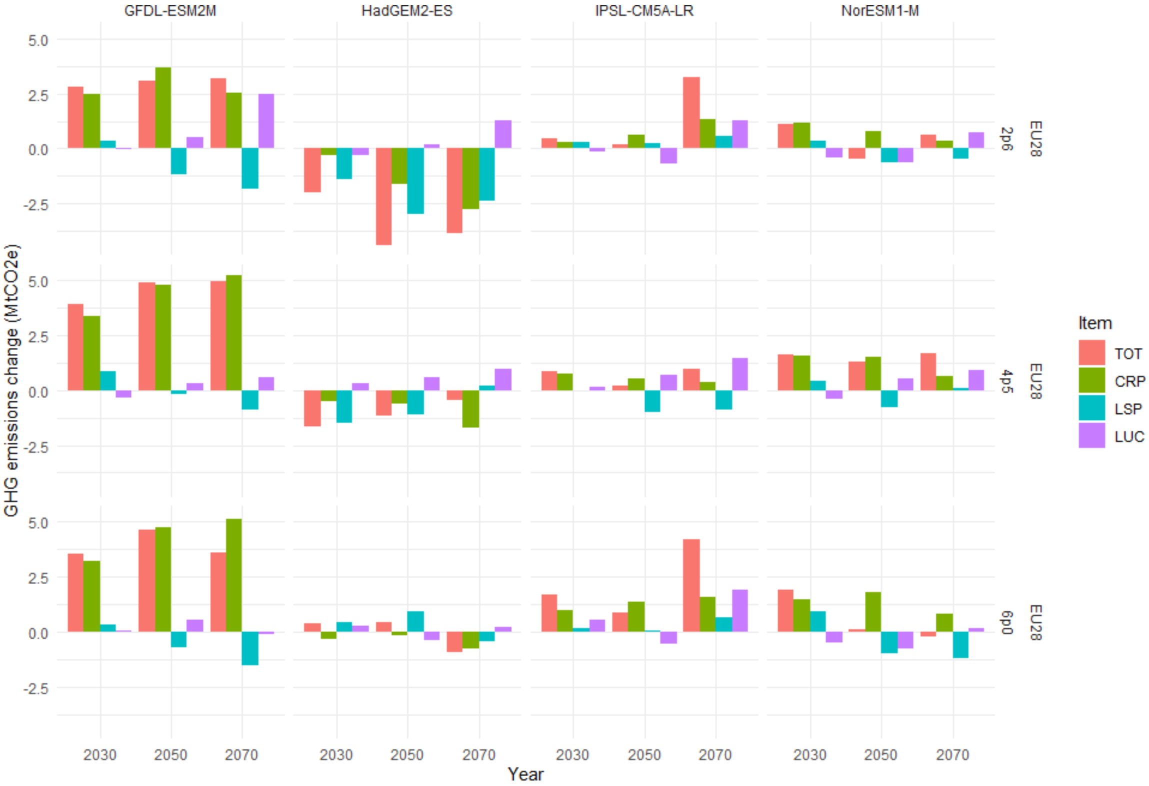

Figure 12: Impact of climate change in emission flows in the EU compared to the baseline. (TOT= total emissions, CRP = crop emissions, LSP = livestock emissions, LUC = land use change emissions).

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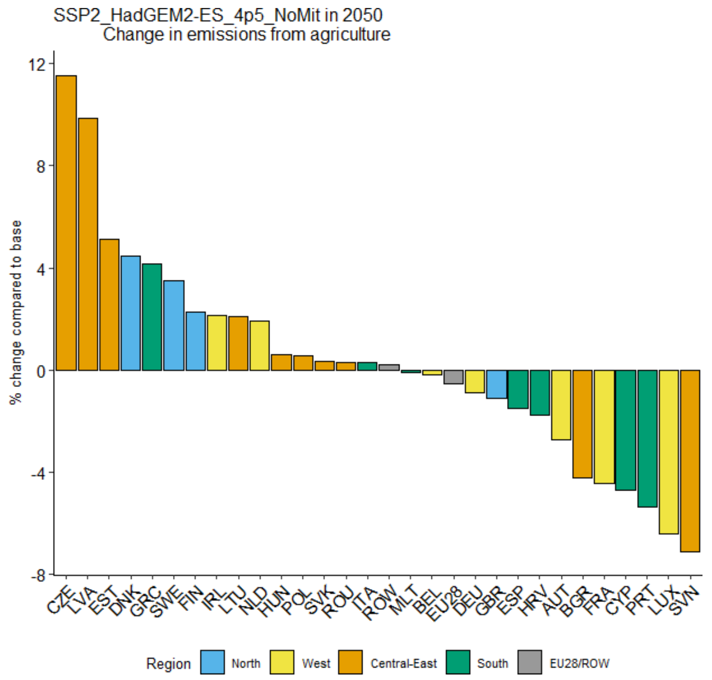

