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Key Points:
- We isolate effects of land use changes and fossil-fuel emissions in RCPs
- Climate and CO_2 feedbacks strongly affect mitigation potential of reforestation
- Adaptation to mean temperature changes is still needed, but extremes might be reduced

Supporting Information:
- Supporting Information S1

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Reforestation in a high-CO_2 world—Higher mitigation potential than expected, lower adaptation potential than hoped for

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Abstract We assess the potential and possible consequences for the global climate of a strong reforestation scenario for this century. We perform model experiments using the Max Planck Institute Earth System Model (MPI-ESM), forced by fossil-fuel CO_2 emissions according to the high-emission scenario Representative Concentration Pathway (RCP) 8.5, but using land use transitions according to RCP4.5, which assumes strong reforestation. Thereby, we isolate the land use change effects of the RCPs from those of other anthropogenic forcings. We find that by 2100 atmospheric CO_2 is reduced by 85 ppm in the reforestation model experiment compared to the reference RCP8.5 model experiment. This reduction is higher than previous estimates and is due to increased forest cover in combination with climate and CO_2 feedbacks. We find that reforestation leads to global annual mean temperatures being lower by 0.27 K in 2100. We find large annual mean warming reductions in sparsely populated areas, whereas reductions in temperature extremes are also large in densely populated areas.

1. Introduction

As future efforts to reduce CO_2 emissions might not be enough to prevent substantial climate change, several large-scale technological measures to reduce its risks have been proposed [*Vaughan and Lenton*, 2011]. One group of these so-called geoengineering or climate engineering methods aims at reducing the amount of absorbed solar radiation (also known as solar radiation management, SRM), while another group focuses on the reduction of atmospheric CO_2 concentration (carbon dioxide removal, CDR). Important factors influencing atmospheric CO_2 concentration are the terrestrial sources and sinks. Besides fossil-fuel burning, also, land use changes strongly affect the exchange of carbon between atmosphere and land [*Le Quéré et al.*, 2013]. Therefore, increasing the terrestrial carbon sinks by extending the world's forest cover has been frequently suggested as a tool to mitigate climate change, even more so as associated risks for the Earth system are deemed low as compared to climate engineering methods such as SRM [*R. Soc.*, 2009]. However, impacts of land use and land cover change on climate are still incompletely understood—and thus will be addressed in a coordinated effort by the Land Use Intercomparison Project (LUMIP) [*Lawrence et al.*, 2016]—and the net global effect of a drastic extension of forest cover is still highly uncertain.

Earlier studies have estimated that the carbon sequestration potential for the maximum feasible afforestation (the establishment of forest on land where there was no forest recently) and reforestation (the reestablishment of forest) over the period of 1995 to 2050 amounts to 60–87 GtC [*Brown et al.*, 1996], which would correspond to a reduction in atmospheric CO_2 by about 15–30 ppm [*House et al.*, 2002]. These numbers were first-order approximations under baseline conditions of today's climate and thus ignore effects of future climate change on forest growth. Additionally, estimates of only the carbon sequestration potential do not reveal the effects that afforestation and reforestation can have on climate via biogeophysical pathways, which may enhance or weaken the potential to reduce the global warming signal in particular at the local scale. In both these aspects, our study goes beyond these early estimates: We assess the potential for CO_2 removal from the atmosphere and the consequences for the global climate of a strong reforestation scenario that is based on the land use changes according to the Representative Concentration Pathway (RCP) 4.5 [*Thomson et al.*, 2011] in a high-CO_2 world, taking into account both biogeochemical and biogeophysical effects. Previous Earth System Model studies on land use changes in the different RCPs assessed the pure biogeophysical effects of different land use scenarios [*Jones et al.*, 2013] or the climate change signal induced by land use changes compared to a case with

Table 1. Overview of the Model Experiments Used in This Study[a]

Experiment Name	Model Setup	Forcing	Land Use Transitions	Wood Harvest Rates
REF	coupled ESM	RCP8.5 fossil fuel emissions	RCP8.5	RCP8.5
FOR	coupled ESM	RCP8.5 fossil fuel emissions	RCP4.5	RCP4.5
FORPRES	land carbon and land cover only	present-day climate and CO_2	RCP4.5	RCP4.5
FORREF	land carbon and land cover only	climate and CO_2 from REF	RCP4.5	RCP4.5
FORWH	land carbon and land cover only	climate and CO_2 from FOR	RCP4.5	RCP8.5
HIST	coupled ESM	historical fossil fuel emissions	historical	historical

