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Title: Simulating sustained yield harvesting adaptive to future climate change

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Abstract

Forests are the main source of biomass production from solar energy and take up globally around 2.4 ± 0.4 PgC per year. Future changes in climate may affect forest growth and productivity. Currently, state-of-the-art Earth system models use prescribed wood harvest rates in future climate projections. These rates are defined by integrated assessment models (IAMs) only accounting for regional wood demand and largely ignoring the supply side from forests. Therefore, we apply the concept of "sustained yield" (SY) to represent a climate-adaptive forest management allowing a wood harvest rate oriented towards the actual rate of forest growth. Applying SY in "JSBACH", the land component of the Max-Planck-Institute's Earth System Model, forced by several future climate scenarios, we realized a wood harvest amount twice to four times (3-9 $PgCy^{-1}$) the rates prescribed by IAMs (1-3 $PgCy^{-1}$). This highlights the need to account for the dependence of forest growth on climate. A life cycle analysis showed that the higher supply with SY as an adaptive forest harvesting rule may improve the net mitigation effects of forest harvest during the 21st century by sequestering carbon in anthropogenic wood products (max. 379 PgC).

Keywords: Adaptation to climate change, Mitigation, Mortality, Carbon forestry, stainable forest management, Global forest model, Forest risks

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1. Introduction

Forest ecosystems play a major role in taking up global CO_2 emissions and affect global climate conditions through a range of complex biophysical and biogeochemical processes. Forests are the main source of biomass production from solar energy through photosynthesis and are estimated to take up globally around 2.4 ± 0.4 $PgCy^{-1}$ (Pan et al., 2011) . A large part of this uptake can be attributed to direct and indirect human interference: Direct human impact by forest management creates young forests sequestering carbon during regrowth (Houghton et al., 2012), and provides material for fossil-fuel substitution (Nabuurs et al., 2007). However, forest utilization and interaction of management with large-scale natural disturbances, such as forest fires, may emit tonnes of CO_2 immediately to the atmosphere and act as a source of CO_2 emissions (Bonan, 2008). Indirect human impact alters environmental conditions, in particular climate and atmospheric CO_2 concentrations, which historically has caused a carbon uptake by the terrestrial vegetation (Le Quere et al., 2015). Any change in environmental conditions affects forest growth, risks of hazards, and productivity and, consequently, the amount of wood that can be harvested (Temperli et al., 2012; Sohngen and Tian, 2016).

The effects of changes in environmental conditions on the state of the biosphere are represented in state-of-the-art Earth system models (ESMs). However, the description of forest management in these models is largely independent of environmental changes: So far, ESMs employ prescribed wood harvest amounts. These are derived from national statistics for the historical period and from global integrated assessment models (IAMs) for future scenarios. IAMs determine the wood harvest rates based on the supply of woody materials from vegetation and demands of regional industries and population (van Vuuren et al., 2011). However, forest growth and structural conditions especially under climate change, and increasing CO_2 concentrations are ignored. The main drivers of these models are economic, i.e. market price, and population growth scenarios and forest harvest decisions are only reactive to the assumed socioeconomic scenarios and do not take forest ecosystem dynamics and growth into account.

In this study we investigate the relevance of allowing wood harvest decisions to respond to changes in environmental conditions. Moreover, we explore the ecological potential of world forest resources for wood production and the implications for carbon mitigation. For this we apply the concept of "sustained yield" (SY) to illustrate the consequences of representing adaptive forest management in ESMs and compare the results with wood harvest prescribed from IAMs. SY is a strong sustainability policy applied in sustainable forest management, which aims to maintain forest stocks as natural capital and controls wood extraction (Luckert and Williamson, 2005). According to SY, the maximum wood harvest rate to utilize forest resources equals the actual rate of forest growth. Exceeding regrowth rates would result in the exploitation of forest ecosystems and would decrease forest yield and productivity. On the other hand, minimalistic usage, i.e. falling below regrowth rates, would not be an optimal allocation of forest resources from the perspective of production. Forest growth rates are highly dependent on the environmental conditions, especially climate and CO_2 concentrations, which are projected to be substantially altered as compared to the conditions observed in the past for future climate scenarios (Collins et al. 2013). Therefore, any decision about forest management should take into account the effects of changes in climate and CO_2 concentrations on forest growth (Sohngen et al., 2016; Yousefpour et al., 2012; Hickler et al., 2015; Sohngen and Tian, 2016) and consequently on the harvest rate (Temperli et al., 2012)(Jönsson et al., 2015; Temperli et al., 2012; Jönsson et al., 2015). The traditional concept of SY, as defined above, does not account for changes in the regrowth rates (Luckert und Williamson, 2005). Therefore, the concept is broadened for this study, allowing for dependence of wood harvest on altered climate conditions and CO_2 concentrations. However, we remain consistent with the aim of applying sustained yield to safeguard the current level of wood stocks in the forest.