Figure 13: Change in emissions from agriculture under HadGEM2-ES, RCP4.5, in 2050

When looking at global level, the impacts from climate change on GHG emissions is much higher, although also significantly varying across scenarios (Figure 14). Like the variations observed at the EU level, the role of fertilizer emissions, strongly responding to crop yield and related management changes play a crucial role, in particular in the case of NorESM1-M scenario by 2070 under RCP2.6. Livestock still plays a relatively secondary role in the emission fluctuations, but the indirect impacts from climate change are also characterised by a strong variation in land use change emissions. This isdriven by the adjustment of cropland described above. As crop yields decrease in some regions, harvested area increases, and cropland expansion leads to further natural land conversion and deforestation emissions. This effect plays a predominant role in several climate scenarios, in particular in the HadGEM case, where emissions are found to decrease. Overall, GHG emission fluctuations can reach in magnitude 100 $MtCO_2$-eq, which represents about 0.2% of global current GHG anthropogenic emissions. The direction of the emission variation is however highly dependent on the scenario considered.

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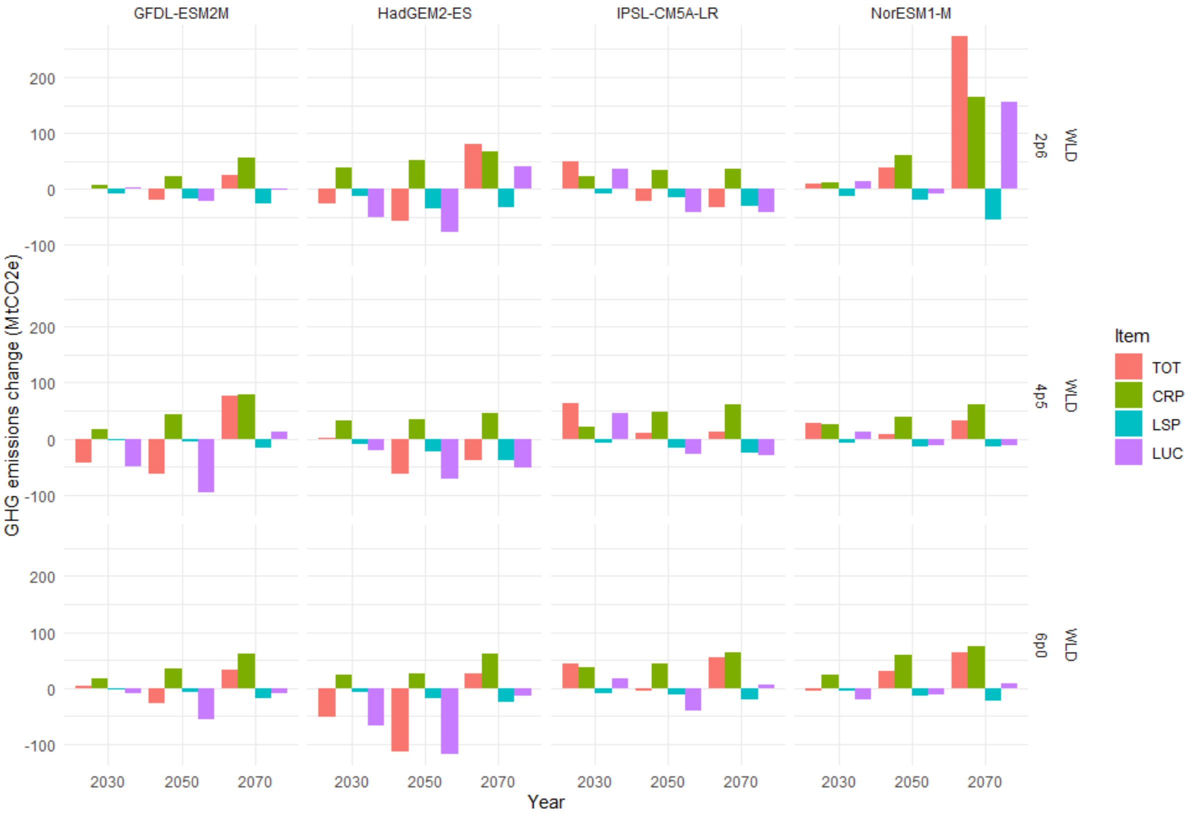

Figure 14: Impact of climate change in emission flows at global level compared to the baseline. (TOT= total emissions, CRP = crop emissions, LSP = livestock emissions, LUC = land use change emissions).