[a] The present-day climate and CO_2 forcing is a composite of the experiments HIST and FOR. Details are given in the text.

no land use changes [*Brovkin et al.*, 2013; *Boysen et al.*, 2014; *Davies-Barnard et al.*, 2014]. We isolate the land use change effects from those of other anthropogenic forcings due to greenhouse gas or aerosol emissions against a policy-relevant baseline scenario for land use change including the feedbacks via changes in atmospheric CO_2. We do so by using CO_2 emissions due to fossil-fuel burning and cement production according to the high-emission scenario RCP8.5, but land use transitions according to the strong-reforestation scenario RCP4.5 and compare this mixed RCP scenario with the standard RCP8.5 scenario. Thereby, we can assess the impact of the reforestation assumed in RCP4.5 on the mean climate as well as on climate extremes in a consistent way taking into account both the effects of increased forest cover on the climate and CO_2 levels and the feedbacks of changing climate and CO_2 on the natural vegetation.

2. Model Setups

For the reforestation model experiment (“FOR”) we use the Max Planck Institute Earth System Model (MPI-ESM) in the low-resolution (LR) configuration, using a T63 (1.9°) horizontal resolution and 47 hybrid sigma-pressure levels for the atmosphere and a bipolar grid with 1.5° resolution (near the equator) and 40 *z*-levels for the ocean [*Giorgetta et al.*, 2013]. More specifically, we use the same model configuration as for the Coupled Model Intercomparison Project Phase 5 (CMIP5) experiment *esmrcp85* [*Reick et al.*, 2012a], which serves as a reference experiment and which we refer to as “REF” here. Both experiments FOR and REF are driven by CO_2 emissions due to fossil fuel burning and cement production, while atmospheric CO_2 concentrations are calculated prognostically, as opposed to the more widely used CMIP5 experimental setups in which atmospheric CO_2 concentrations are prescribed. Both experiments are initialized from the end of the historical CMIP5 experiment *esmHistorical* (“HIST”) [*Reick et al.*, 2012b] at the beginning of the year 2006 and are run until the year 2100. Both experiments also use the same boundary data for Earth orbit parameters and solar irradiance, as well as for atmospheric concentrations of CH_4, N_2O, CFCs, ozone, and aerosols according to the RCP8.5 [*Riahi et al.*, 2011].

Since we are interested in isolating land use change effects, the two model experiments only differ in the land use transitions and wood harvest rates, which are taken from RCP8.5 in experiment REF but from RCP4.5 in experiment FOR. In both experiments, we use the land use harmonization data set according to *Hurtt et al.* [2011], where transitions between different land use types are described. In MPI-ESM, the transitions between crops, pasture, and natural vegetation types as well as the distribution of natural vegetation among different plant functional types are simulated as described by *Reick et al.* [2013]. Since the model includes an interactive carbon cycle, CO_2 emissions due to land use changes are calculated prognostically.

For further isolation of land use changes we perform three additional model experiments with the submodel of MPI-ESM for the terrestrial carbon cycle and land cover change in a stand-alone setup. (See Table 1 for an overview of all model experiments used in this study.) By the nature of these uncoupled setups the feedback from land to atmosphere is missing so that by comparison with the fully coupled experiments we can estimate the contribution from the missing feedbacks. For all three of the uncoupled experiments we use land use changes according to RCP4.5. With the help of experiment “FORPRES” we estimate the effect of the different climate and CO_2 levels at the end of the century compared to present day on the carbon sequestration potential of reforestation. Hence, we use forcing data describing present-day climate and CO_2 levels for this experiment. These forcing data are derived from a detrended repeated cycle of model output composed of the years 1990–2005 of experiment HIST and the years 2006–2020 of experiment FOR. Experiment FORREF aims at quantifying potential climate and CO_2 feedbacks on the carbon sequestration potential due

