Land-use and carbon cycle responses to moderate climate change: implications for land-based mitigation?

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Abstract

Climate change has impacts on agricultural yields, which could alter cropland requirements and hence deforestation rates. Thus, land-use responses to climate change might influence terrestrial carbon stocks. Moreover, climate change could alter the carbon storage capacity of the terrestrial biosphere and hence the land-based mitigation potential. Here, we use a global spatially explicit economic land-use optimization model to a) estimate the mitigation potential of a climate policy that provides economic incentives for carbon stock conservation and enhancement, b) simulate land-use and carbon cycle responses to moderate climate change (RCP2.6), and c) investigate the combined effects throughout the 21st century. The climate policy immediately stops deforestation and strongly increases afforestation, resulting in a global mitigation potential of 191 GtC in 2100. Climate change increases terrestrial carbon stocks not only directly through enhanced carbon sequestration (62 GtC until 2100), but also indirectly through less deforestation due to higher crop yields (16 GtC until 2100). However, such beneficial climate impacts increase the potential of the climate policy only marginally, as the potential is already large under static climatic conditions. In the broader picture, this study highlights the importance of land-use dynamics for modelling carbon cycle responses to climate change in integrated assessment modelling.

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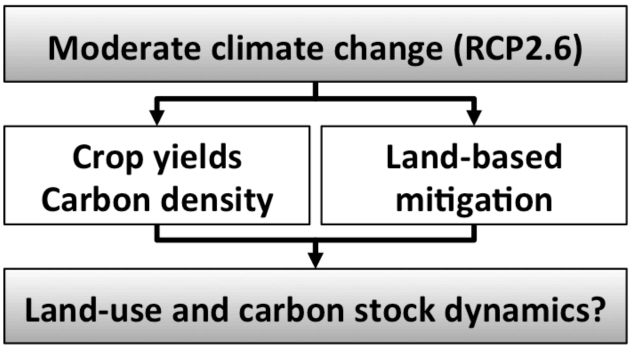

Introduction

After fossil fuel combustion, deforestation is the second-largest source of anthropogenic carbon dioxide (CO_2) emissions, currently accounting for about 12% of total anthropogenic CO_2 emissions[1,2]. Land-based climate policies, such as the inclusion of CO_2 emissions from deforestation in carbon pricing mechanisms, could reduce deforestation and associated CO_2 emissions[3]. In addition to emission reductions, afforestation can enhance above- and belowground carbon stocks (hereafter summarized under the term *carbon stocks* unless indicated otherwise) since trees take up more CO_2 through photosynthesis than they respire and thereupon store the absorbed carbon in vegetation and soil (biological carbon sequestration and storage)[4,5]. Therefore, afforestation can remove CO_2 from the atmosphere, which is also known as negative CO_2 emissions[5,6]. Recent modelling studies show that feasibility and costs of ambitious climate targets, such as limiting the increase in global mean temperature to 2°C compared to preindustrial levels, strongly depend on the availability of carbon dioxide removal options, such as afforestation or bioenergy with Carbon Capture and Storage (CCS)[7,8].

The Representative Concentration Pathways (RCPs) describe future pathways for anthropogenic greenhouse gas (GHG) emissions, atmospheric concentrations of GHGs and radiative forcing[9]. The RCP2.6, with a radiative forcing of 2.6 W/m^2 in 2100, is a scenario of moderate climate change and is consistent with the 2°C target[10–12]. Even under the RCP2.6, current climatic conditions, such as temperature and precipitation, are subject to change in the course of the 21st century[12]. Climate change is rather moderate under the RCP2.6 compared to scenarios with higher radiative forcing, such as the RCP8.5[12]. Nevertheless, moderate climate change under the RCP2.6 has impacts on agricultural crop yields[13]. Rising temperatures and reduced precipitation typically have negative impacts on crop yields, while rising atmospheric CO_2 concentrations stimulate photosynthesis in C3 crops (CO_2 fertilization) and improve water use efficiency in all crops[14–16]. The net effect on crop productivity depends on the prevailing climatic conditions[14]. Changes in temperature, precipitation, radiation and CO_2 concentration (hereafter summarized under the term *climate change* unless indicated otherwise), can have positive effects on crop yields at low levels of climate change, especially in higher latitudes, while tropical regions are typically affected negatively even under low levels of warming[13,17,18]. Increases in agricultural yields might reduce cropland requirements, which in turn could lower deforestation or free-up land for afforestation. Thus, direct effects of climate change on crop yields could indirectly affect carbon stocks through altered land management.

In addition, climate change has direct impacts on the carbon stocks of the terrestrial biosphere (in particular of forests). Similar to agricultural crops, climate change can reduce or increase carbon stocks, depending on the prevailing climatic conditions[19,20]. Biophysical process models project that climate change increases global vegetation carbon stocks throughout the 21st century[19,21]. Above 4°C additional global warming, the increase in global vegetation carbon stocks may stall or reverse[21]. Moreover, climate change affects not only actual carbon stocks but more general the carbon storage capacity of land, i.e. the potential of a unit of land to sequester and store carbon in vegetation and soil[4,22]. The carbon storage capacity plays a central role for afforestation projects since it determines their mitigation potential. Hence, climate change could influence the mitigation potential of afforestation projects. Furthermore, climate impacts on carbon stocks are heterogeneous across the globe[21]. Thus, climate change could additionally alter the spatial suitability of land for afforestation.

Projecting the direct impacts of climate change on carbon stocks of the terrestrial biosphere is typically the domain of models that simulate carbon cycle feedbacks to climate change[21,23]. However, such biophysical process models are not capable of simulating land-use responses to climate change that might indirectly alter carbon stocks (e.g. less deforestation due to climate-change-induced crop yield gains). In principle, information from biophysical process models can be used in models with explicit land-use representation to account for both, direct and indirect carbon cycle responses to climate change. So far, detailed information on climate impacts from biophysical process models has been used in economic land-use models mainly with respect to crop yields[24,25], but associated carbon stock dynamics have not been addressed. With regards to land-based mitigation, economic land-use models and integrated assessment models (IAMs) with explicit land-use representation have been used to estimate the mitigation potential of deforestation avoidance and afforestation[3,26–28]. However, none of these studies accounted for possible land-use responses to climate change (e.g. less deforestation due to climate-change induced crop yield increases that reduce cropland requirements) and their impacts on the terrestrial carbon balance. Few studies used an inverse approach by supplying time-series of land-use patterns derived from economic land-use models to biophysical process models for simulating the effects on carbon stocks[29,30].

Here, we use results from an energy-economy-climate model and a biophysical process model as input for an economic land-use optimization model. Both inputs, climate policy from the energy-economy-climate model and climate impacts from the biophysical process model, are consistent with the RCP2.6. Using these inputs, we simulate land-use and carbon stock dynamics throughout the 21st century with the Model of Agricultural Production and its Impacts on the Environment (MAgPIE)[26,31–33]. We investigate three scenarios: a) a climate policy that provides economic incentives for deforestation avoidance and afforestation[26], b) climate impacts on crops yields and carbon densities following from the RCP2.6 and c) the combined effects of climate policy and climate impacts. After describing the MAgPIE model, input data and the study design, we present global projections for land-use change (cropland, pasture, forest and other land) and carbon stock dynamics (attributed to land management and direct climate change). Finally, we discuss the implications of our findings for future modelling of land-based climate polices and carbon cycle responses to climate change.

Methods

Land-use model MAgPIE

MAgPIE is an economic land-use optimization model that integrates several spatial scales[26,31–33] (see Figure 1 for an overview of the model structure and the Supporting Information (SI) for details). The objective function of MAgPIE is the fulfilment of agricultural demand for ten world regions at minimum global costs. For meeting the demand, the model endogenously decides, based on cost-effectiveness, about the level of intensification (yield-increasing technological change), extensification (land-use change) and production relocation (international trade)[34,35]. The model is solved in a recursive dynamic mode with a variable time step length of five or ten years on a timescale from 1995 to 2100.

For this study, MAgPIE is parameterized based on the Shared Socio-economic Pathway 2 (SSP2), a scenario for climate change research with medium challenges for adaptation and mitigation[36]. In general, historic trends of recent decades with respect to demographics, economic development, environmental protection and technological development continue in SSP2. Food and material demand in MAgPIE is calculated using the SSP2 population and income projections[37,38]. Global food and material demand increases from 30 EJ in 1995 to 65 EJ in 2100 (Figure S2 in the SI).

Land types in MAgPIE consist of cropland, pasture, forest and other land (e.g. non-forest natural vegetation, abandoned agricultural land, deserts, urban land)[39]. In the initial year 1995, the global land area consists of 1438 Mha cropland, 2913 Mha pasture, 4235 Mha forest and 4321 Mha other land (12907 Mha in total) (Figure S4 in the SI). The cropland covers cultivation of 18 different crop types (C3 and C4), both rainfed and irrigated systems. Biophysical yields for theses crop types are derived from the Lund-Potsdam-Jena model for managed Land (LPJmL)[40,41] (see the SI for model details and mapping of crops). In addition, carbon densities for each land type are derived from LPJmL (see SI for details). Biophysical information on crop yields, initial land-cover and carbon densities is spatially explicit (0.5 degree longitude/latitude). Due to computational constraints, spatially explicit data is aggregated to 600 simulation units for the optimization process. For each of the ten world regions in MAgPIE, the clustering algorithm combines grid cells to simulation units based on the similarity of data[42].

MAgPIE calculates carbon stocks at the cell level as the product of land-type specific area and carbon density. If, for instance, forest is converted to cropland within the same simulation unit, the carbon stock of this unit decreases according to the difference in carbon density of forest and cropland. In case agricultural land is abandoned (other land pool) or intentionally used for afforestation (forest land pool), ecological succession leads to regrowth of natural vegetation carbon stocks along sigmoid growth curves[26]. Growth of carbon stocks in MAgPIE is constrained by the LPJmL carbon density.

We validate the MAgPIE results by comparing model projections to historical data for a) cropland, pasture and forest area (Figures S12-S14), b) land-use change emissions (Figure S15) and c) agricultural yields (Figure S9). The validation includes evaluation of model projections with respect to trends in historical data. To some extent, model projections are directly validated against observed data, where the temporal overlap with historical data allows for it. In general, MAgPIE is capable of reproducing historical patterns and trends for the aforementioned variables.