Keeping in mind the above-mentioned problem of not accounting for changing environmental conditions in global forest utilization modelling, we aim in this paper to integrate a novel forest decision-making process. This process is based on the sustained yield harvesting rule in JSBACH, which is the land component of the Max-Planck-Institute's Earth System Model (MPI-ESM; Giorgetta et al., 2013). JSBACH is a state-of-the-art dynamic vegetation model with an integrated wood harvest module (Reick et al., 2013). The goals of this study are (1) to establish a coupled, interactive harvest-climate module based on the concept of sustained yield to account for the reaction of the forest production system to climate change and increasing CO_2 concentration in the atmosphere, and (2) to assess the maximum CO_2 mitigation potentials of global forest resources by an active and dynamic management strategy. We compare the outcome of the sustained yield modelling approach with the outcome when applying prescribed wood harvest amounts from different Representative Concentration Pathways (RCPs) realized by IAMs and commonly used by ESMs as an external forcing (Hurtt et al., 2011). We perform all simulations with JSBACH, driven by atmospheric fields derived from MPI-ESM simulations as part of the Coupled Model Intercomparison Project Phase 5 (see Methods for details). We implemented the sustained yield harvest in JSBACH such that above-ground wood carbon pools are stabilized, and defined the maximum level simulated for the present period (1996-2005) as the reference value for our study. To determine the mitigation potential by wood products we allocate the harvested material to products of different lifetimes according to FAO country-specific statistics (FAOSTAT, 2016). The change in atmospheric carbon content resulting from the release of CO_2 by the decay of these products is quantified accounting for compensating fluxes by the ocean and the terrestrial vegetation (Maier-Reimer und Hasselmann, 1987). The net mitigation effect of wood harvest is then defined as the difference between the total amount of harvested material and the change in atmospheric carbon content.

2. Materials and methods

2.1. Dynamic global vegetation model JSBACH

We implemented the sustained yield harvesting rule in JSBACH, the land component of the MPI-ESM (Reick et al., 2013). With this model we simulated the effect of forest management activities, i.e. wood harvest according to different harvesting rules, on the future (2006-2100) carbon balance of terrestrial ecosystems.

In the applied version of JSBACH vegetation is represented by 11 plant functional types (PFTs) including six woody PFTS. Each PFT is globally endowed with properties in relation to integrated processes in JSBACH and PFT-specific phenology, albedo, morphology, and photosynthetic parameters (Pongratz et al., 2009). Organic carbon is stored in three vegetation pools: living tissue as "green", woody material as "wood", sugar and starches as "reserve pool", and two soil pools with a fast (about 1 year) and a slow (about 100 years) turnover time (Raddatz et al., 2007). Wood harvest activities do not change the area occupied by the different PFTs, but affect the carbon pools of woody PFTs (forests and shrubs) by removing carbon from the wood pool, resembling trees' stem and branches removal via harvesting (Reick et al., 2013). Harvest thus affects the vegetation carbon stocks, but the model does not represent a feedback of the harvest activity on the forest productivity.

We applied JSBACH in 'offline' mode, i.e. not coupled to the atmosphere, but driven by the CMIP5 output of the MPI-ESM (Giorgetta et al., 2013) from experiments with CO_2 forcing according to three different RCP scenarios (RCP2.6, RCP4.5 and RCP8.5). We used a T63/1.9° horizontal resolution and conducted our simulations with disturbances due to fire and wind. The simulations were conducted without dynamic vegetation and without land-use transitions to prevent changes in the areas occupied by the different PFTs and to be thus able to isolate the effects of forest management activities. Further details on the model version and the simulation setup are given in the supplementary material (S1).

2.2.RCPs wood harvest

The current standard module for anthropogenic land cover and land-use change in JSBACH is based on the harmonized land-use protocol (Reick et al., 2013), which provides land-use scenarios for the period 1500-2100 (Hurtt et al., 2011). As part of this protocol, a set of globally gridded harvest maps from the IAM implementations of the RCPs is provided (Hurtt et al., 2011). In JSBACH simulations, the harvest prescribed in these maps is fulfilled taking above-ground carbon of all vegetation pools and all PFTs proportionally to the different pool sizes. In this paper, however, we concentrate on the carbon harvested from the wood pool of the woody PFTs, which by far contributes most of the harvested volume.

2.3.Sustained yield (SY) harvesting rule

As an alternative for the prescribed harvest maps, we implemented the SY harvesting rule, which allows for adaptive wood harvesting reacting to changes in wood increments, and accordingly dependent on climate and CO_2 conditions. We define the SY rule as the allowance to harvest specific volumes of wood to the extent of the average increment (i.e. the average annual growth). Applying the SY rule, we aim to stabilize the wood carbon pool in the woody PFTs at the level of a selected reference period. In the current paper we selected the maximum level for the present period (1996-2005) simulated with JSBACH (see S1). Using a reference level determined from the last ten years of the historical simulation allows us to keep the standing wood on the present level and to account for the dependence of forest growing stocks (carbon pools) to disturbances, silvicultural interventions and varying environmental conditions.

Under the SY harvesting rule, the wood harvest is only allowed to reduce the wood carbon pool down to the reference level. Aside from environmentally driven decreases, the wood carbon pool thus nearly remains constant over the whole simulation time.

2.4. Simulation runs with JSBACH

We conducted six simulations (Table 1) from 2006-2100, all starting from the same initial state (see S1). The simulations differ in the applied harvest rule and in their climate and CO_2 forcing. While the different RCP harvest maps were applied in simulations with the corresponding MPI-ESM RCP forcing, each MPI-ESM RCP forcing was additionally run applying SY harvest.