MAgPIE

For this European analysis, CH_4 emissions (see Figure 15) are mainly caused by the enteric fermentation of ruminants and to a lesser degree by manure management. Rice cultivation plays only a minor role in Europe. In our simulations, CH4 emissions are therefore mostly dependent on the endogenous production quantity of livestock products and on the exogenous scenario-dependent feed mix. We do not cover the impact of temperature on emission factors, which are of some importance in the case of manure management, and we also do not account for a potential adaptation of livestock feed mixes. Our model therefore shows very little impact of climate change on CH_4 emissions, mostly because livestock production is not significantly reallocated in our scenarios.

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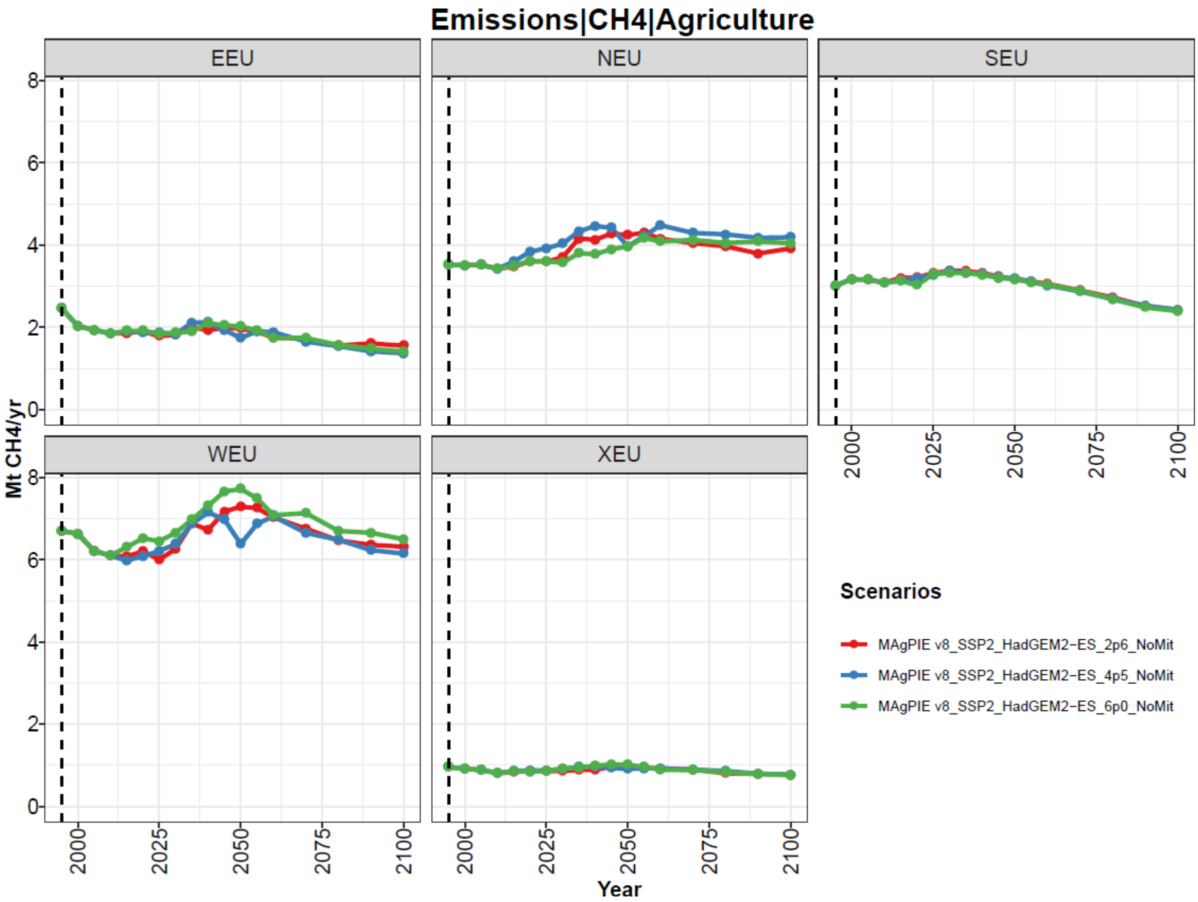