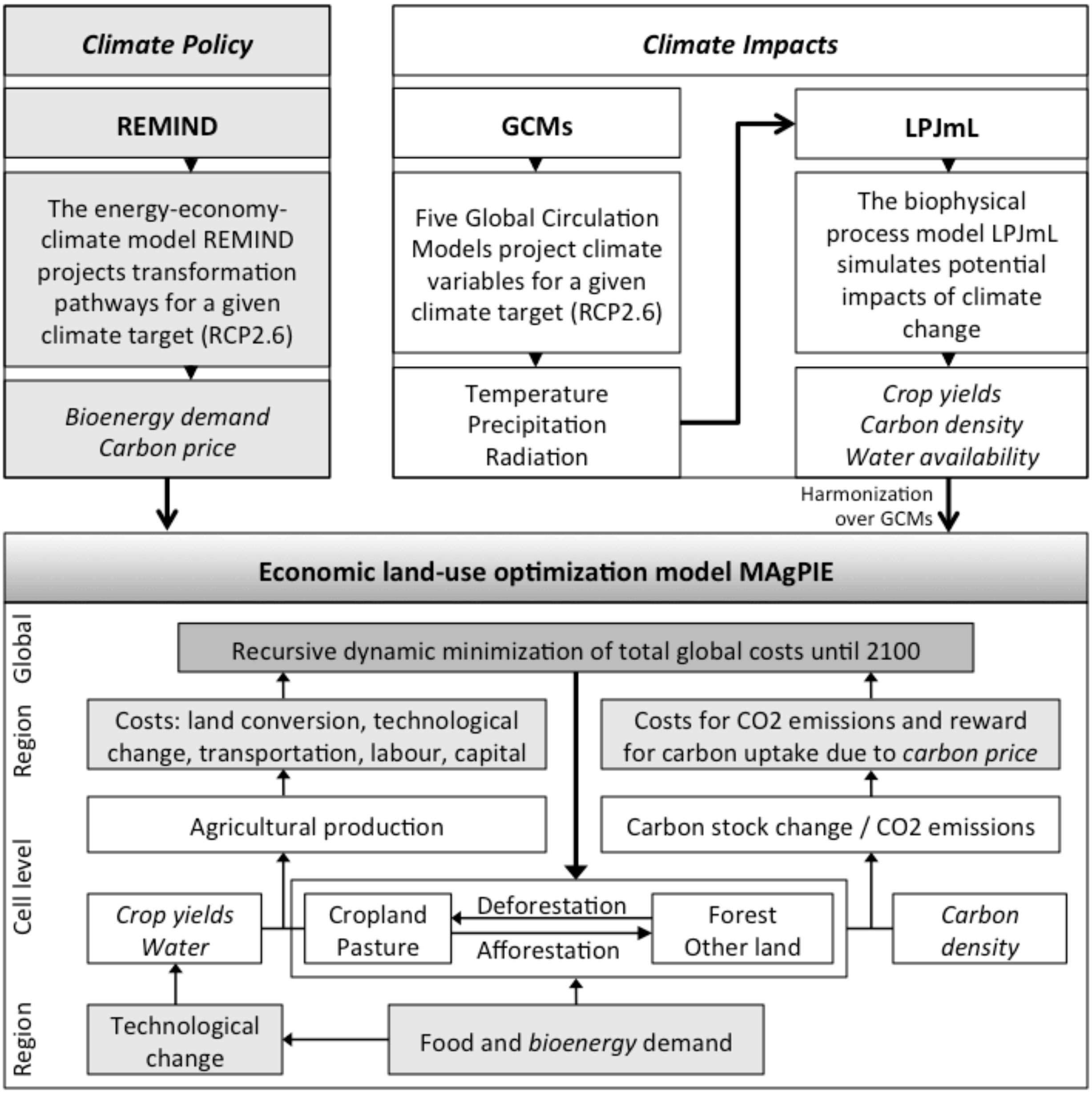

Figure 1: Overview of methodology. Grey tones indicate the spatial resolution: dark grey (global), light grey (world regions), white (cell level). Italic font shows the usage of data from REMIND and LPJmL in MAgPIE.

Climate policy in MAgPIE

The energy-economy-climate model REMIND[43,44] (REgional Model of Investments and Development) projects transformation pathways for a given climate target. These transformation pathways include regional bioenergy demand (1st and 2nd generation) and a globally uniform carbon price, which are taken as input by MAgPIE (see Figure 1). We here use results from REMIND that correspond to the RCP2.6 climate target (see Figures S2 and S3 in the SI). In such ambitious climate protection scenarios, a large share of 2nd generation bioenergy is used in combination with CCS for generating negative CO_2 emissions in the energy sector[45,46]. Here, the MAgPIE simulations cover CO_2 emissions due to land expansion for bioenergy crop production, but do not account for emissions or emission savings due to bioenergy use in other sectors. The carbon price is applied to all carbon stock changes that originate from anthropogenic land-use change (hereafter referred to as Land Carbon Pricing

(LCP)). Technically, the product of released CO_2 to the atmosphere (tCO_2) and the carbon price ($\$/tCO_2$) enters the cost-minimizing objective function of the model as additional term on top of agricultural production cost. For carbon stock gains, which reflect negative CO_2 emissions, this additional term in the objective function becomes negative. Thus, LCP provides economic incentives for carbon stock conservation and enhancement through land management, such as deforestation avoidance and afforestation. A number of studies indicate that in high latitude regions a decrease in surface albedo due to afforestation (darker land-cover) could counteract the associated carbon sequestration effect[47–50]. Accordingly, we assume that no afforestation should occur in high latitude regions above 50 degree North and South. Expansion of agriculture into boreal forests and all other land-use changes in high latitudes are still allowed in the model. Potential carbon emissions from peat lands are not modelled.

Climate impacts in MAgPIE

General Circulation Models (GCMs) compute changes in climate variables, such as temperature and precipitation, for a given RCP. To account for uncertainty in climate projections, we use climate projections from five different GCMs (HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2M and NorESM1-M) that have been bias-corrected for the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP)[51]. Consistent with the choice of climate policy, we here use climate projections for the RCP2.6. The dynamic global crop growth, vegetation and hydrology model LPJmL[30,41] uses climate projections as input to simulate spatio-temporal biophysical impacts on crop yields (Figures S7 and S8 in the SI), carbon densities of natural vegetation (Figures S5 and S6 in the SI) and surface freshwater availability. LPJmL considers the impact of temperature, precipitation, radiation and CO_2 concentration. Elevated CO_2 concentrations enhance plant photosynthesis in C3 plants, which is known as CO_2 fertilization, and simultaneously increases water use efficiency in all plants[15,16]. There is indication that the current generation of biophysical process models overestimates CO_2 fertilization due to missing feedback representations in photosynthetic activity[52,53]. The current version of LPJmL does not explicitly represent nutrient dynamics and might therefore overestimate CO_2 fertilization[41]. Crop yields and carbon densities from LPJmL are harmonized for the initial MAgPIE time step (see SI for details). Finally, MAgPIE integrates the biophysical information derived from LPJmL into the cost-optimization of land-use patterns (see Figure 1).

Study setup

In order to investigate if land-use and carbon cycle responses to moderate climate change interact with a land-based climate policy throughout the 21st century, we analyse the isolated and combined effects of a LCP climate policy and RCP2.6 climate impacts with the MAgPIE model. For this purpose, we define reference cases for the LCP climate policy and the RCP2.6 climate impacts. In NoLCP, carbon stock changes are not priced, i.e. there is no incentive for deforestation avoidance and afforestation. In NoCC (No Climate Change), biophysical crop yields and carbon densities are assumed to be static at 1995 levels throughout the simulation period. The combinations of the two climate policy cases (LCP / NoLCP) and the two climate impact cases (RCP2.6 / NoCC) result in four scenarios: *reference* (NoLCP & NoCC), *LCP only* (LCP & NoCC), *RCP2.6 only* (NoLCP & RCP2.6) and the *combined setting* (LCP & RCP2.6). To account for uncertainty in climate projections, all scenarios with climate impacts are simulated with RCP2.6 biophysical climate impact projections from LPJmL that are based on climate projections from five different GCMs. Table 1 summarizes the study design.

Table 1: Summary of study design

Socio-economic setting, bioenergy demand and carbon price
The economic land-use optimization model MAgPIE is parameterized with a socio-economic setting for the 21st century based on SSP2 (e.g. population, income, food demand). Regional bioenergy demand (1st and 2nd generation) and a globally uniform carbon price derived from REMIND correspond to the RCP2.6 climate target.
Land-based climate policy
In the Land Carbon Pricing (LCP) case, the carbon price in MAgPIE is applied to all carbon stock changes that originate from anthropogenic land-use change. Hence, LCP provides economic incentives for deforestation avoidance and afforestation. NoLCP represents a reference case, in which carbon stock changes are not priced.
Climate impacts on the land system
In the RCP2.6 case, spatially explicit information on biophysical crop yields and carbon densities varies over time in MAgPIE according to LPJmL simulations for the RCP2.6. NoCC represents a reference case, in which biophysical crop yields and carbon densities are assumed to be static at 1995 levels.
Study setup
The combinations of the two climate policy cases (LCP / NoLCP) and the two climate impact cases (RCP2.6 / NoCC) result in four scenarios: *reference* (NoLCP & NoCC), *LCP only* (LCP & NoCC), *RCP2.6 only* (NoLCP & RCP2.6) and the *combined setting* (LCP & RCP2.6).

Results

Across all scenarios global land-use changes range from about -1500 Mha for pastureland to +1700 Mha for forestland by 2100 (Figure 2), associated with global carbon stock changes ranging from about -100 GtC to +200 GtC by 2100 (Figure 3). We report land-use and carbon stock changes for scenarios with RCP2.6 climate impacts as average over the five GCM-specific RCP2.6 climate projections, while the respective Figures 1 and 2 show the full range of results. In the SI, we show regional results in Figure S10 and Figure S11, and provide GCM-specific results at the global scale in Table S3 and Table S4 (land-use and carbon stock dynamics respectively).

Reference scenario

In the *reference* scenario (NoLCP & NoCC), global cropland increases by 698 Mha between 1995 and 2100 (Figure 2, left, dashed lines), which reflects a strong rise in 2nd generation bioenergy demand between 2030 and 2060 (Figure S2). The increase in cropland mainly comes at the cost of forest area, which decreases by 511 Mha in the same period. The remaining cropland increase of 187 Mha originates from the conversion of pastureland. In addition, 1025 Mha of pastureland are abandoned until 2100 (other land) due to efficiency improvements in the livestock sector and stagnating demand for livestock products in the 2nd half of the 21st century (Figure S2). In order to fulfil the agricultural demand, land-use intensification and changes in spatial production patterns complement agricultural expansion. In the *reference* scenario, global average agricultural yields increase from 3.1 tDM ha^{-1} in 2005 to 5.0 tDM ha^{-1} in 2100, which reflects average yield increases of about 0.5% per year until 2100. Simulated agricultural yields in 2005 as well as the historical trend of yield-growth compare well to observed data on agricultural yields at the global scale (Figure S9).

The net effect of these land-use changes in the *reference* scenario is a loss of global terrestrial carbon of 90 GtC until 2100 (Figure 3, left, dashed lines; Table 2). Loss of terrestrial carbon largely coincides with deforestation, in particular between 2030 and 2060. In the *reference* scenario, carbon stocks are assumed to be unaffected by climate change (NoCC).