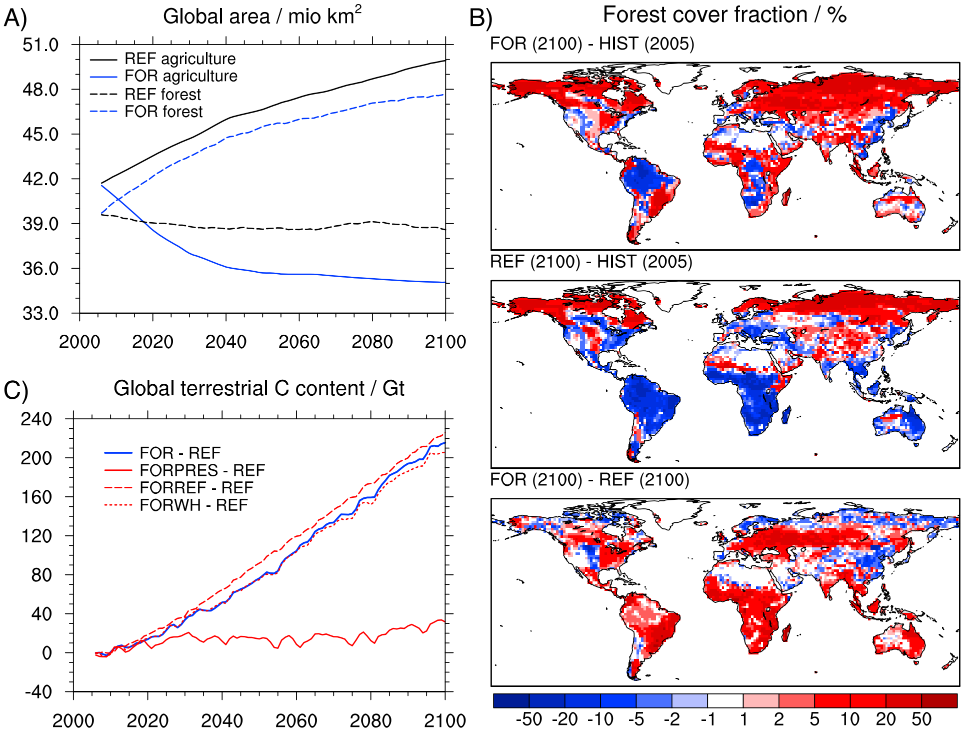

Figure 1. (a) Global annual mean agricultural (crops + pastures) and forest areas for the years 2006 to 2100 in experiments REF and FOR. (b) Differences in annual mean forest cover fractions between experiment FOR in the year 2100 and HIST in 2005, between REF in 2100 and HIST in 2005, and between FOR and REF in the year 2100. (c) Differences in global annual mean terrestrial carbon contents of experiments FOR, FORPRES, FORREF, and FORWH, to experiment REF, respectively.

to the different climates and CO_2 levels in experiments FOR and REF and uses forcing from model output of experiment REF. To quantify the contribution of different wood harvest rates in the different RCPs, experiment “FORWH” uses forcing from output of experiment FOR, land use transitions from RCP4.5, but wood harvest rates from RCP8.5.

3. Large CO_2 Removal Potential of Increase in Global Forest Area Under High Emission Scenario

The land use changes in the scenario RCP4.5 describe large-scale reforestation of formerly agricultural areas, whereas RCP8.5 assumes no mitigation or climate engineering options resulting in a strong global warming. Global agricultural area (cropland and pastures) declines by about 7 million km^2 in RCP4.5, while it increases by about 8 million km^2 in RCP8.5 in the course of the 21st century, with the largest part of the changes occurring already by 2050 (Figure 1a). These changes in agricultural area are accompanied by an increase in forested area in RCP4.5 and a decrease in RCP8.5. The actual extent of forested area in the model experiments is calculated prognostically. In the experiment REF global forest area decreases by about 1 million km^2, with much of the land use-induced deforestation compensated by climate-induced forest expansion on the global scale, while in experiment FOR it increases by about 8 million km^2 over the 21st century (Figures 1a and 1b).

The increase in global forest cover leads to an increase of 215 Gt in terrestrial carbon content (Figure 1c) and to a decrease of about 85 ppm in atmospheric CO_2 concentration by the year 2100 in the experiment FOR compared to experiment REF (Figure 2a). A minor fraction of the carbon is taken up by soils and litter pools, but the larger fraction (165 GtC of the increase by the year 2100) is stored in the vegetation pool.