Table 1

2.5. Analysis of wood harvest impacts on forest disturbances and natural mortality

To analyze the mechanisms driving differences in SY and RCP wood harvest amounts we can formulate changes in above-ground wood carbon stocks over time (*dCw/dt*) as carbon gains from net primary production allocated to the wood pools (*NPPw*) minus losses due to natural disturbances and anthropogenic management (i.e., wood harvest, *h*):

$$\frac{dCw}{dt} = NPPw - \frac{Cw}{\tau} - h \quad (1)$$

In this conceptual formulation, the loss due to natural disturbances depends on the size of the carbon stock and a time constant (τ). As net primary production in our model does not depend on harvest, RCP and SY harvest can be related as

$$h_{SY} = h_{RCP} + \left(\frac{Cw_{RCP}}{\tau_{RCP}} - \frac{Cw_{SY}}{\tau_{SY}}\right) + \left(\frac{dCw_{RCP}}{dt} - \frac{dCw_{SY}}{dt}\right) \quad (2)$$

The amount of sustained yields can thus be split into several terms: The first term is the reference harvest rate of the RCPs. The second term accounts for the difference in loss due to natural disturbances in the RCP and the SY simulation. In JSBACH this can further be split into differences in losses due to background mortality, such as self-thinning of forests, due to fire, and due to windbreak. JSBACH explicitly integrates two modules for the simulation of fire and wind disturbances depending on climate and carbon pools. The third term accounts for the changes in the above-ground wood pool realized over time in the simulations. As shown below, the RCP harvest results in an increase of above-ground woody biomass over the 21st century for all three scenarios. For SY, on the other hand, dCw_{SY}/dt should theoretically be close to zero over time as SY aims to sustain the above-ground carbon pools of woody PFTs; however, reductions in NPP due to less favorable climatic conditions or increased disturbances can entail negative dCw_{SY}/dt. To summarize, SY includes the RCP wood harvest and, moreover, makes use of additionally accumulated carbon and eventually reduced mortalities to adapt harvest decisions to the novel climate and forest growing conditions.

2.6. Accounting for the mitigation potential of forest management in the Earth system

Many wood products have lifetimes of decades to centuries. Here, we assess the effect on atmospheric carbon content when harvested carbon is transferred, at least to a part, to longer-lived product pools, instead of entering the atmosphere immediately. We compare this "mitigation effect" achievable by the wood products harvested under the SY concept to those achievable according to the three RCP harvest maps. To this end, we distinguish three anthropogenic wood product pools -- bioenergy, paper, and construction -- with 1, 10, and 100 year life times, respectively, as are typically assumed in global modeling studies (Houghton et al., 1983; McGuire et al., 2001).

To allocate the wood biomass harvested in our JSBACH simulations to different product pools, we made use of FAO country-specific statistics reporting wood production in fourteen different categories (FAOSTAT, 2016). For our analysis, we assume that the production technology and allocated percentage of each country's total wood production to these fourteen categories remains constant at 2005 levels over the 21st century and used these percentages to allocate wood biomass harvest from JSBACH (remapped to countries - see a calculus example in supplementary material S2). The fourteen categories are then assigned to the three anthropogenic wood product pools. We assume that the harvested material entering one of the three product pools in a year decays at a rate of 1/lifetime, i.e. that all material used for bioenergy is respired to the atmosphere within the same year it is harvested, while the material entering the paper and construction pool is emitted at a constant rate over the following 10 or 100 years, respectively. The emissions at a given year for paper and construction pools are therefore composed of a fraction of that year's harvest, but also of the legacy of material harvested earlier, yielding annual emissions E from all three product pools as follows:

$$E(t) = f_b h(t) + \sum_{s=t-9}^{t} \frac{1}{10} f_p h(s) + \sum_{s=t-99}^{t} \frac{1}{100} f_c h(s) \quad (1)$$

Here, f for bioenergy (b), paper (p), and construction wood (c) are the fractions with which the harvested biomass is assigned to the product pools (see S2). We call E "emissions from product decay" in the following.

To account for the fact that the emissions from product decay leave the atmosphere over time to be taken up by the terrestrial biosphere and the ocean, we apply the response function (Eq. 2) by Maier-Reimer and Hasselmann (1987). Convolution of this response function with the time series of annual emissions from product decay until year t results in the change in atmospheric carbon content in that year, C(t) (Eq. 3).

$$G(t) = A_0 + \sum_{p=1}^{4} A_p \, exp^{-t/\tau_p} \quad (2)$$

$$C(t) = \int_0^t G(t-s) \cdot E(s) ds \quad (3)$$

Emissions are present in the atmosphere as they occur and, therefore, G(0) = 1 and $A_0 = 1 - \sum_p A_p$.The constants A_p and the time constants τ_p are fitted for $p > 0$ using one of the best fits found by Maier-Reimer und Hasselmann (1987): the sum of four exponential terms with time constants τ_1, τ_2, τ_3 and τ_4 of approximately 1.9, 17.3, 73.6, and 362.9 years, and constants a_1, a_2, a_3 and a_4 of 0.098, 0.249, 0.321, and 0.201. Accordingly, Equation 2 is an exponential function that accounts for the uptake of CO_2 by ocean and land over time and Eq. (3) integrates the accumulated amount of total CO_2 concentrations in the atmosphere at each time step regarding past and present emissions. The mitigation effect of wood products is then determined as the difference between the harvested material and the change in atmospheric carbon content.