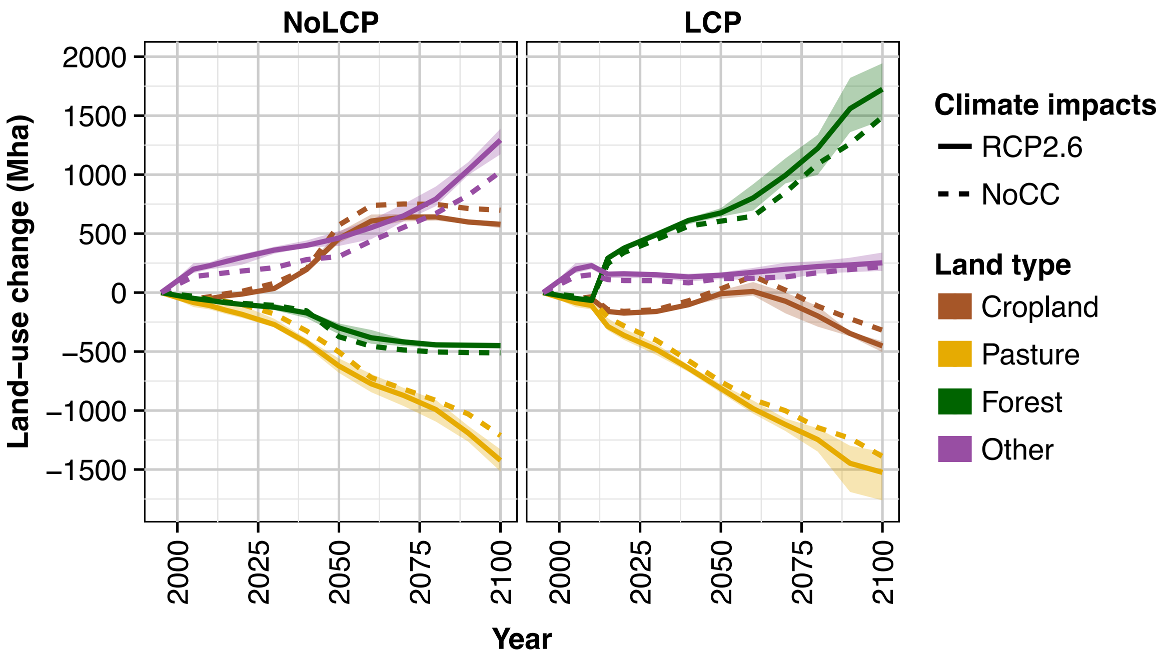

Figure 2: Time-series of global land-use change (Mha) for four major land types between 1995 and 2100. The combinations of climate policy (*NoLCP*, *LCP*; left vs. right column) and climate impacts (*RCP2.6*, *NoCC*; solid vs. dashed lines) result in four scenarios. Solid lines represent the average over individual model results for five GCM-specific RCP2.6 climate projections, while shaded areas indicate the full range of results.

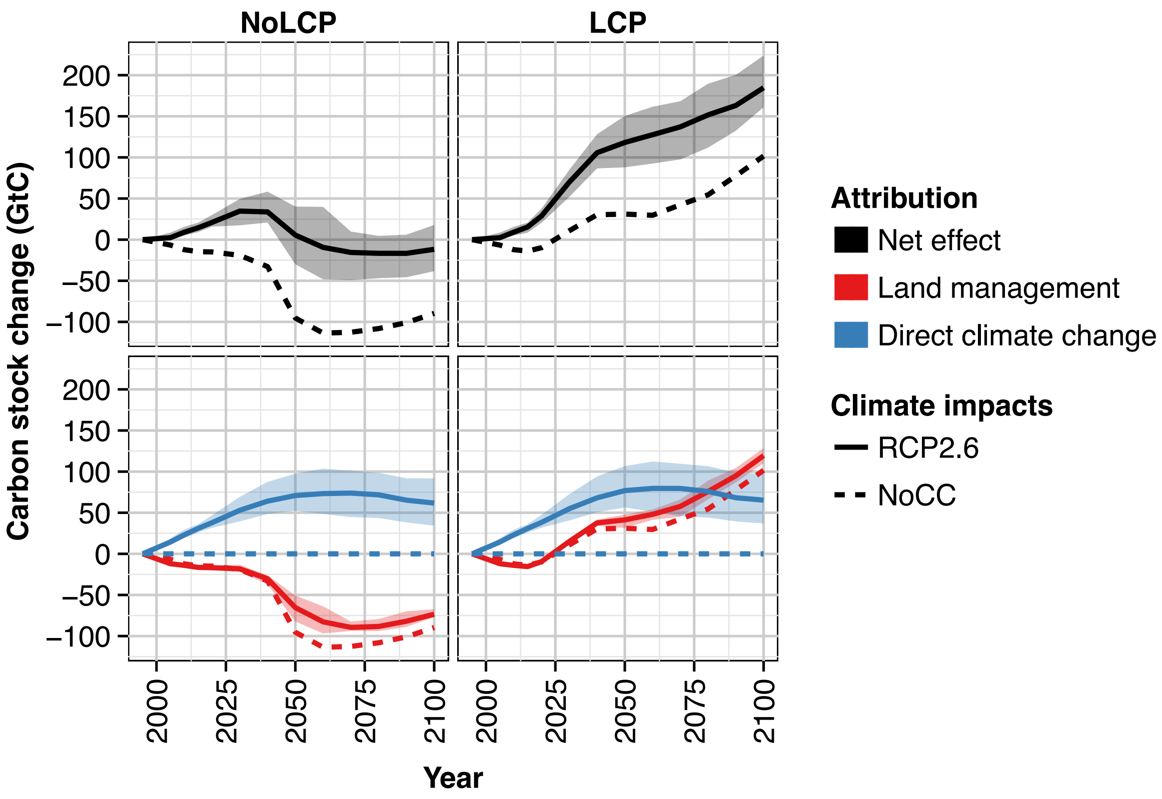

Figure 3: Time-series of global terrestrial carbon stock change (GtC) between 1995 and 2100. The combinations of climate policy (*NoLCP*, *LCP*; left vs. right column) and climate impacts (*RCP2.6*, *NoCC*; solid vs. dashed lines) result in four scenarios. Colours indicate the attribution of changes in carbon stocks. *Land management* reflects carbon stock changes associated with the land-use dynamics shown in Figure 2 and includes indirect effects of climate change on carbon stocks through altered land management. *Direct climate change* reflects carbon stock changes due to direct impacts of climate change on carbon sequestration in the terrestrial biosphere. The *net effect* on carbon stocks is represented by the sum of *land management* and *direct climate change*. Solid lines represent the average over individual model results for five GCM-specific RCP2.6 climate projections, while shaded areas indicate the full range of results.

Land-based climate policy

In the *LCP only* scenario (LCP & NoCC), the carbon price creates a strong incentive to conserve and enhance carbon stocks (Figure 2, right, dashed lines). The introduction of the global carbon price in 2015 at 24 $/tCO_2$ immediately stops deforestation and strongly increases afforestation. In total, global forest area increases by 1489 Mha throughout the 21st century, which results in 2000 Mha more forest in 2100 compared to the *reference* scenario. About half of the increase in forest area is realized by cropland contraction. Global cropland area decreases in total by 319 Mha throughout the 21st century, which results in 1018 Mha less cropland in 2100 compared to the *reference* scenario. To facilitate such strong cropland contraction, agricultural yields have to rise much stronger throughout the 21st century than in the *reference* scenario. In *LCP only*, global average agricultural yields increase from 3.1 tDM ha^{-1} in 2005 to 11.2 tDM ha^{-1} in 2100, which reflects average annual yield increases until 2100 of about 1.36%, compared to 0.5% in the *reference* scenario (Figure S9). The remaining increase in forest area originates from abandoned pasture area. Pasture area decreases by 1390 Mha throughout the 21st century, which is similar to pasture contraction in the *reference* scenario (1212 Mha until 2100). But in contrast to the *reference* scenario, converted pastureland is primarily used for afforestation in *LCP only*, while just 220 Mha of converted pastureland are abandoned (other land). On-going afforestation throughout the 21st century in

LCP only increases global carbon stocks by 101 GtC until 2100 (Figure 3, right, dashed lines; Table 2). In addition, deforestation and other conversions of carbon-rich ecosystems that occur in the *reference* scenario are stopped. Therefore, the global mitigation potential attributable to a land-based climate policy that provides economic incentives for carbon stock conservation and enhancement is 191 GtC between 1995 and 2100. As in the *reference* scenario, carbon stocks are assumed to be not affected by climate change (NoCC) in *LCP only*.

RCP2.6 climate impacts

In general, land-use dynamics under static climatic conditions (NoCC) and moderate climate change (RCP2.6) are similar throughout the 21st century (Figure 2, left, solid vs. dashed lines). However, in the *RCP2.6 only* scenario (NoLCP & RCP2.6) global agricultural area (cropland and pasture) is 330 Mha smaller in 2100 compared to the *reference* scenario with static climatic conditions. The reduced land requirement for agriculture translates until 2100 into 62 Mha more forest (less deforestation) and 268 Mha more other land with potentially re-growing natural vegetation. This land-saving effect originates from the land-use response to higher agricultural yields under RCP2.6 climate projections: global average agricultural yields are 0.3 tDM ha^{-1} higher in 2100 compared to the *reference* scenario (Figure S9).

Altered land management in *RCP2.6 only* results in 16 GtC higher global carbon stocks in 2100 compared to the *reference* scenario (Figure 3, left, solid vs. dashed lines). In addition to this indirect effect via land management, climate change has direct impacts on the carbon stocks of the terrestrial biosphere through altered plant photosynthesis and respiration. Due to direct impacts of climate change, global carbon stocks in *RCP2.6 only* are 62 GtC higher in 2100 compared to the *reference* scenario. The overall global carbon stock dynamics in *RCP2.6 only* follow the trajectory of the atmospheric CO_2 concentration for RCP2.6 climate projections: increase until mid-21st century followed by a smaller decrease until 2100[11]. In total, global carbon stocks in *RCP2.6 only* are 78 GtC higher in 2100 compared to the *reference* scenario, which shows carbon losses of 90 GtC until 2100. Therefore, in absolute terms global carbon stocks still decrease by 12 GtC until 2100 in *RCP2.6 only*.

Overall, the uncertainties in land-use dynamics (Figure 2), carbon stock dynamics (Figure 3) and agricultural yields (Figure S9), which are introduced by the five GCM-specific RCP2.6 climate projections, do not change our results qualitatively.