The reduction of 85 ppm in atmospheric CO_2 concentration by the year 2100 as simulated in our experiments is higher than previous estimates of the CO_2 removal potential by reforestation. *House et al.* [2002] estimate a reduction of 40–70 ppm by the end of the century for the extreme scenario that all historical CO_2 land use change emissions could be reverted and a reduction of about 15–30 ppm by the end of the century for the

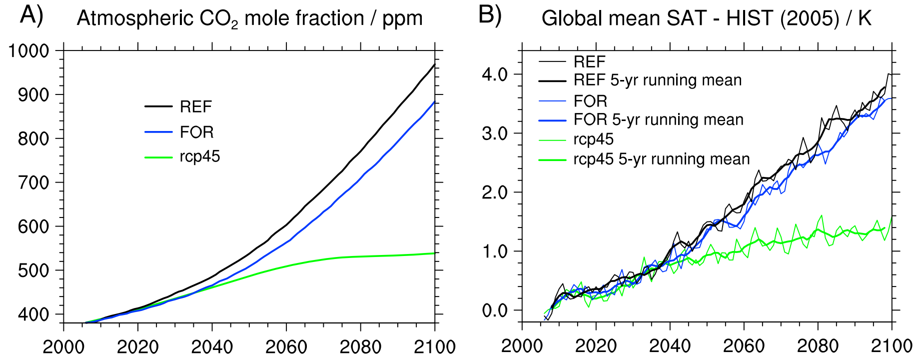

Figure 2. (a) Global annual mean atmospheric CO_2 concentrations and (b) surface air temperature (SAT) differences to the 2005 value of experiment HIST in the reforestation experiment FOR (forced by RCP8.5 fossil-fuel CO_2 emissions and RCP4.5 land use) and the reference experiment REF (forced by RCP8.5 fossil-fuel CO_2 emissions and RCP8.5 land use) for the years 2006 to 2100. The CMIP5 experiment *rcp45* [*Giorgetta et al.*, 2012] is shown for comparison.

maximum feasible afforestation and reforestation. A major difference of our setup to previous estimates is that we include the feedbacks via changing climate and CO_2 on the terrestrial biosphere in the model. For our model experiment FORPRES that does not take into account these feedbacks the carbon sequestration potential is weaker by 185 Gt compared to the experiment FOR by the end of the century (Figure 1c), indicating the large effect of changing climate and CO_2 on the carbon sequestration potential. An additional difference complicating comparability of our approach to earlier ones is the fact that our baseline scenario RCP8.5 includes deforestation and natural expansion of forests, whereas other studies compare to a reference with constant land cover conditions.

4. Regional Biogeophysical Effects Dominated by Global Cooling CO_2 Signal

The lower atmospheric CO_2 concentration and the altered land cover in experiment FOR lead to changes in temperature due to partially counteracting effects. While the biogeochemical effect of the reforestation leads to atmospheric CO_2 reduction and thus to a cooling, the biogeophysical effects can be a cooling or a warming. Since evapotranspiration is usually higher in forested compared to nonforested areas, increased forest cover can lead to a cooling; on the other hand, the surface albedo is usually lower in forested compared to nonforested areas, which can lead to a warming due to increased forest cover [*Claussen et al.*, 2001]. While the cooling due to increased evapotranspiration primarily plays a role in tropical areas, the warming due to surface albedo decrease is particularly important in boreal areas [*Bonan et al.*, 1992]. Whether the net global effect of afforestation and reforestation is a warming or a cooling has been under debate. Previous idealized large-scale afforestation studies suggested that the albedo warming dominates over the CO_2 cooling in boreal regions [*Bonan et al.*, 1992; *Claussen et al.*, 2001; *Sitch et al.*, 2005; *Bathiany et al.*, 2010]. However, for historical land use changes, *Pongratz et al.* [2010] found that the warming due to land use change CO_2 emissions is stronger than the cooling caused by biogeophysical effects. Also, *Pongratz et al.* [2011] concluded that past land use decisions were biased toward stronger CO_2 effects and weaker biogeophysical effects, since more productive and little-snow regions were preferentially picked for agriculture. This suggests that a reversal of past deforestation should have a net global cooling effect. Despite large interannual variability, in our model experiment FOR the simulated global annual mean surface air temperature is generally lower compared to REF with a cooling of 0.27 K averaged over the years 2081 to 2100 (significant at the 5% level according to a Student's *t* test modified to account for temporal autocorrelation [*von Storch and Zwiers*, 1999], Figure 2b). Thus, our study supports the mentioned conclusion by *Pongratz et al.* [2011] for a scenario of reforesting previously cleared land for agricultural use as described by the RCP4.5 scenario.