Figure 15: Change in methane emissions (CH_4) caused by agricultural adaptation to climate change, simulated for three scenarios with climate impacts from LPJmL, driven by simulations with HadGEM2-ES for three different degrees of climate forcing (RCPs 2p6, 4p5 and 6p0). The regions are Eastern EU (EEU), Northern EU (NEU), Southern EU (SEU), Western EU (WEU), and non-EU Europe (XEU).

N_2O emissions (Figure 16) in turn are dependent on the fertilization with organic and inorganic fertilizers, and to a lower degree caused also by manure management. Here, climate change has an impact on emissions, which go strongly in line with the change in nitrogen surplus described in the last section. Again, they follow the re-allocation of nitrogen-rich crop production.

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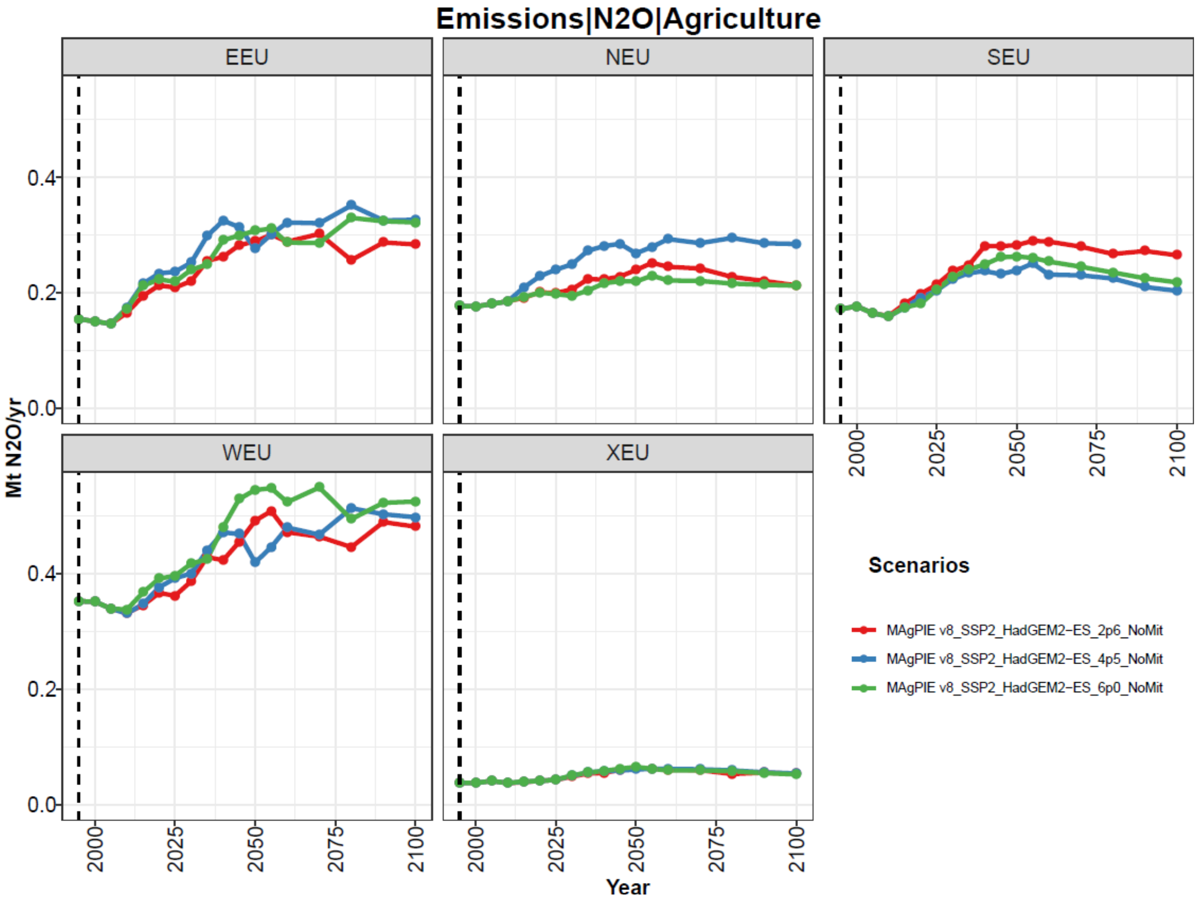

Figure 16: Change in nitrous oxide(N_2O) emissions caused by agricultural adaptation to climate change, for three scenarios with climate impacts from LPJmL, driven by simulations with HadGEM2-ES for three different degrees of climate forcing (RCPs 2p6, 4p5 and 6p0). The regions are Eastern EU (EEU), Northern EU (NEU), Southern EU (SEU), Western EU (WEU), and non-EU Europe (XEU).