Combined effects

In the *combined setting* of a LCP climate policy and RCP2.6 climate impacts (LCP & RCP2.6), overall land-use dynamics are similar to *LCP only* (Figure 2, right, solid vs. dashed lines). In the *combined setting*, however, agricultural land requirements are 267 Mha lower in 2100, which is similar to the identified land-saving effect for *RCP2.6 only* (330 Mha in 2100). Contrary to *RCP2.6 only*, most of the agricultural land released by the land-saving effect is immediately used for afforestation in the *combined setting* (235 Mha until 2100). Regrowth of natural vegetation with associated carbon stock gains takes place regardless of the allocation to forest or other land sine afforestation is a managed re-growth of natural vegetation in the MAgPIE model[26]. Accordingly, the climate-change-induced gain in global carbon stocks due to land management is similar to *RCP2.6 only* (Figure 3, left vs. right, solid vs. dashed lines). Also the increase in global carbon stocks due to direct impacts of climate change is similar to *RCP2.6 only*. Thus, RCP2.6 climate impacts seem to increase global carbon stocks independent from a LCP climate policy.

In the *combined setting*, the net effect of land management and climate change is an increase of global carbon stocks by 185 GtC until 2100 (Figure 3, right, solid lines; Table 2).

Since global carbon stocks decrease by 90 GtC until 2100 in the *reference* scenario, the full cumulative carbon mitigation effect in 2100 attributable to the *combined setting* is 275 GtC. This full effect is 191 GtC for *LCP only* and 78 GtC for *RCP2.6 only*. The sum of these isolated effects is 269 GtC in 2100. Thus, the additional carbon stock gain that emerges from the *combined setting* is 6 GtC throughout the 21st century (Table 2). If this gain is completely accounted to the mitigation potential of the *LCP only* scenario (191 GtC in 2100), the mitigation potential increases by just 3%. Therefore, land-use and carbon cycle responses to RCP2.6 climate impacts only marginally affect the mitigation potential that can be attributed to a land-based climate policy in the 21st century.

Table 2: Summary of scenario results. Carbon stock changes and full carbon mitigation effect in GtC. Carbon stock changes show the net effect of land management and direct climate change between 1995 and 2100 at the global scale (Figure 3). The full carbon mitigation effect reflects the difference in these carbon stock changes between the respective scenario and the *reference* scenario. To identify the interaction between a LCP climate policy and RCP2.6 climate impacts, we compare the sum of the full mitigation effects of the *LCP only* (191 GtC) and the *RCP2.6 only* scenario (78 GtC) to the full mitigation effect of the *combined setting* (275 GtC). The small difference of 6 GtC suggests that the interaction between a LCP climate policy and RCP2.6 climate impacts is low. This table shows average values over five GCM-specific RCP2.6 climate projections.

	NoLCP		LCP	
NoCC	*Reference*		*LCP only*	
	Δ Carbon stock	Full effect	Δ Carbon stock	Full effect
	-90 GtC	0 GtC	101 GtC	191 GtC
RCP2.6	*RCP2.6 only*		*Combined setting*	
	Δ Carbon stock	Full effect	Δ Carbon stock	Full effect
	-12 GtC	78 GtC	185 GtC	275 GtC

191 GtC + 78 GtC = 269 GtC ~ 275 GtC

Discussion

Land-based climate policy

We find that the introduction of a carbon price in the land-use sector immediately stops deforestation and strongly increases afforestation throughout the 21st century. According to our results, current global forest area increases by about one third until 2100, associated with carbon stock gains of 101 GtC globally until 2100. A reference scenario without carbon pricing shows carbon losses of 90 GtC until 2100, mainly due to deforestation. Therefore, the cumulative mitigation potential attributed to the land-based climate policy analysed in this study is 191 GtC throughout the 21st century.

The reward for carbon sequestration entails strong intensification of the agricultural system to free up land for afforestation (see also *Humpenöder et al.*[26]). Typically, rates of technological change leading to yield increases are exogenous to economic land-use models[25]. MAgPIE, however, derives technological change rates endogenously as part of the cost-optimization[34], i.e. the model dynamically adjusts investments in yield-increasing technological change depending on the scenario. Using different rates of technological change would affect the land-use and carbon stock dynamics shown here as land-use intensification and land expansion are strongly interrelated.

In this study, we do not consider market feedback effects of afforestation with respect to bioenergy demand and carbon price, i.e. bioenergy demand and carbon price are exogenous to the model. Due to competition for land, afforestation might increase bioenergy prices, which in turn might lower bioenergy demand from the energy system. Moreover, carbon sequestration following from afforestation could lower carbon prices in the overall economy, potentially leading to less afforestation. Accounting for such market feedback effects is beyond the scope of this study but critical for the evaluation of afforestation as mitigation strategy.

According to previous modelling studies, competition for land between agricultural production and afforestation might more than double food prices throughout the 21st century[27,54]. This gives reason to consider food security implications of land-based climate policies, such as the United Nations' REDD+ (*reducing emissions from deforestation and forest degradation)* mechanism, which aims to provide economic incentives for deforestation avoidance and afforestation[55,56]. Keeping food consumption levels unaffected from such land-based climate policies, as we did for these model runs, would require substantial redistribution policies to assure food security for low-income households (see also *Edmonds et al.*[28]). Analysis of the economic aspects of food security is critical for the implementation of land-based climate policies, but beyond the scope of this study.

Land-use and carbon cycle responses to RCP2.6 climate impacts

We find that accounting for RCP2.6 climate impacts in an economic land-use model increases global carbon stocks by 78 GtC until 2100, compared to a reference scenario with static climatic conditions. Enhanced carbon sequestration of the terrestrial biosphere under RCP2.6 causes the major part of this difference (62 GtC in 2100). However, 21% of the total climate-change-induced carbon stock gains originate from a land-saving effect due to higher agricultural yields under RCP2.6 (16 GtC in 2100). This finding highlights the importance of land-use dynamics for modelling carbon cycle responses to climate change

As already noted in the methods part, LPJmL estimates of CO_2 fertilization on crop yields are more positive than in many other global crop models[13]. Therefore, the projected gains in carbon stocks due to RCP2.6 climate impacts might be overestimated. On the other hand, atmospheric CO_2 concentrations in the RCP2.6 return to current levels in 2100 (383-385 ppm) after a peak caused by exceeding the climate target around mid-century ("overshooting")[10,11]. Thus, the choice of the RCP2.6 should limit the overall magnitude of CO_2 fertilization and associated nutrient demand. Higher levels of global warming, such as the RCP8.5, are projected to have strong negative effects on agricultural yields at low latitudes[13]. In this case land-use and carbon stock dynamics could reverse: lower agricultural yields might increase cropland requirements, causing more deforestation or hampering ecological succession. On the other hand, many regions at low latitudes are currently far away from closing the "yield gap"[57,58]. The potential for yield increases in Africa, Asia, and Latin America, e.g. through better crop and soil management, irrigation or access to fertilizer, is considerable. Thus, improved agricultural productivity can potentially alleviate negative effects of climate change at low latitudes.

Why RCP2.6 climate impacts hardly affect a land-based climate policy

In this study, we project a) that the global mitigation potential of a land-based climate policy is 191 GtC in 2100, and b) that carbon stock gains due to RCP2.6 climate impacts cumulate to 78 GtC until 2100. The sum of these isolated effects (269 GtC) is just slightly lower than the actual result for the combined setting in 2100 (275 GtC), which suggests that moderate climate change in the 21st century only marginally affects the mitigation potential that can be attributed to the land-based climate policy.

There are two reasons for this loose link between RCP2.6 climate impacts and a land-based climate policy. First, the carbon price creates a strong incentive for deforestation avoidance and afforestation already under static climatic conditions. Hence, beneficial impacts of climate change on crop yields and carbon storage capacity, as we project in this study for the RCP2.6, do not substantially increase the mitigation potential attributable to a land-based climate policy. Second, afforestation projects typically last for 20-60 years[59]. Over such long periods, climate change might alter the carbon sequestration in forests[21]. Thus, owing to its long-term character, the mitigation potential of afforestation projects could increase or decrease due to climate change. In particular, negative impacts on the outcome of afforestation projects are critical. If negative climate impacts would offset re-growth of carbon stocks in future time steps, stopping an afforestation project and using the land for other purposes is only a limited option since a clear-cutting of the already existing forest comes with costs for the associated CO_2 emissions. Therefore, afforestation projects introduce a path dependency for land-use, which prevents abrupt changes in land-use due to climate change.

Implications for future modelling

In general, our results stress that land-use responses to climate change should be considered in simulations of carbon cycle feedbacks to climate change. This could be of particular importance for IAMs, which are typically used for estimating mitigation efforts and costs across economic sectors for a specific climate target[11]. Currently, several IAMs use the Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) to account for the feedbacks between the carbon cycle and the climate system[11]. MAGICC simulates simplified CO_2 fertilization and temperature feedbacks on the terrestrial biosphere without consideration of land-use dynamics[11,23]. Accordingly, carbon stock changes that result from land-use responses to climate change are disregarded. For instance, our results suggest global carbon stocks gains of 16 GtC until 2100 due to land-saving effects under RCP2.6. Depending on potential carbon prices of several hundred dollars by 2100, as projected by several IAMs[7,10,11], the net present value of these 16 GtC could be huge. A more sophisticated representation of the interactions between climate, terrestrial biosphere and anthropogenic land-use dynamics with respect to carbon stocks could therefore play a vital role for improving estimates of mitigation efforts and costs in IAMs.

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Supporting Information (SI)

Additional model description and detailed results. This material is available free of charge via the Internet at http://pubs.acs.org.

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Supplementary Information (SI)

Land-use and carbon cycle responses to moderate climate change: implications for land-based mitigation?

by Florian Humpenöder, Alexander Popp, Miodrag Stevanovic, Christoph Müller, Benjamin Leon Bodirsky, Markus Bonsch, Jan Philipp Dietrich, Hermann Lotze-Campen, Isabelle Weindl, Anne Biewald and Susanne Rolinski

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Figures and Tables

Detailed model descriptions

1.1. Land-use optimization model MAgPIE

MAgPIE is a land-use optimization model that integrates spatially explicit biophysical constraints into an economic decision-making process[1,2].
Humpenöder et al.[3] provide a detailed description of the MAgPIE model version used here (revision 7753), in particular with respect to the afforestation implementation.
http://iopscience.iop.org/1748-9326/9/6/064029
http://iopscience.iop.org/1748-9326/9/6/064029/media/erl495870suppdata.pdf

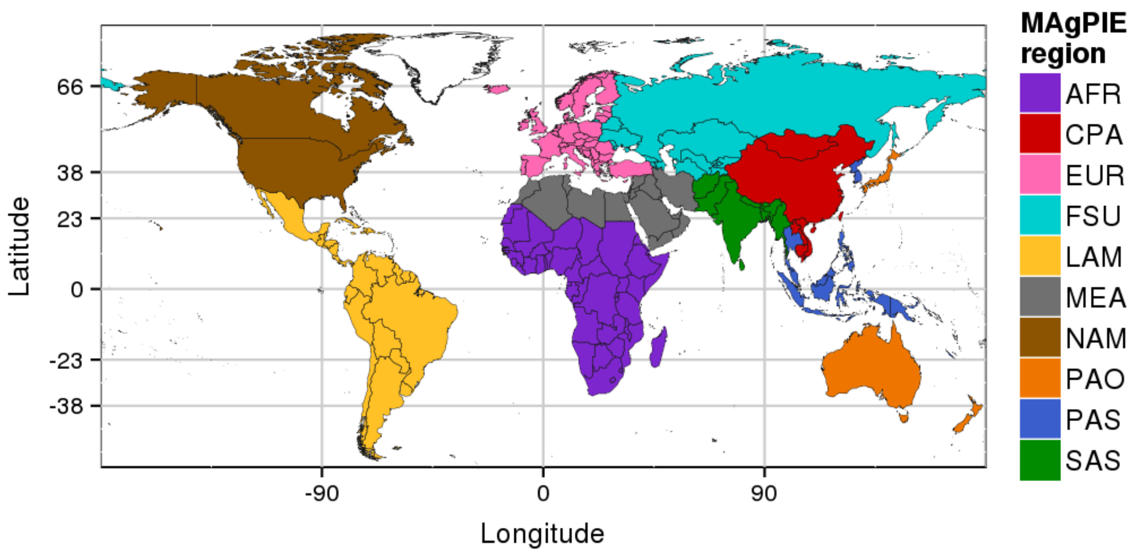

Figure S1: MAgPIE economic world regions.