5. Limited Potential of Reforestation to Alleviate Adaptation Needs

The simulated mitigation of climate change by lowering atmospheric CO_2 levels suggests that reforestation is not just a mitigation tool but could also reduce the need for adaptation of society, which depends on the amount of warming and associated impacts on natural and human systems [*Intergovernmental Panel on Climate Change (IPCC)*, 2014]. The annual mean warming signals in experiments FOR and REF compared to HIST show similar spatial patterns with the strongest warming over the Arctic and stronger warming over

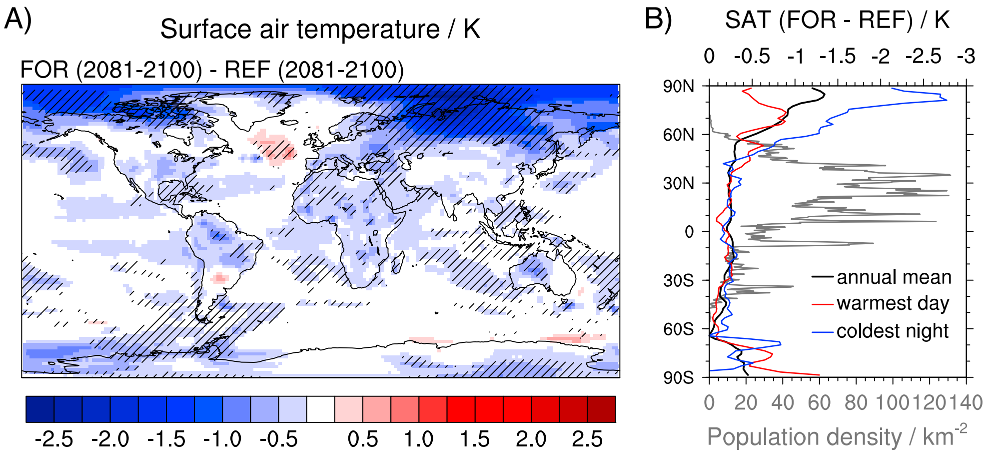

Figure 3. (a) Global multiannual (2081 to 2100) mean surface air temperature difference between experiments FOR and REF. Hatched areas indicate a significance at the 5% level, which was calculated using a Student's *t* test modified to account for temporal autocorrelation [*von Storch and Zwiers*, 1999]. (b) Zonal means of Figure 3a, of the multiannual (2081 – 2100) mean surface air temperature (SAT) differences on the warmest day and the coldest night of a year between experiments FOR and REF and of the population density for 2005 according to the HYDE 3.1 database [*Klein Goldewijk et al.*, 2011].

land than over ocean (Figure S1 in the supporting information). Yet the warming signal is less pronounced in experiment FOR than in REF in many regions of the world with the strongest warming reduction over the Arctic (Figure 3a). Moreover, we find strong warming reductions by up to 2 K due to reforestation mostly in sparsely populated areas of the world, whereas in densely populated areas the warming reduction by reforestation is small (Figure 3b). These findings suggest that under this reforestation scenario adaptation is still needed in large parts of the world.

Since forests have been shown to affect extreme heat in both observational [*Teuling et al.*, 2010] and model [*Christidis et al.*, 2013] studies, we also analyzed the effect of reforestation on temperature extremes in our model experiments. The temperature difference between experiments FOR and REF is larger for the coldest night (CN) of a year than for the warmest day (WD) in high latitudes (Figure 3b), with a similar spatial pattern for CN as for the annual mean (Figures 3a and S2 and S3 in the supporting information). Interestingly, in the midnorthern latitudes the temperature difference for WD is larger than for the annual mean with a significant signal for WD over parts of Europe which we do not find for the annual mean (Figure S4 in the supporting information). This suggests a potential for a reduction in extremely warm days due to reforestation in this region. As warm extremes can be related to negative effects on human well-being by impacts, e.g., on crop yields, wildfire risk, and mortality by heat stress [*IPCC*, 2014], reforestation may alleviate the need for adaptation under extreme heat on regional level.

6. Carbon Uptake Potential Dominated by Forest Area Increase and Only Slightly Reduced by Climate Feedbacks

Several factors contribute to the net land carbon uptake in experiment FOR compared to the reference experiment REF. First, by following the RCP4.5 land use transitions, agricultural land is abandoned in large regions of the world, leading to an increase in forest area and in carbon uptake in the model in the course of the 21st century. As a second-order effect of this land use change, the loss of carbon sink capacity by replacing forests with agricultural land [*Gitz and Ciais*, 2003; *Pongratz et al.*, 2009] is reversed, leading to an additional sink for atmospheric carbon. Second, in RCP8.5 larger areas are deforested compared to RCP4.5, also leading to more forest area and higher carbon uptake in experiment FOR compared to REF. A third factor positively contributing to the carbon uptake is the wood harvest, which is lower in RCP4.5 than in RCP8.5. In our model, harvested material is generally decomposed faster than when it remained part of the living vegetation, because part of the harvested material is directly released to the atmosphere and the rest is transferred to carbon pools with lifetimes of few years to decades.