The indirect cumulative CO_2 emissions (Figure 17) are in our scenarios mostly negative and reflect the growth of biomass on non-agricultural land and the regrowth of biomass on abandoned land. This growth is to a certain degree enhanced by CO_2 fertilization and nitrogen deposition. Only in the Western EU, we see net-positive emissions towards the end of the century, which are actually directly climate-induced and have to be interpreted as declining carbon intensity of forests, as cropland and pasture areas in this region stay constant.

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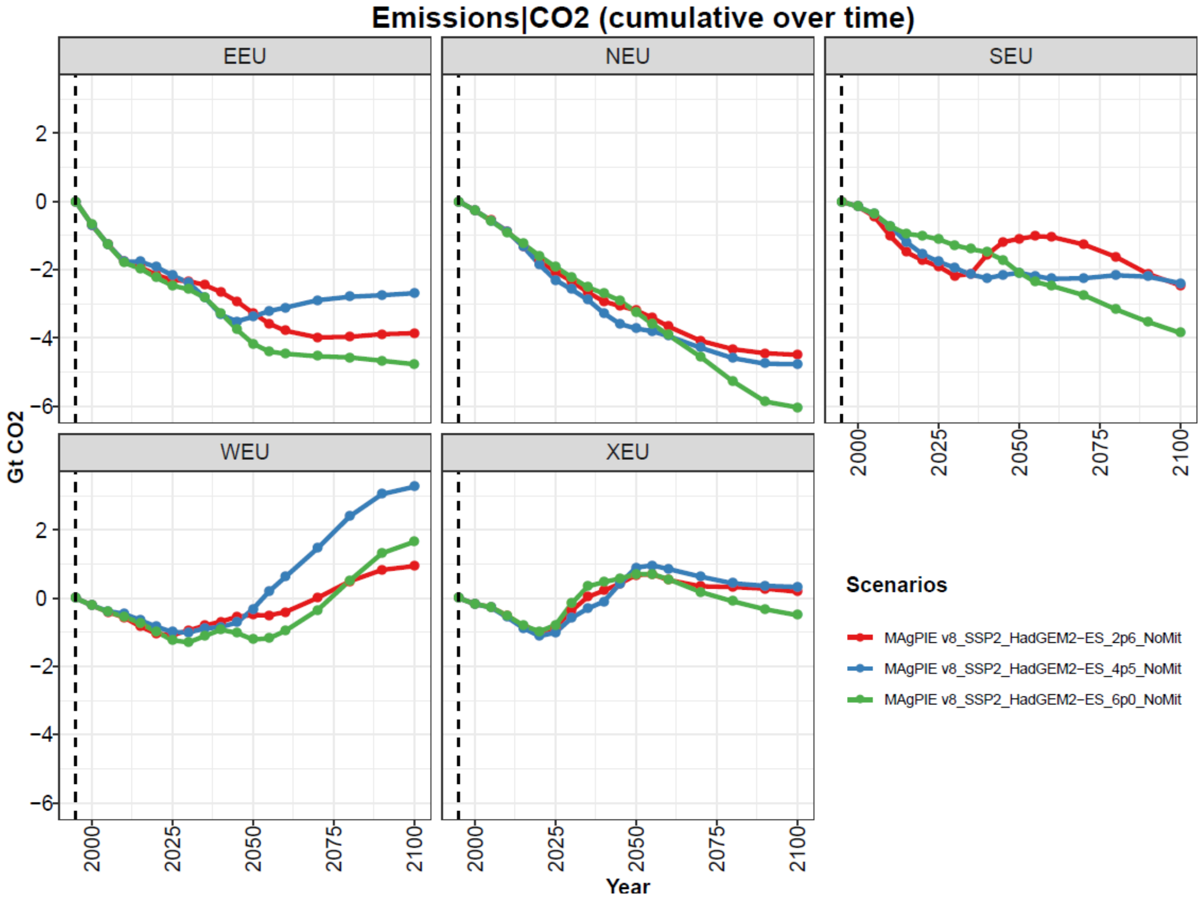

Figure 17: Cumulative CO_2 emissions since 1995 driven by climate impacts and agricultural adaptation, simulated for three scenarios with climate impacts from LPJmL, driven by simulations with HadGEM2-ES for three different degrees of climate forcing (RCPs 2p6, 4p5 and 6p0). The regions are Eastern EU (EEU), Northern EU (NEU), Southern EU (SEU), Western EU (WEU), and non-EU Europe (XEU).