MAgPIE	Region	SSP
AFR	Sub-Saharan Africa	MAF
CPA	Centrally planned Asia including China	ASIA
EUR	Europe including Turkey	OECD
FSU	States of the former Soviet Union	REF
LAM	Latin America	LAM
MEA	Middle East/North Africa	MAF
NAM	North America	OECD
PAO	Pacific OECD including Japan, Australia, New Zealand	OECD
PAS	Pacific (or Southeast) Asia	ASIA
SAS	South Asia including India	ASIA

Table S1: Abbreviations and names of the 10 economic world regions in MAgPIE, and mapping to the 5 SSP regions used in Figure S10 and Figure S11.

MAgPIE	LPJmL	
tece	tece	Temperate cereals
maiz	maize	Maize
trce	trce	Tropical cereals
rice_pro	rice	Rice
soybean	soybean	Soybean
rapeseed	rapeseed	Rapeseed
groundnut	groundnut	Groundnut
sunflower	sunflower	Sunflower
oilpalm	groundnut	Palm oil (not existent in LPJmL; groundnut is used as surrogate)
puls_pro	puls	Pulses
potato	tero	Potato / temperate roots
cassav_sp	trro	Tropical roots
sugr_cane	sugarcane	Sugarcane
sugr_beet	tero	Temperate roots
cottn_pro	groundnut	Cotton (not existent in LPJmL; groundnut is used as surrogate)
begr	begr	Bioenergy grasses
betr	betr	Bioenergy trees

Table S2: Crop types in MAgPIE and mapping to LPJmL crop functional types (CFTs)

1.2. Biophysical process model LPJmL

LPJmL simulates growth dynamics of natural and agricultural vegetation depending on daily climatic conditions and soil texture. Natural vegetation is represented in LPJmL at the biome level by 9 Plant Functional Types (PFTs)[4]. Agricultural vegetation is represented by 12 crop functional types (CFTs), managed grassland and 2 bioenergy crops (grass and short-rotation coppice trees)[5–7]. The setup for simulating agricultural productivity in LPJmL is described in more detail in *Müller et Robertson*[8]. The model calculates closed balances of carbon fluxes (gross primary production, auto- and heterotrophic respiration) and pools (in leaves, sapwood, heartwood, storage organs, roots, litter and soil), as well as water fluxes (interception, evaporation, transpiration, snowmelt, runoff, discharge)[9,10]. Photosynthesis is simulated following the Farquhar model approach[11–14]. Processes of carbon assimilation and water consumption are parameterized on the leaf level and scaled to the ecosystem level. Carbon and water dynamics are closely linked so that the effects of changing temperatures, declining water availability and rising CO_2 concentrations are accounted for and their net effect can be evaluated[9,15]. Physiological and structural plant responses determine water requirements and consumption.

The suitability of the LPJmL framework for vegetation and water studies has been demonstrated by validating simulated phenology[5], river discharge[9,16], soil moisture[17], evapotranspiration[4,9] and carbon stored in litter biomass on the ground for temperate and boreal European ecosystems[18].

For computing carbon densities of natural vegetation, competition between PFTs due to differences in their performance under given climate conditions, can lead to changes in vegetation composition as less adapted PFTs can be out-competed and replaced. Subsequently to changes in vegetation composition, i.e. changes in the PFT distribution, changes in the productivity and the respective carbon fluxes can also be quantified. This applies to long-term climate trends as well as interannual climate variability, including the impact of extreme events.

Plant growth and crop productivity in LPJmL is simulated taking into account various effects of temperature, such as on phenological development, photosynthesis and autotrophic respiration, various effects of precipitation, such as reduced carbon uptake under water limitation (stomata closure) and changes in biomass partitioning (intensified growth of roots at the expense of leaves under water limitation), which are mediated by soil properties (percolation, storage, evaporation), as well as combined effects of temperature and water, such as the atmospheric water vapour pressure deficit.

Here, LPJmL simulations are used to supply data on crop yields, carbon densities of natural vegetation and water availability for irrigation from surface water to the land-use model MAgPIE. Simulations of crop yields assume that all crops are grown in all grid cells to assess the possible crop productivity also in areas currently not used for the cultivation of that crop to inform possible shifts in cropping areas. In seven individual LPJmL runs, crop yields are derived for seven different intensity levels. Cropping intensities are selected to match observed yields from the FAO[19] at country level under the initial land-use pattern in MAgPIE. An additional LPJmL simulation assumes that all grid cells are covered with natural vegetation, which involves a spin-up period of 1000 years to bring vegetation patterns and carbon pools into equilibrium. Results from this simulation of natural vegetation are used to provide data on biophysical carbon densities and water availability to the MAgPIE model.

1.3. Energy-economy-climate model REMIND

REMIND is a global multi-regional model for the assessment of climate change mitigation polices throughout the 21st century that integrates interactions of the energy system, the economy and the climate system.
Luderer et al.[20] provide a detailed description of the REMIND model (version 1.5).
http://papers.ssrn.com/abstract=2312844

2. Detailed description of MAgPIE input

2.1. Demand

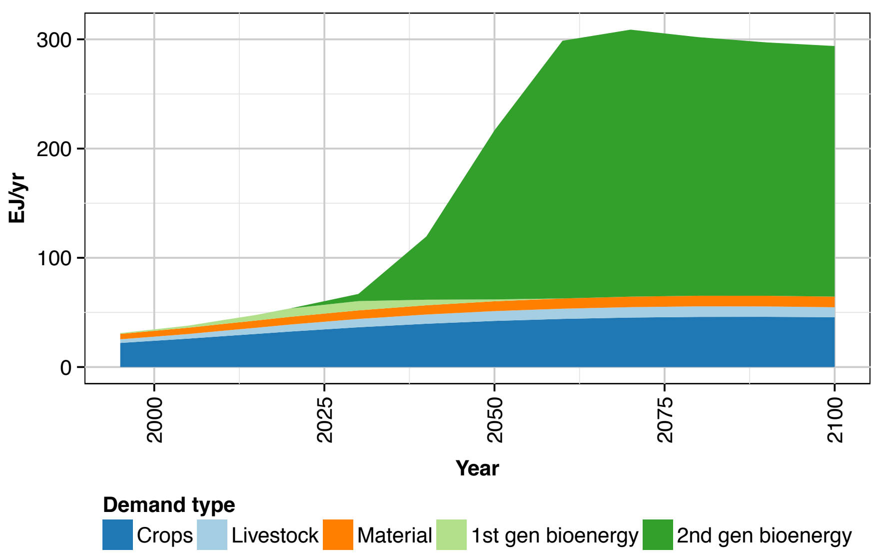

Figure S2: Time-series of global demand in MAgPIE between 1995 and 2100 in EJ/yr. Food (crops and livestock) and material demand is calculated using the SSP2 population and GDP projections[21,22]. 1st and 2nd generation bioenergy demand is taken from the 450 FullTech REMIND/MAgPIE scenario in Popp *et al*[23]. A 450 ppm CO_2eq stabilization target in in 2100 corresponds to the RCP2.6[24–26].

2.2. Carbon price

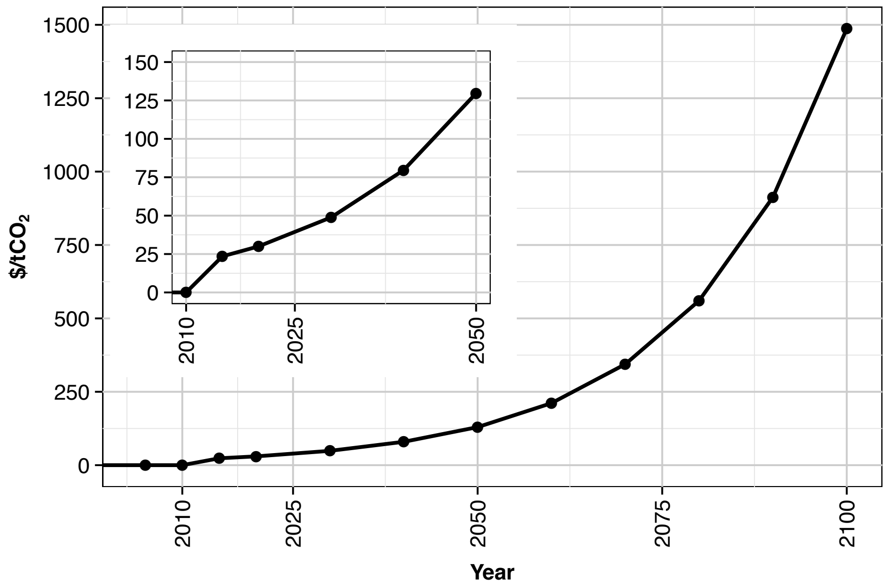

Figure S3: Time-series of the globally uniform carbon price between 1995 and 2100 in $/tCO$_2$. The carbon price starts at 24 $/tCO$_2$ in 2015 and increases non-linearly at a rate of 5% per year, reaching 130 $/tCO$_2$ in 2050, and 1487 $/tCO$_2$ in 2100[27]. This carbon price trajectory, taken from REMIND, is close to the carbon prices projected for a 450 ppm CO$_2$eq stabilization target in 2100[27]. Other assessment models report similar carbon prices for such ambitious climate targets[25,28].