3. Results

3.1. Comparison of sustained-yield and RCP harvest rates

Above-ground woody biomass is simulated to increase by the end of the 21st century for the RCP wood harvest (Figure 1a), despite an increase of the amounts of wood harvest (Figure 1b). This implies that the changes in environmental conditions lead to a larger accumulation of woody biomass than is removed by the increased harvest. The temporal pattern of this increase, with strong increase only in the first half of the century for RCP2.6 or throughout the century for RCP8.5 reflects the projected evolution of changes in CO_2 and climate (Collins et al., 2013). For the SY rule, woody biomass remains more or less constant over time (Figure 1a), as the average annual increment is removed by harvest by definition of the SY rule (see Methods). Consequently, the wood harvest potential of global forest resources under SY is simulated to be as high as 9 $PgCy^{-1}$ at the end of the century subject to the realization of RCP8.5 climatic conditions, or about 4 to 6 $PgCy^{-1}$ for the other two scenarios (Figure 1b). SY wood harvest amounts are thus twice to four times as high as those of prescribed wood harvest simulated by IAMs for the RCPs. Depending on RCPs, the simulated increase in above-ground woody biomass may reach 133% (425 PgC in 2100) of the initial level in 2005 (320 PgC) for RCP8.5 and substantially higher levels of 128% and 117% for RCP4.5 and RCP2.6, respectively (Figure 1b).

We map the geographical allocation of harvest potentials, applying both SY and RCPs wood harvest, to recognize the regional hotspots (Figures 2). Central Latin America including the Amazon forests, large parts of North America, central Africa, eastern Asia and Europe including Russia can be recognized in all maps as hotspots for allocation of simulated SY harvest activities. The large harvest potentials of SY in the tropics contrast with the patterns of

RCP harvest; in particular in RCP2.6 and RCP4.5 much of the global harvest is provided from eastern North America, central Europe and East Asia.

Figure 1

Figure 2

3.2.Wood harvest impacts on forest disturbances and regrowth

The realized SY harvest in JSBACH exceeds RCPs wood harvest defined by IAMs not only because of taking into account changes in growth rates caused by changed climatic conditions, but also due to avoided mortality and disturbances (see methods section). Figure 3 shows the separation of the realized SY harvest into changes in standing wood as compared to RCP harvest, avoided background mortality, natural fire, and wind disturbances, and the amount prescribed originally by RCPs. The largest contribution to the higher harvesting potential under SY is the lower background mortality, which is directly related to lower accumulation of woody biomass (see Figure 1a). This lower accumulation also leads to the decreased carbon losses from fire and wind disturbances. Depending on the climate scenario (RCPs) the simulated reduction of mortality and disturbances add up to 2-5 $PgCy^{-1}$ at the end of the century and thus to sustained yield and increase harvest potentials of over 100%, over 200%, and over 250% for RCP2.6, and RCP4.5 and RCP8.5, respectively. Under the RCP harvest, woody biomass is simulated to mostly increase beyond what is required by the increasing harvest rates (see Figure 1). Harvesting this “surplus”, i.e. the increase of standing biomass, under SY also contributes to the larger SY harvest potentials. The temporal evolution is different from that of avoided mortality and disturbances, reflecting the projected changes in CO_2 and climate. Greater fluctuation of yearly wood harvest from sustained yield comparing to the RCPs’ wood harvest amounts is because of the direct dependency to climate and accordingly fluctuation of forest growth and productivity.

Figure 3

3.3. Mitigation potential of SY versus RCP wood harvest

We show the mitigation potential of forest resources in the 21st century applying SY harvest rule versus the RCP wood harvest prescribed from IAMs in Figure 4a-f. Due to the larger harvested amounts, the mitigation potential is higher for SY compared to RCP harvest and the magnitude depends on the underlying climate scenario (RCPs). The advantage of SY lies in storing a larger amount of carbon in wood products whilst keeping above-ground woody carbon pools constant. These aspects are largely ignored by IAMs. Table 2 below shows the net mitigation potentials of world forest resources (SY against RCP harvest) by wood harvest at the middle and end of the 21st century (2050 and 2100). The highest mitigation effect is achieved in the SY8.5 scenario with 140.6 PgC and 379.1 PgC up to 2050 and 2100, respectively. These figures account for 287% and 286% more global carbon storage than in the RCP8.5 scenario with prescribed RCP wood harvest with 50.6 and 132.1 PgC mitigation up to 2050 and 2100, respectively.

Table 2

Figure 4

4. Discussion

RCPs define wood harvest in each region according to scenarios realized by IAMs about social and economic developments in the 21st century, but independent of ecological capacities of forest ecosystems. Although SY asks for a globally larger wood harvest amount than the RCPs, it remains as per definition a sustained-yield forest harvesting approach and guarantees sustainability of the current ecological conditions at each region with respect to standing biomass. However, as a consequence, regions with low standing biomass, for example due to extensive historical harvest, will maintain these low biomass levels. Below we discuss the effectivity of SY in adapting to new environmental conditions and the mitigation potential and highlight the missing issues in our simulation analysis, especially about the provisioning of multiple goods and services, and the future research themes about integration of diversified management strategies in ESMs.