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4. Conclusions

Biodiversity direct climate change impacts

The GLOBIO model has been used to identify the effects of climate change on Mean Species Abundance as an indicator of biodiversity. Specifically, GLOBIO uses a pressure-impact relationship relating MSA to global mean temperature. The impacts of climate change on both vertebrates and plants are found to be negative – though the negative effect is more pronounced for plants who are less able to move location in the face of temperature change. More specifically, regression analysis suggests a 25-30% decline in plant biodiversity for 4 degrees warming and a 10-20% decline in vertebrate biodiversity.

In order to generate estimates of the non-market damage costs associated with biodiversity changes at the European scale we have utilised evidence from existing global valuation studies, updated with data from new European studies. The unit values per hectare were applied to the MSA hectare-equivalent changes to derive total damage costs. The SSP2 scenario was used as the socio-economic baseline, whilst RCPs ranged from 2.6 to 6.0 for two time periods – 2050 and 2100. Whilst the results range between €15 billion per annum (RCP2.6 in 2050) to almost €60 billion per annum (RCP6.0 in 2100) it should be noted that – as Table 4 highlights - the coverage of the non-market valuation of ecosystem services is very partial. Thus, these can be regarded as under-estimates of the actual values. In Section 3.2, we discuss the uncertainties in these numbers (in qualitative sense).

Indirect climate change impacts on land, fertilizer and emissions

We utilised the GLOBIOM and MAgPIE models to identify and quantify the impacts on land use, fertiliser use and greenhouse gases as a consequence of adaptation in agriculture and forestry management. The impacts of these models reflect indirectimpacts, in the sense that they result from the adaptation response of agriculture and forestry to climate change through shifts in management practices, production reallocation and land use change. Non-market impacts on the other hand receive no price in the optimization algorithm. For example, agricultural production costs do not include the external costs of N_2O, CH_4 or CO_2 emissions or the damages of nitrogen pollution. In the case of land expansion, the optimization only considers the land- expansion costs but not for the environmental damage of removing natural vegetation. Also, in the case of fertilizer, only the costs for the nutrients have to be paid but not the environmental externality. The consequence is a market-failure, in which agricultural activity is higher and more resource-intensive than in the welfare optimum. The externalities are practically invisible to the optimization algorithm. The adaptation behaviour of farmers to climate change in the model therefore does not consider these non-market impacts.

Against this background, GLOBIOM and MAgPIE draw some common conclusions on implications of climate change on land cover use, fertilizer use and GHG emissions. Both GLOBIOM and MAgPIE notice a change in land cover due to a change in the relative competitiveness in different regions. Whilst both models report that the results

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are sensitive to the climate-socio-economic scenario combination analysed, both models find that land cover changes are more induced due to changes in climatic conditions relative to other regional cultivation areas and other climatic zones in the world market. For example, GLOBIOM finds that areas at the latitude of South of Spain respond to climate change with significant decrease of cropland, whereas there is an increase in cropland further North.

For both models, this reallocation effect is reflected in matching shifts of fertiliser use that in turn can be expected to affect biodiversity as nitrogen leaches into the local environment. Hence, both models show that nitrogen fertilizer application increases with productivity and production growth. Furthermore, MAgPIE shows that nitrogen use efficiency does not really improve.

Parallel associated shifts in GHG emissions are also expected though their size is not significant compared to global changes. As deforestation is rather limited in Europe, the largest changes in GHG emissions stem from changes to nitrogen application, which go strongly in line with the change in nitrogen surplus following the re-allocation of nitrogen-rich crop production.

Overall, the model results indicate strongly that the effects of climate change on biodiversity are likely to be non-negligible by 2050, particularly under the high emission scenarios. They therefore provide an early signalling as to the value of advanced planning for biodiversity conservation that adequately accounts for theseprojected changes.

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