2.3. Land types

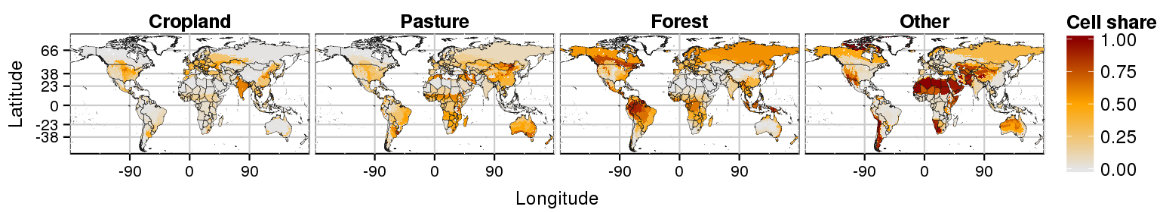

Figure S4: Initial (year 1995) spatially explicit land-use patterns for four land types used as input in the MAgPIE model[29]. Colours indicate the share of the respective land type in each cell. The sum of shares across the four land types for a single cell equals one.

2.4. Carbon densites

LPJmL derives spatio-temporal carbon densities of natural vegetation under consideration of climate change effects (see section 1.2 for details) based on RCP2.6 climate projections for the 21st century. MAgPIE uses these biophysical carbon densities for different land types as input (Figures S5 and S6). The actual cell-specific carbon density in MAgPIE depends on the land allocation within each cell (calculated as area weighted mean). Cropland and pasture carbon densities are estimated based on LPJmL and data from IPCC[30] (chap 5–6, table 5.5 and 6.2). For forest and other land, the LPJmL information is used without modification for all carbon pools.

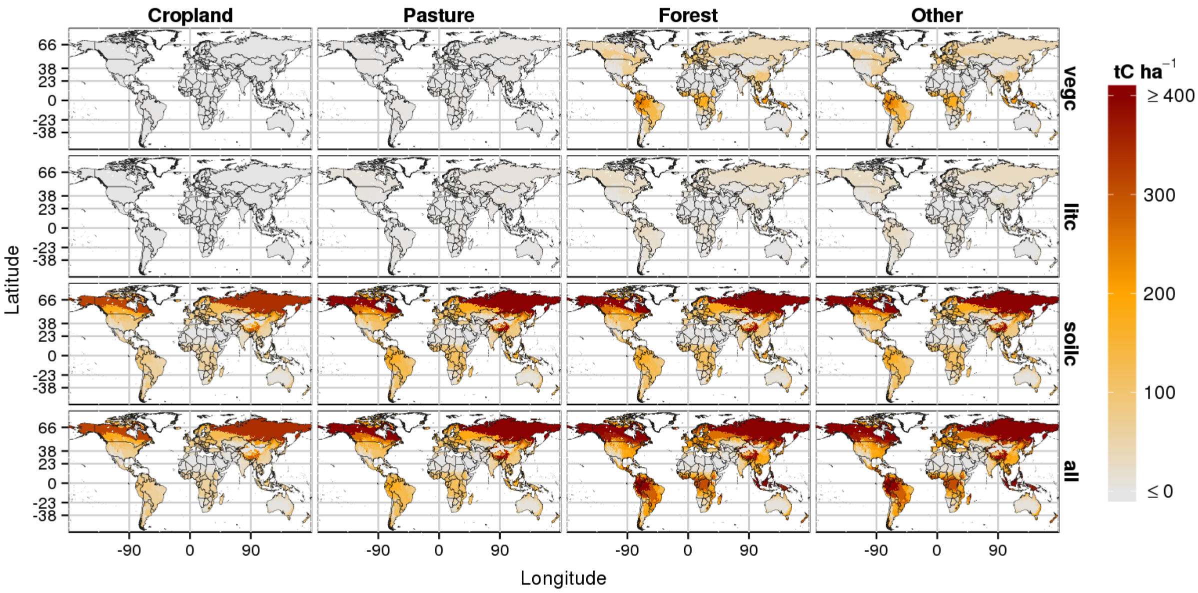

Figure S5: Spatially explicit carbon density (tC ha^{-1}) for four land types and the three carbon pools vegetation, litter and soil (vegc, litc, soilc) used as input in the MAgPIE model for the initial time step (year 1995). The last row (all) shows the cell-specific sum of vegetation, litter and soil carbon densities for each land type.

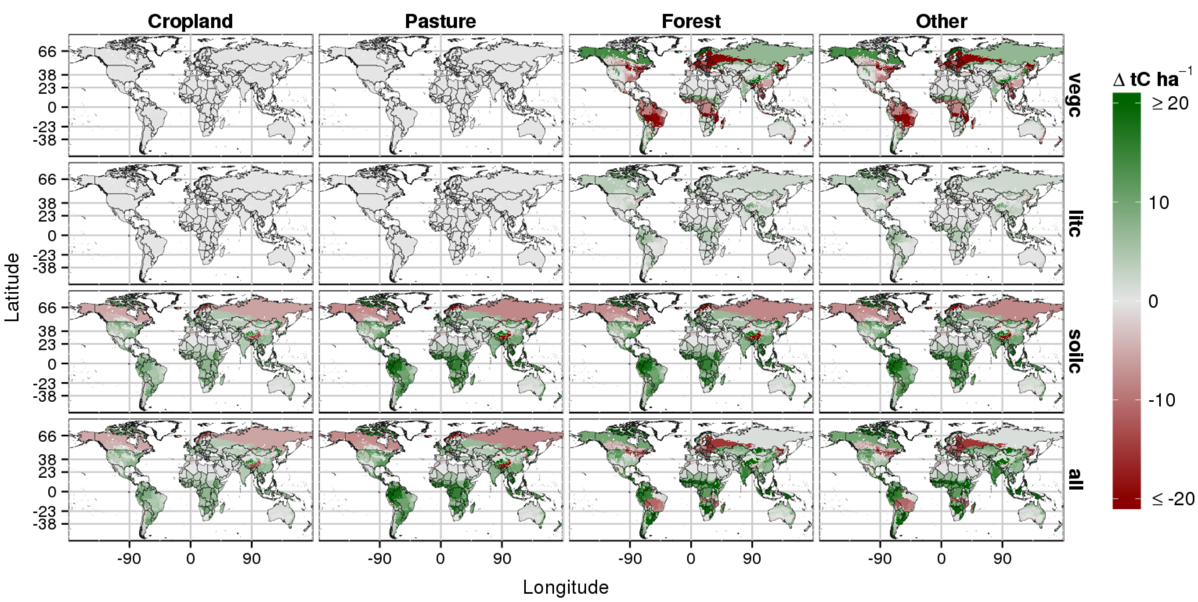

Figure S6: Spatially explicit change in carbon density (tC ha^{-1}) between 1995 and 2100 for RCP2.6 climate projections derived by LPJmL (see Figure S5 for initial carbon densities and carbon pool abbreviations). This plot shows average values over the five GCM-specific RCP2.6 climate projections used in this study.

2.5. Crop yields

LPJmL derives spatio-temporal crop yields under consideration of climate change effects (see section 1.2 for details) based RCP2.6 climate projections for the 21st century. MAgPIE uses these biophysical yields for different crop types as input (Figures S7 and S8). In total, MAgPIE accounts for 18 crop types, each rainfed and irrigated (see Table S2 for mapping). Agricultural yields (see Figure S9) emerge from the cropping pattern in MAgPIE, i.e. from the yield of crops that are actually grown in MAgPIE.

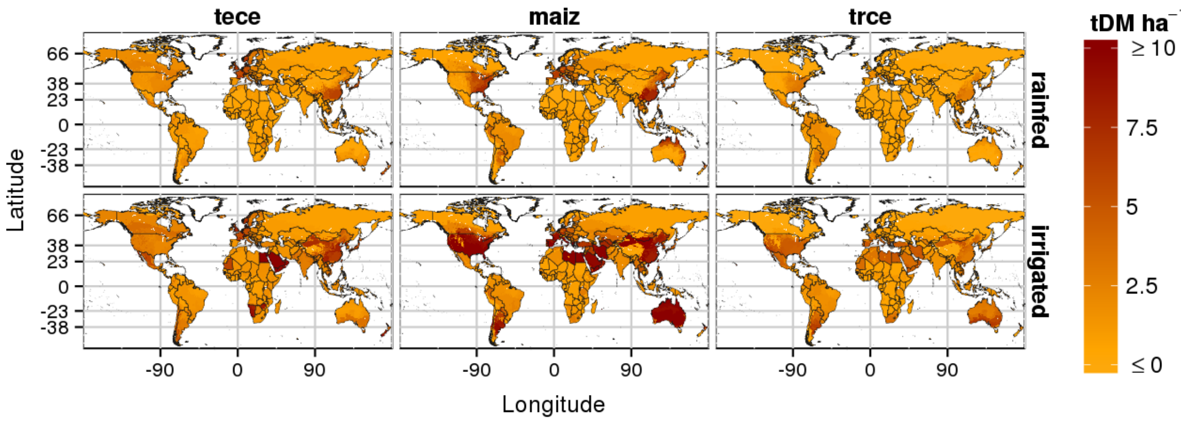

Figure S7: Spatially explicit rainfed and irrigated crop yields (tDM ha^{-1}) for the three crop types temperate cereals, maize and tropical cereals (tece, maiz and trce) derived from LPJmL.

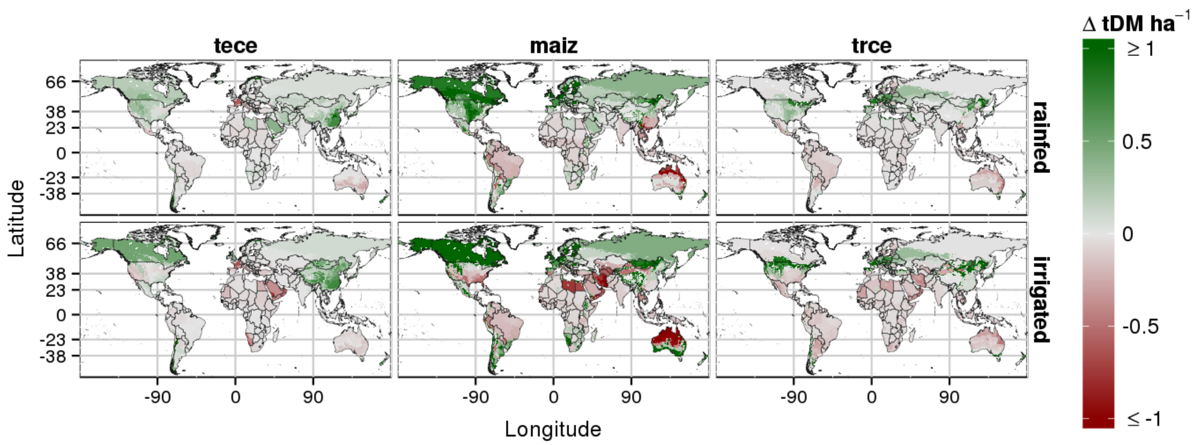

Figure S8: Spatially explicit change in crop yields (tDM ha^{-1}) between 1995 and 2100 for RCP2.6 climate projections derived by LPJmL (see Figure S7 for initial crop yields and abbreviations). This plot shows average values over the five GCM-specific RCP2.6 climate projections used in this study.