Climate feedbacks due to these changes in the biosphere lead to weaker boreal forest expansion because of weaker warming, which leads to less forest in the high-latitude regions in the experiment FOR compared to REF and thus decreases the carbon uptake. In contrast, weaker heat stress on forests in temperate regions leads to more forest at the warm-dry forest boundary and therefore to increased carbon uptake. Another negative feedback on the carbon uptake is due to CO_2 fertilization being weaker in experiment FOR compared to REF.

Additional effects due to the combination of anthropogenic and natural land cover changes that tend to weaken the terrestrial carbon uptake in experiment FOR are not quantified here. A detailed analysis of the combined effects of land use transitions and dynamic natural vegetation changes in the MPI-ESM CMIP5 experiments can be found in *Schneck et al.* [2015].

To quantify the contribution of the net combined climate and CO_2 feedback on the land carbon uptake, we use the model experiment FORREF, where the total terrestrial carbon content is higher by about 10 Gt by the year 2100 compared to experiment FOR (Figure 1c). Thus, the combined climate and CO_2 feedback reduces the carbon uptake potential of this reforestation scenario by about 10 Gt by the year 2100 and represents only a slight reduction compared to the carbon sequestration potential of 215 Gt in experiment FOR. This high potential despite the negative feedback via weakened CO_2 fertilization of the terrestrial vegetation indicates that this fertilization effect is weaker between the high CO_2 levels of REF and FOR at the end of the century than between present-day and the FOR levels.

The contribution of different wood harvest rates in the different scenarios can be quantified using experiment FORWH in which the carbon content on land is 10 Gt smaller by the year 2100 compared to experiment FOR (Figure 1c). This means that the wood harvest rates being lower in RCP4.5 than in RCP8.5 lead to an additional carbon uptake of about 10 Gt by the year 2100 and therefore are a small contribution to the net carbon uptake in experiment FOR.

To further quantify the contributions to the carbon uptake in experiment FOR compared to experiment REF, we split the difference in forest carbon content between the two experiments into contributions from changes in forest area only, from changes in carbon density only, and from changes in both area and carbon density. Since we find that the contributions involving changes in forest area are larger than the contribution from changes in carbon density (Figure S5 in the supporting information), we conclude that the carbon uptake potential of the reforestation scenario is dominated by the forest area increase.

A factor that is not accounted for in the present study is the possible limitation of terrestrial primary productivity due to nutrient availability, which is not implemented explicitly in the version of MPI-ESM used here. This factor could decrease the CO_2 fertilization effect [*Hungate et al.*, 2003] and thus also the CO_2 reduction potential of our reforestation scenario. *Goll et al.* [2012] found a reduction of accumulated land C uptake between 1860 and 2100 of up to 25% when N and P limitation are accounted for in the model. However, the model setup, land use, and CO_2 emission scenarios all affect the magnitude of the limitation effect and are different in our study than in *Goll et al.* [2012].

Our analysis suggests that the effect of larger forest area in experiment FOR using RCP4.5 land use compared to experiment REF using RCP8.5 land use is large compared to the potentially counteracting feedbacks of climate and CO_2 changes induced by the reforestation and compared to the different wood harvest rates.

7. Conclusion

Based on our model study we conclude that the mitigation potential of the RCP4.5 land use, which is a large-scale yet plausible reforestation scenario, has been underestimated previously. Our results suggest that when following this scenario without reducing fossil-fuel burning below unmitigated amounts, adaptation to global warming in large regions of the world will still be needed. Yet the results also suggest that the reduction of temperature extremes can reduce the need for adaptation in some regions, which indicates that it is important to look at climate extremes when it comes to an assessment of different climate engineering options, even more so for land-based methods that act directly locally or regionally, as opposed to global methods such as SRM.

The carbon sequestration potential of this reforestation scenario is due to the combined effect of land use changes and enhanced carbon uptake of the terrestrial biosphere in a warm and high-CO_2 climate.

In particular, increased forest cover due to reforestation and avoided deforestation provides additional CO_2 sinks and is responsible for the strong carbon uptake rather than increased productivity due to future high CO_2 levels.

Our study highlights that the potential of reforestation as a climate engineering tool strongly depends on the background climate and CO_2 levels. As climate engineering by land use changes due to its overall small mitigation potential as compared to, e.g., solar radiation management is often just seen as one method in a larger portfolio, this context is important to consider.

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