Accounting for the climate state in simulating future forest harvest is crucial (Temperli et al., 2012; Sohngen and Tian, 2016) . Accordingly, the novelty of the applied SY in this study is the dynamic nature of this management approach based on the ecology of forest ecosystems and climatic and atmospheric conditions. According to Schelhaas et al. (2010), an accelerated level of wood harvest to reduce the vulnerability of European old forests to wind and fire disturbances is needed to stop the current built-up of growing stock. Applying SY in this study realized an increased wood harvest rate for European forests (see Figure 2) showing first signs of carbon sink saturation and high vulnerability to natural disturbances (Nabuurs and Maseraet, 2013). Global studies of this nature are largely missing due to the lack of data and forest ecosystems complexity on global scale. Our simulations suggest that SY does not only effectively safeguard sustainability of the current forest biomass on the global scale, but also positively affects the resistance of forest resources against natural disturbances and efficiently utilizes forest growth and productivity potentials. Our estimates are, of course, sensitive to the choice of reference level: In this study, we applied the maximum current (1996-2005) above-ground wood biomass as the reference level. Any changes in this reference may affect the realized harvest amounts and should be carefully defined regarding ecological potentials and economic implications.

In our study, future environmental changes are simulated to be beneficial for accumulation of forest biomass, as expressed by increasing standing biomass in the RCP harvest scenarios or the increase of SY harvest rates over the 21st century. This is in line with other studies projecting above-ground forest carbon storage to increase in the future (e.g. Tian et al., 2016). These effects of environmental changes on forest growth are largely missing in the IAMs providing the wood harvest scenarios to DGVMs and ESMs. The RCP wood harvest rates are based on the demand for wood and bioenergy as the main driver of decisions by IAMs on forest harvest.

For example, RCP8.5 applies the forest sector model DIMA (Riahi et al., 2011), which is a spatial model for simulating forestry processes to meet specific regional demand on wood and bioenergy. RCP4.5 bases wood harvest rates solely on the price of carbon affected by emissions and mitigation potentials of forestry and agricultural activities (Hurtt et al., 2011). Finally, RCP2.6 relies on the forecasted demand on timber and fuelwood from forest resources and applies a series of forest management rules (plantation, clear cutting, selective logging) to meet this demand as the only driver of wood harvest rate in the IMAGE model (Stehfest et al., 2014). IAMs do not account for the fact that the demand side may also be influenced by the availability of the resource and, accordingly, the increased biomass stocks projected for the future would likely lead to larger wood harvest rates than IAMs simulate by assuming present-day growth conditions. The extent to which accounting for environmental changes may influence estimates of harvestable material (cumulatively over the 21st century, harvest amounts under the SY rule are simulated in our study to be about three times higher than under the respective RCP harvest, see Table 1) highlights the need to include these effects in models, such as IAMs, that estimate future wood harvest. Note that the estimates of SY wood harvest as provided by our model are not meant as plausible estimates of actual future harvest, which as described before depends not just on resource availability, but demand driven by other economic and political considerations. Instead, our study provides an estimate of the ecological potentials for wood harvest.

There is uncertainty in simulating ecosystem response to environmental changes. Regional forest inventories show an increase in biomass due to historical environmental changes (excluding effects of land-use change) (Pan et al., 2011). The largest sinks are found by these studies to be in the tropical regions, coinciding with our simulated regions of largest potentials for additional wood harvest. Also the other regions showing larger potential for wood harvest under SY than RCP, such as North America, Europe, Russia and East Asia, currently exhibit carbon uptake due to historical environmental changes. This gives some confidence in the robustness of our results for SY harvest, in particular since most models project the carbon sink in vegetation to continue for the future; however, its magnitude is uncertain (Sitch et al., 2008). A large source of uncertainty is the strength of the CO_2-fertilization effect (Hickler et al., 2015; Kauwe et al., 2013), which reflects in a large spread across models in estimates of global total (vegetation plus soil) terrestrial carbon stocks (Arora et al., 2013) and of vegetation productivity (Zaehle et al., 2014). The model we used did not account for nitrogen, which may become a limiting factor for the additional uptake of carbon in vegetation, although future climate change might also lead to higher nutrient availability due to faster decomposition rates (Friedlingstein and Prentice, 2010). Further, nitrogen deposition may reduce nitrogen limitation (Churkina et al., 2010), and it is not predictable if artificial fertilization of managed forests may find wide-spread application in the future. Overall, therefore, quantifications of effects of future climate change on global carbon stocks derived from individual models have to be treated with care. However, the location of the largest potentials of SY harvest simulated in our study being in the tropical forests is consistent with the large carbon sinks derived from inventories for past environmental change (Pan et al., 2011).