2.6. Harmonization of biophysical input data

LPJmL translates RCP2.6 climate projections from five different GCMs (HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2M and NorESM1-M)[31] into spatio-temporal changes in crop yields and carbon densities. The climate projections, as supplied by the GCMs, differ for the historic period so that simulated crop yields and carbon densities for the reference period differ between the GCMs-specific climate projections. To facilitate comparison of outcomes, the results of the five GCM-specific biophysical climate impact simulations of the RCP2.6 climate projections have been harmonized for the initial MAgPIE time step. Yield harmonization is achieved by defining a reference GCM (HadGEM2-ES) and multiplication of the relative changes (all time steps divided by initial time step) of all other GCMs with this reference. This method preserves the relative differences and assures that the input data is identical for the initial time step. For carbon densities, this approach leads to a distortion of the temporal dynamics compared to the original data. Therefore, GCM specific differences with respect to 1995 have been added to the 1995 reference value. Resulting negative values are set to 0 and values that exceed the maximum carbon density in the original data have been cut off.

3. Detailed MAgPIE results

3.1. Agricultural yields

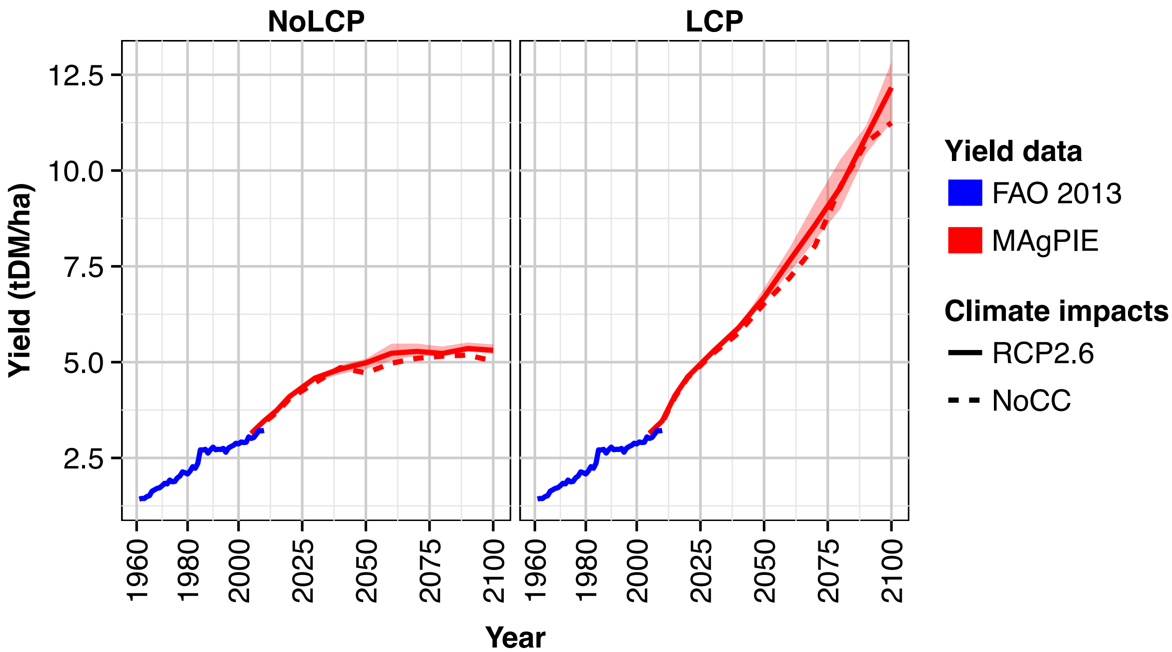

Figure S9: Time-series of global average food and feed crops yields (t DM ha^{-1}). The blue line shows historical data on agricultural yields taken from the FAO[19]. The red color depicts simulated agricultural yields from MAgPIE. For the MAgPIE data, the combinations of climate policy (*NoLCP*, *LCP*; left vs. right panel) and climate impacts (*RCP2.6*, *NoCC*; solid vs. dashed lines) result in four scenarios. Hereby, solid lines represent the average over individual model results for five GCM-specific RCP2.6 climate projections, while shaded areas indicate the full range of results.

3.2. Land-use dynamics

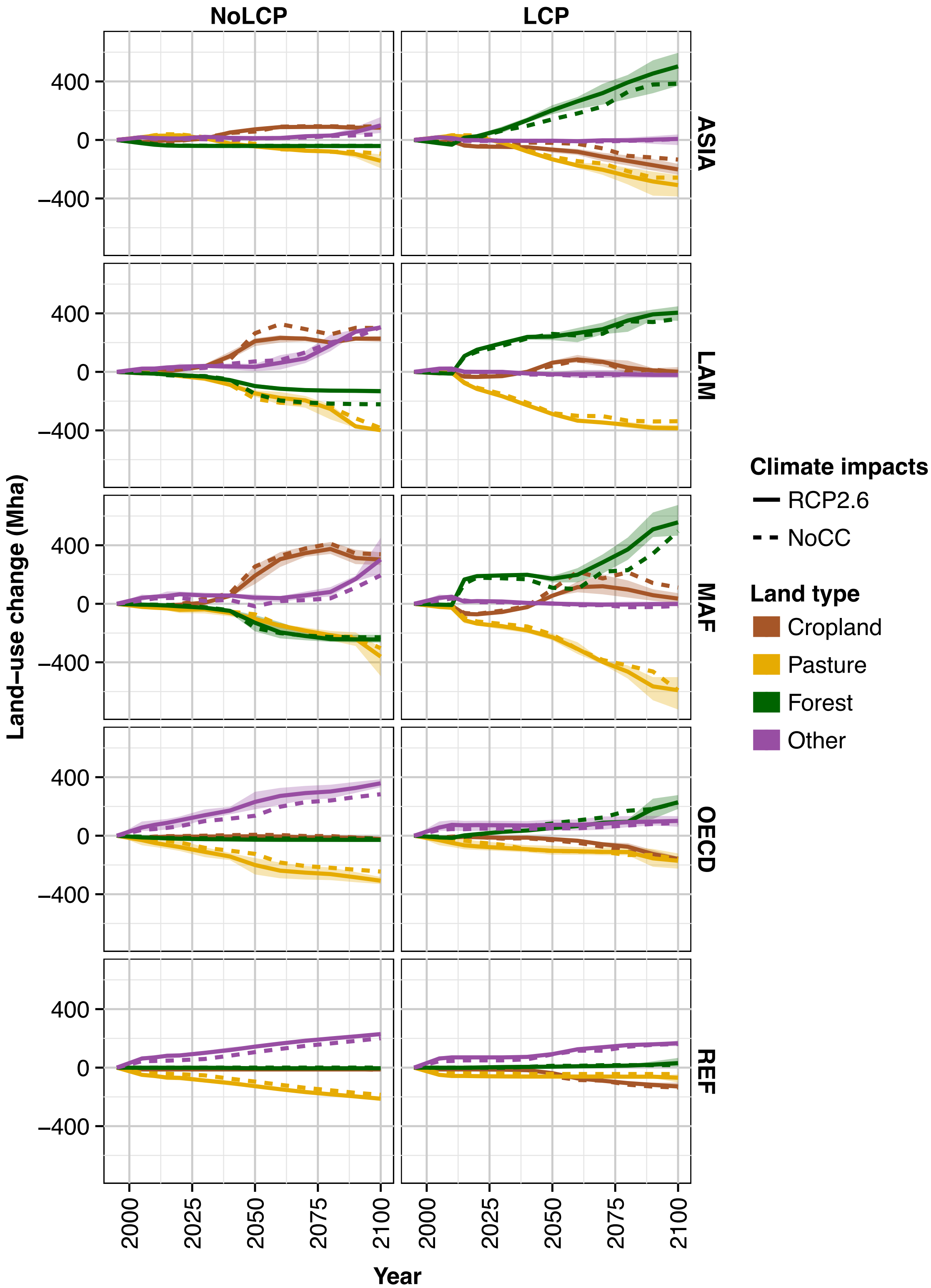

Figure S10: Time-series of regional land-use change (Mha) for four major land types between 1995 and 2100. The combinations of climate policy (*NoLCP*, *LCP*; left vs. right panel) and climate impacts (*RCP2.6*, *NoCC*; solid vs. dashed lines) result in four scenarios. Solid lines represent the average over individual model results for five GCM-specific RCP2.6 climate projections, while shaded areas indicate the full range of results.

3.3. Carbon stock dynamics

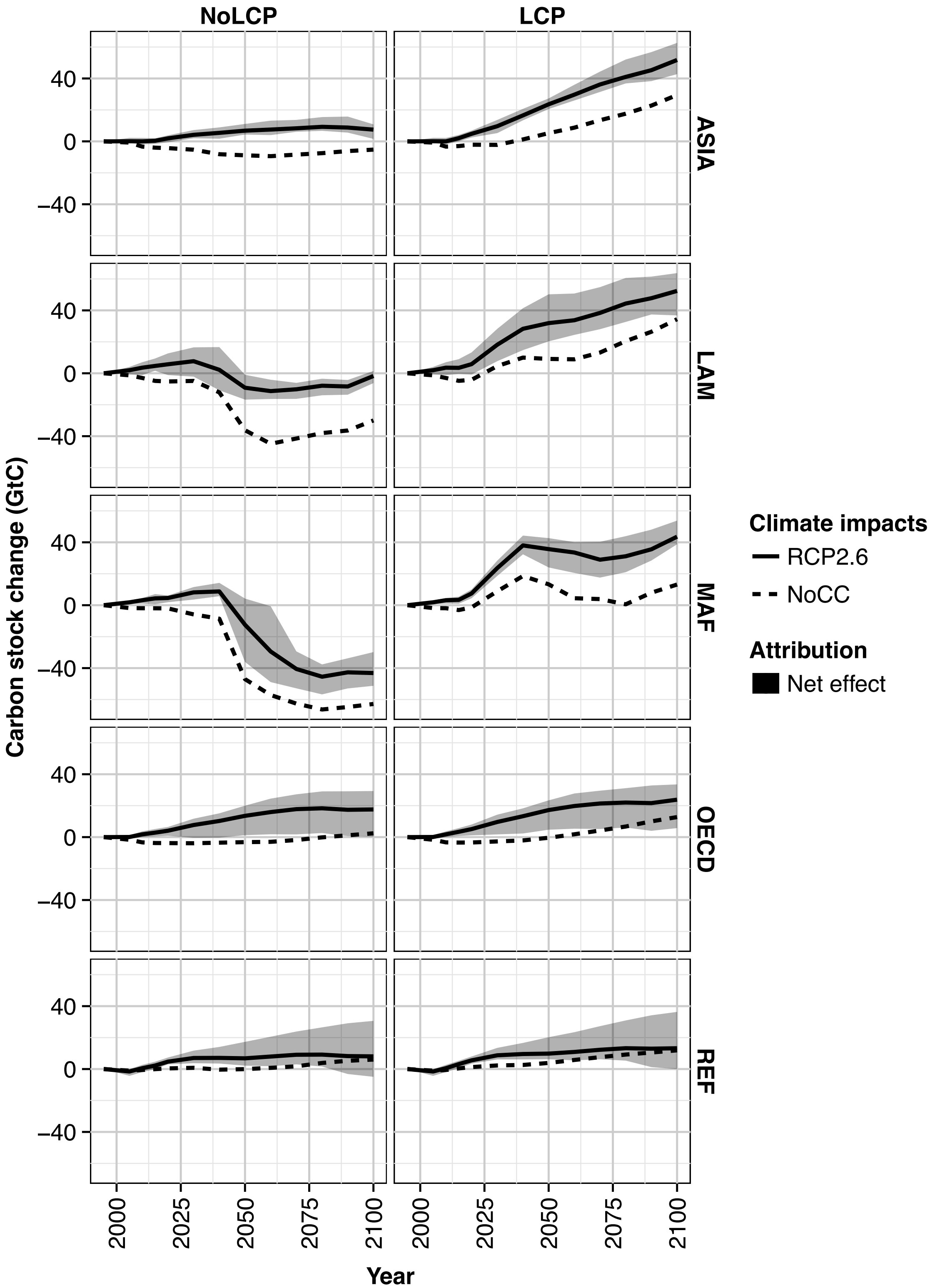

Figure S11: Time-series of regional terrestrial carbon stock change (GtC) between 1995 and 2100. The combinations of climate policy (*NoLCP*, *LCP*; left vs. right panel) and climate impacts (*RCP2.6*, *NoCC*; solid vs. dashed lines) result in four scenarios. Solid lines represent the average over individual model results for five GCM-specific RCP2.6 climate projections, while shaded areas indicate the full range of results.

3.4.   Validation

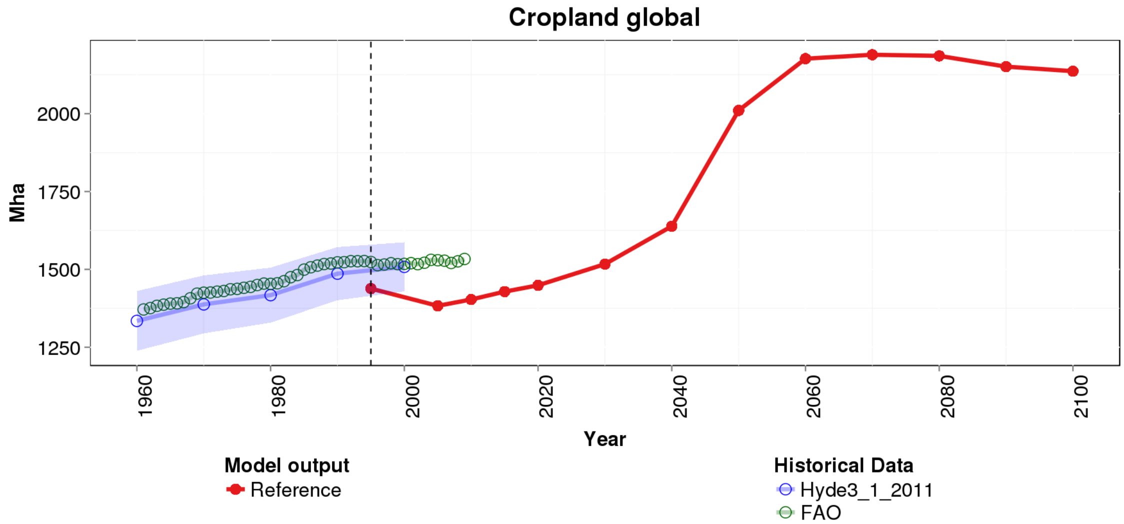

Figure S12: Time-series of simulated global cropland for the reference scenario, and historical data from HYDE 3.1[32] and FAO[19].

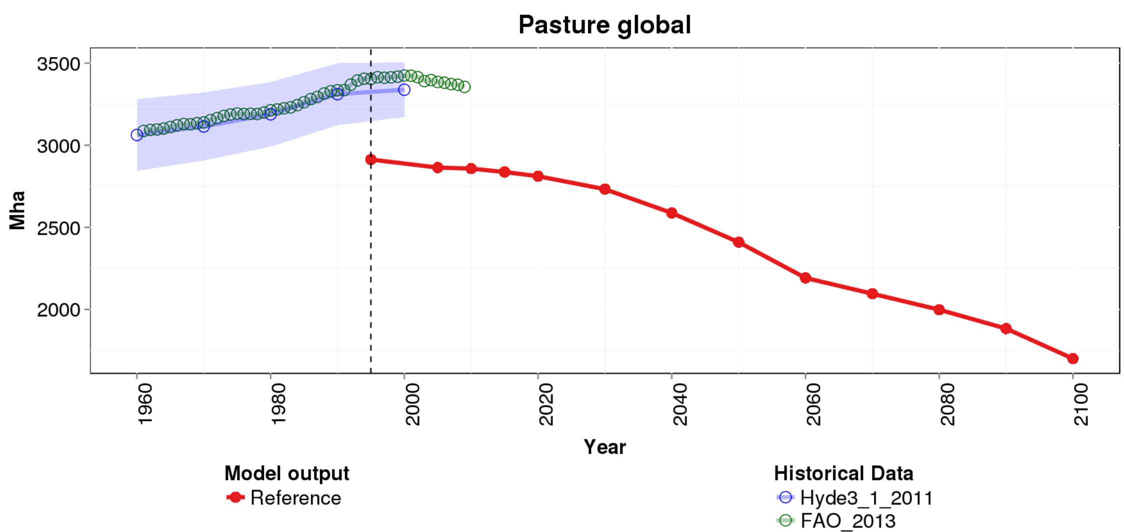

Figure S13: Time-series of simulated global pasture land for the reference scenario, and historical data from HYDE 3.1[32] and FAO[19].

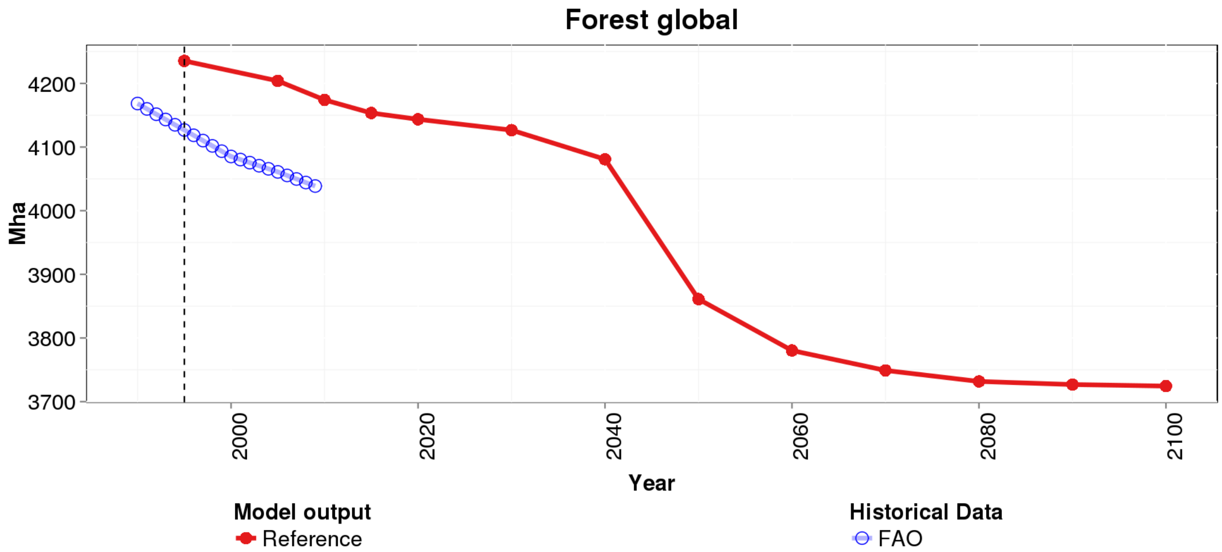

Figure S14: Time-series of simulated global forest land for the reference scenario, and historical data from FAO[19]

Figure S15: Time-series of simulated global land-use change emissions for the reference scenario, and historical data from Houghton *et al*[33], Friedlingstein *et al*[34] and Canadell *et al*[35].

3.5. GCM-specific results

		NoLCP				LCP			
		Cropland	**Pasture**	**Forest**	**Other**	**Cropland**	**Pasture**	**Forest**	**Other**
RCP2.6	HadGEM2_ES	601	-1442	-475	1316	-486	-1638	1914	210
	IPSL_CM5A_LR	547	-1412	-430	1295	-413	-1387	1461	339
	MIROC_ESM_CHEM	572	-1516	-445	1389	-431	-1762	1944	249
	GFDL_ESM2M	599	-1329	-442	1172	-505	-1483	1708	280
	NorESM1_M	576	-1416	-455	1295	-426	-1351	1593	184
	Mean	579	-1423	-449	1293	-452	-1524	1724	253
NoCC	Static climate	698	-1212	-511	1025	-319	-1390	1489	220

Table S3: GCM-specific land-use change (Mha) for four land types between 1995 and 2100. The combinations of climate policy (*NoLCP*, *LCP*; horizontal axis) and climate impacts (*RCP2.6*, *NoCC*; vertical axis) result in four scenarios.

		NoLCP			LCP		
		Net effect	**Land management**	**Direct climate change**	**Net effect**	**Land management**	**Direct climate change**
RCP2.6	HadGEM2_ES	-38	-73	34	161	125	37
	IPSL_CM5A_LR	-20	-67	47	161	114	47
	MIROC_ESM_CHEM	-30	-77	46	170	120	50
	GFDL_ESM2M	18	-74	92	224	129	95
	NorESM1_M	12	-77	89	207	110	97
	Mean	-12	-73	62	185	119	65
NoCC	Static climate	-90	-90	0	101	101	0

Table S4: GCM-specific carbon stock change (GtC) between 1995 and 2100 at the global scale. The combinations of climate policy (*NoLCP*, *LCP*; horizontal axis) and climate impacts (*RCP2.6*, *NoCC*; vertical axis) result in four scenarios. *Land management* reflects carbon stock changes associated with the land-use dynamics shown in Table S3 and includes indirect effects of climate change on carbon stocks through land-use responses. *Direct climate change* reflects carbon stock changes due to direct impacts of climate change on carbon sequestration in the terrestrial biosphere. The *net effect* on carbon stocks is represented by the sum of *land management* and *direct climate change*.

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