SY harvest was simulated to mitigate 255-380 PgC, depending on the realized RCP, through wood product usage for the period 2005-2100. Moreover, SY accounted for sustaining the above-ground wood carbon pool at the reference level of 1996-2005. A comprehensive mitigation study, however, should take into account the total carbon balance of forest ecosystems including soil plus litter carbon. Growth enhanced by environmental changes, as simulated to lead to accumulation of woody biomass in the RCP harvest simulations (Fig. 1a), may lead to larger input to the soil (if not removed by wood harvest). However, soil carbon pools respond differently to environmental changes than forest biomass. In particular, soil carbon models generally assume enhanced soil respiration under higher temperatures (Friedlingstein et al., 2006), which may substantially offset the additional carbon uptake by the vegetation (Ciais et al., 2013). As these processes act the same in our simulations of SY and

RCP harvest (as they share the same climate scenarios), effects of environmental changes on soil carbon will likely not substantially affect our comparison of SY and RCP harvest in relative terms, but may alter the net carbon balance in each of them. Further, the usage of wood products implies removal of carbon off-field. This can lead to depletion of soil plus litter carbon stocks. Observational data generally found small decreases of soil carbon, but substantial reduction of deadwood material (Erb et al., 2017). Such effects must be expected to be stronger for SY harvest with its larger harvested amounts than for RCP harvest, reducing on-site carbon stocks, but consequently also soil respiration. Estimating a mitigation potential based on the net carbon balance of vegetation, soil plus litter and product pools therefore would depend on the actual size of soil and vegetation carbon pools and the lifetimes of products relative to the lifetimes of the on-site carbon, which are further subject to a changing climate.

Despite carbon fluxes being the focus of land use change as mitigation tool (e.g., UNFCC, 2012), forest management may enhance or mitigate climate change by a range of other mechanisms such as a change in surface albedo (e.g., Rautiainen et al., 2011; Otto et al., 2014) or turbulent heat fluxes (e.g., Miller et al., 2011). Such biogeophysical effects needed to be accounted for in a complete assessment of the mitigation potentials, as has been done for global land cover change (Pongratz et al., 2011) or for forest management on local (Bright et al., 2011) or regional scale (Naudts et al., 2016). These biogeophysical effects are particularly important for the local climate. In our study, we restrict estimates of mitigation potential to carbon fluxes only and thus focus on the perspective of mitigating global greenhouse gas concentrations. This further allows for a direct comparison of the wood harvest scenarios provided as part of the RCPs.

Different from economic models, ESMs do not consider costs associated with early mitigation measures and thereby implicitly assume a zero social discount rate, meaning that there is no preference for immediate mitigation. However, the discount rate plays a major role to find economically the most efficient mitigation action (Stern, 2007). van Kooten et al. (1999)

analyzed the sensitivity of investments for carbon sequestration to discount rate in western Canada and found that applying zero discount may not provide enough incentive for increasing carbon storage. However, most forest carbon cost studies are inconsistent in using terms, geographic scope, assumptions, program definitions, and methods (Richards and Stokes, 2004) and may not truly assess carbon sequestration potentials of forest ecosystems. Therefore, if there were a social preference for prompt climate change mitigation, carbon sinks later in the century should be discounted.

5. Conclusions

Finally, future research on integration of management strategies in DGVMs and ESMs should regard ecological sustainability as well as socio-economic challenges. In reality and today, forest management is more of a gamble than a scientific debate (Bellassen and Luyssaert, 2014) and there is no consensus in applying a certain forest harvest rule (e.g. SY) among forest owners, decision-makers and local users. The rationale to manage forest resources sustainably and efficiently is generally recognized and implemented (Luckert and Williamson, 2005; Elbakidze et al., 2013). However, the process of forest management decision-making is based on the past experiences with business-as-usual strategy (BAU). Adaptation to future environmental change and minimizing the risks associated with climate change impacts is recently fully integrated in forest research (Lindner et al., 2014), however, remains in experimental level in implementation (Yousefpour and Hanewinkel, 2015). Mitigation, in turn, is of public interest and there are some attempts internationally to account for mitigation effects of forest management in carbon policy. International programs such as the Kyoto protocol encourage forest managers to store carbon in the forest stocks on the ground applying financial instruments such as tax reduction and direct purchase of carbon offsets. Therefore, inclusion of financial aspects in global forest management modelling and decision-making may help to put scientific results into practice (Hanewinkel et al., 2013). This suggestion is in line with van

Vuuren et al. (2011) about the necessity of strengthening the cooperation between integrated assessment models (IAMs) and Earth system modelling communities to improve the understanding of interactions and joint development of environmental and human systems. Our study of SY is the first implementation to account for the climate-dependence of forest growth on global scale for harvest potentials. It suggests the importance of considering this dependence: the sustained-yield approach as applied in this study may realize wood harvest rates twice to four times as high as those of prescribed wood harvest simulated by IAMs for the RCPs and may triple the net mitigation effects of wood products. To move from estimates of potentials to actual harvest rates, climate-dependent forest growth needs to be integrated with socio-economic factors to fully incorporate economic aspects of forestry practices within a dynamic forest growth and yield modelling system.

Code availability

Scripts used in the analysis and other supplementary information that may be useful in reproducing the authors' work are archived by the Max Planck Institute for Meteorology and can be obtained by contacting publications@mpimet.mpg.de.

Data availability

Primary data are archived by the Max Planck Institute for Meteorology and can be obtained by contacting publications@mpimet.mpg.de.

Sample availability

None

Appendices

None

Supplement link (will be included by Copernicus)

Supplementary includes two main files: a word document on the "details on JSBACH, its model version and the simulation setup" and a zipped excel file as example of how "mitigation potentials of woody products in their life time".

Team list

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Author contribution

R.Y. and J.P. initiated the study. R.Y. performed the model simulations. J.N. implemented the code changes. All authors contributed to analyzing the simulations and writing the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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Figure's Captions

Figure 1 Development of wood carbon pools (1a) and realized wood harvest (1b) forced by three different RCP scenarios and subject to the harvesting rules of the representative concentration pathways (RCP2.6, RCP4.5 and RCP8.5) and sustained yield (SY2.6, SY4.5, and SY8.5). Lines are smoothed over 10 years.

Figure 2 Allocation of wood harvest applying sustained yield (three left figures) and representative concentration pathways (three right figures) rules to different forest regions summed over the entire simulated period (2006-2100).

Figure 3 Composition of sustained-yield (SY) harvest forced by different climate change scenarios (RCP2.6, RCP4.5, and RCP8.5 in figures a, b, and c, respectively). *dCw/dt* refers to the difference in changes in above-ground woody biomass between representative concentration pathways' and SY harvest (where changes in biomass in SY are by construction of the harvest rule close to 0), BGmort refers to the difference in woody carbon losses between RCP and SY harvest due to background mortality, Fire to that due to fire disturbance, and Wind to that due to wind disturbance. SY and RCP harvest are as in Figure 1b.

Figure 4 Mitigation potentials of simulated wood harvest from sustained yields (SY) (a, b, c) and representative concentration pathways' (RCP) harvest (d, e, f). Left axes show the annual carbon fluxes due to harvested material and product decay changing atmospheric CO_2 concentration, and the mitigation potential of wood products as the difference of both. Right axes accumulates the annual figures over time.

Table 1: JSBACH simulations conducted in this study with the applied harvesting rule and climate and CO_2 forcing.

Name	Harvest rule	MPI-ESM forcing
SY2.6	SY	RCP2.6
SY4.5	SY	RCP4.5
SY8.5	SY	RCP8.5
RCP2.6	RCP2.6 map	RCP2.6
RCP4.5	RCP4.5 map	RCP4.5
RCP8.5	RCP8.5 map	RCP8.5

Table 2 Mitigation potentials of SY and RCP harvest at the middle and end of the 21st century

Applied harvest rule	Harvested wood (PgC)		Mitigation effect (PgC)	
	2050	2100	2050	2100
RCP2.6	58.1	137.6	38.3	85.1
RCP4.5	62.9	147.2	40.7	90.2
RCP8.5	76.5	211.8	50.6	132.1
SY2.6	192.7	421.3	124.5	255.0
SY4.5	210.0	513.9	136.4	314.7
SY8.5	215.0	609.4	140.6	379.1

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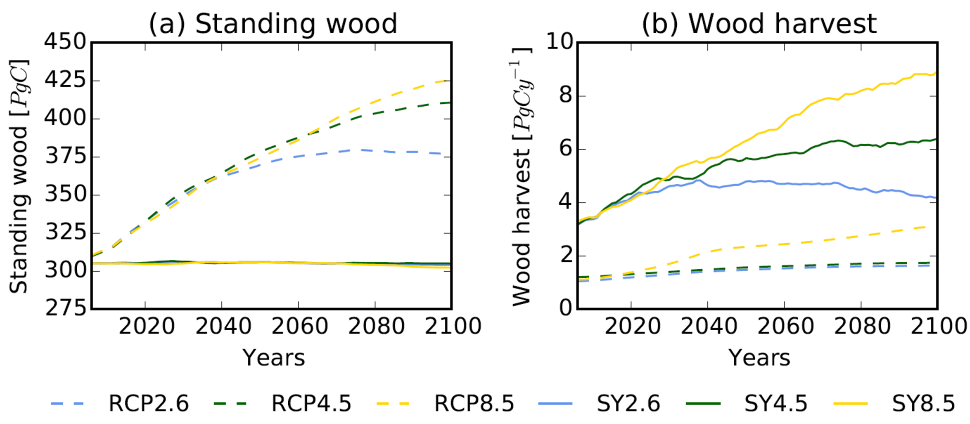
Figure 1



687 **Figure 2**

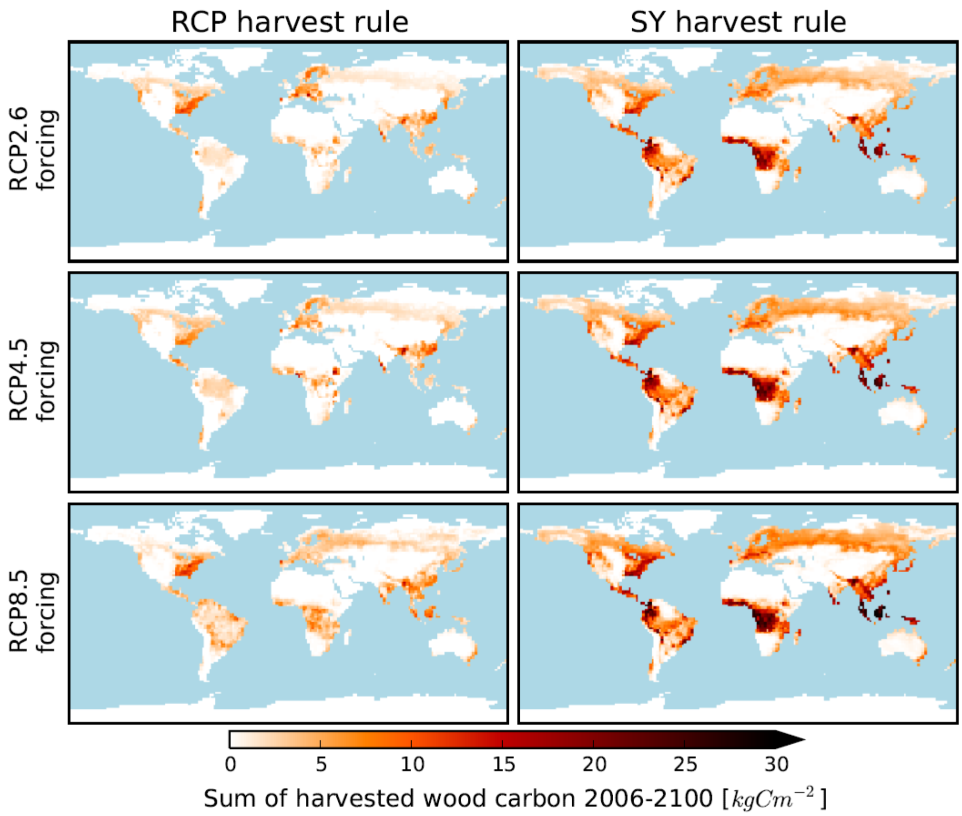


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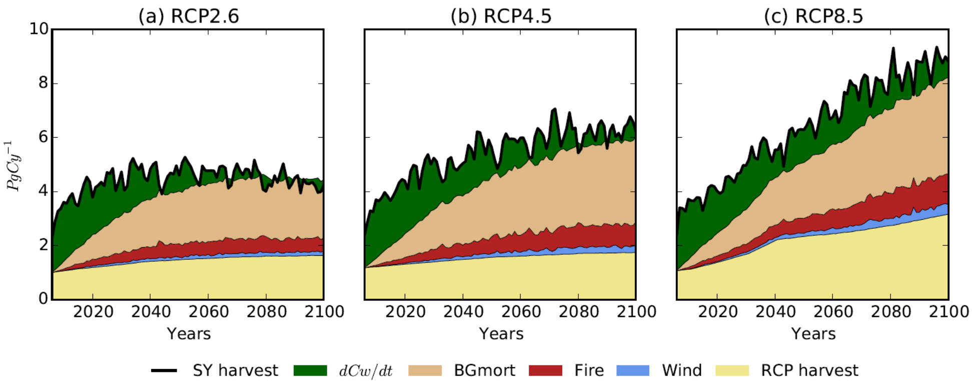
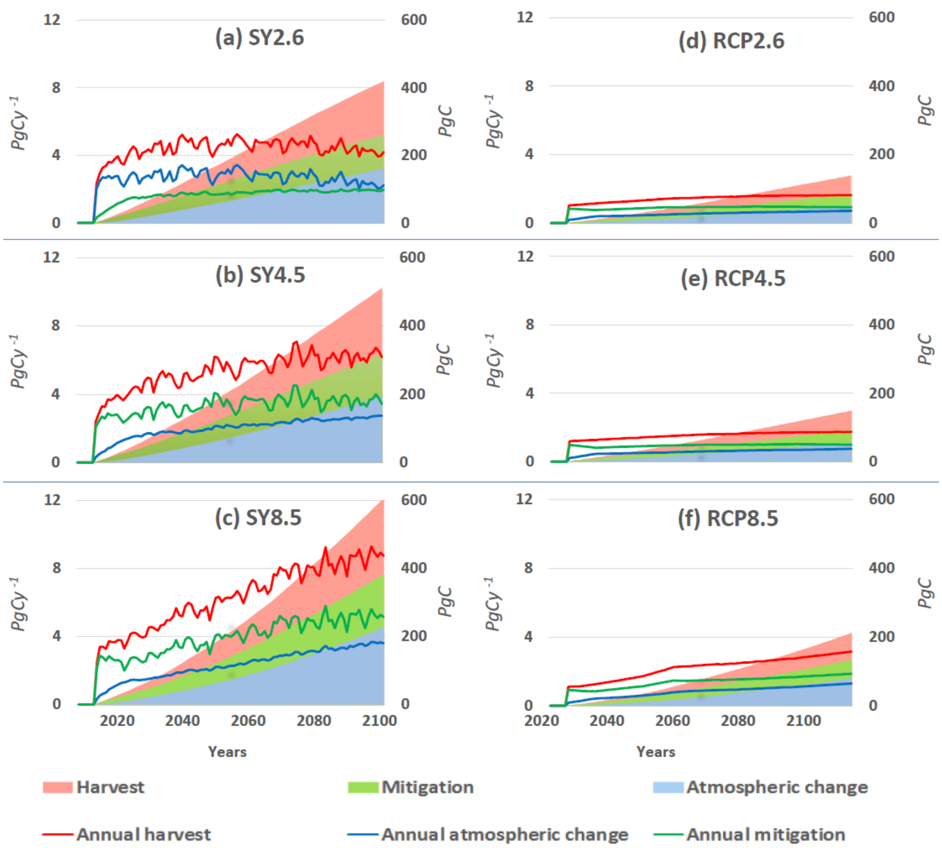
Figure 3


(a) RCP2.6
(b) RCP4.5
(c) RCP8.5
$PgCy^{-1}$
0
2
4
6
8
10
2020 2040 2060 2080 2100
Years
SY harvest
dCw/dt
BGmort
Fire
Wind
RCP harvest

693 **Figure 4**



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