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Nitrogen-Related Constraints of Carbon Uptake by Large-Scale Forest Expansion: Simulation Study for Climate Change and Management Scenarios

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Key Points:

- N limitation of plant growth and soil decomposition often compensate such that effect on C sequestration is small
- C uptake triggered in fertilization experiment is offset by up to approx. 50% due to increase in soil N2O emissions
- Modelling concept used for the C-N coupling determines the effect of N limitation or addition in the experiments

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Abstract Increase of forest areas has the potential to increase the terrestrial carbon (C) sink. However, the efficiency for C sequestration depends on the availability of nutrients such as nitrogen (N), which is affected by climatic conditions and management practices.

In this study, I analyze how N limitation affects C sequestration of afforestation and how it is influenced by individual climate variables, increased harvest, and fertilizer application. To this end, JSBACH, the land component of the Earth system model of the Max Planck Institute for Meteorology is applied in idealized simulation experiments. In those simulations, large-scale afforestation increases the terrestrial C sink in the 21st century by around 100 Pg C compared to a business as usual land-use scenario. N limitation reduces C sequestration roughly by the same amount. The relevance of compensating effects of uptake and release of carbon dioxide by plant productivity and soil decomposition, respectively, gets obvious from the simulations. N limitation of both fluxes compensates particularly in the tropics. Increased mineralization under global warming triggers forest expansion, which otherwise is restricted by N availability. Due to compensating higher plant productivity and soil respiration, the global net effect of warming for C sequestration is however rather small. Fertilizer application and increased harvest enhance C sequestration as well as boreal expansion. The additional C sequestration achieved by fertilizer application is offset to a large part by additional emissions of nitrous oxide.

1. Introduction

Increasing terrestrial carbon dioxide (CO_2) uptake is one option to reduce man-made climate change. In order to increase CO_2 sequestration significantly, large areas would need to be available for either planting forests or plantations, or for natural regrowth of trees, resulting in huge modifications of the landscape. Before realizing such large-scale land-use changes, profound understanding on the efficiency of afforestation for C sequestration and potential side effects is needed.

The productivity of the terrestrial biosphere will increase under higher CO_2 concentrations as has been observed in free-air concentration enrichment (FACE) experiments (De Graaff et al., 2006; Norby et al., 2010; Oren et al., 2001). Climate change will further impact forest productivity by inducing more favorable conditions in higher latitudes leading to expansion of forest areas. In addition, regrowth of forests on abandoned areas leads to an increase in the C sink (Mukul et al., 2016). However, when nutrients are not sufficient, this increase will cease (e.g., Oren et al., 2001; Wieder et al., 2015).

The present study examines how limited availability of nitrogen affects carbon sequestration of forests under future climate in an afforestation scenario. Previous studies looking at future land use and land-use change (LULUC) did not consider either N limitation or boreal expansion explicitly, or focused strictly on emissions induced by LULUC, or did not separate the effect of climate change variables (Lawrence et al., 2012; Meiyappan et al., 2015; Sonntag et al., 2016; Stocker et al., 2014; Wang et al., 2015). Here, I focus on N limitation of C sequestration by forests, and how this limitation is influenced by climate change and management. Thereby I consider forests regrowing on abandoned cropland as described by the Representative Concentration Pathway (RCP)4.5 scenario as well as changes in forest cover due to climate change and CO_2 fertilization, where particularly forest expansion in higher latitudes is of interest. In the following, the expansion of forest areas due to land-use change as well as due to a shift in natural vegetation is referred to as "afforestation".

In the plant–soil system nitrogen is affected and modified by many biogeochemical and abiotic processes. It can for instance be leached with runoff water, transferred to gaseous compounds, taken up by plants or microbes, and released again during mineralization. All those processes are sensitive to temperature and moisture conditions in the soil as well as availability of SOM. Hence, rising CO_2 concentration and climate change will certainly affect N dynamics in the plant–soil system by changing soil temperature and moisture conditions and by changing net primary production (NPP) and thus input of organic matter into the soil. Those changes will affect the potential of large-scale afforestation to sequester C. In this study, I disentangle climate forcing variables in idealized simulations to assess their relevance for N limitation and thus C sequestration of forests.

Besides naturally occurring limitation in N availability, another potential offset is related to the management of forested areas. Particularly application of fertilizer and removal of biomass due to harvest have the potential to change the nutrient status and thus C sequestration of forests. Increased availability of N with fertilizer application will affect the microbial processes in the soil. One process that will likely be affected is decomposition and mineralization, thus the release of CO_2 and mineral N from soil organic matter (SOM). Previous studies have found both a stimulating and a hampering effect of N addition on soil respiration (SR), mainly depending on whether the system is N deficient or saturated in N. For instance, Janssens et al., 2010 found a decrease in soil decomposition with N addition stating that all the sites considered in their analysis are saturated with N. Allen and Schlesinger (2004) as well as Sillen and Dieleman (2012) found an increase in SR with N addition and Chen et al. (2016) found the same for degraded grasslands. Hence, particularly under limited conditions, stimulating effect of N addition on soil decomposition can be expected (Chen et al., 2016; Janssens et al., 2010), while under saturated conditions N addition is likely to hamper decomposition. Another process that will be affected by fertilizer application and that is relevant in context of climate change is the production of nitrous oxide (N_2O). N_2O is a potent greenhouse gas with a global warming potential (GWP) of 298 CO_2-equivalents. The main source of anthropogenic N_2O emissions is agriculture, due to fertilizer application (Syakila & Kroeze, 2011). Another management practice usually accompanying forests is harvesting. Frequent removal of both C and N from the forest ecosystem impact C sequestration and N availability.

All those processes are interlinked and can partly influence each other: Temperature rise leads to increased availability of N due to stimulated mineralization and triggers forest expansion in higher latitudes. Increased forest cover will enhance C sequestration in the soil, which will enhance the N turnover in the soil and at the same time increase N demand by plants and soil processes. N limitation reduces the amount of biomass that can be harvested, while harvesting biomass removes C and N from the forest. Fertilizer application can stimulate both plant growth and SR, while stimulated C decomposition will also increase the amount of N released during mineralization.

In this study, I conduct model simulations for future scenarios combining different climate-change forcing variables and land-use management scenarios. Hence, different aspects of those complex interactions can be disentangled allowing for a better understanding. In particular, I assess the sensitivity of C sequestration by forests and of its regulation by N availability by conducting idealized simulations for 21st century, mostly focusing on the RCP4.5 scenario (van Vuuren et al., 2011).

2. Methods

The simulations are performed with JSBACH, the land component of the Earth system model of the Max Planck Institute for Meteorology, MPI-ESM (Giorgetta et al., 2013; Raddatz et al., 2007). JSBACH calculates daily rates of NPP with the approach by Farquhar et al. (1980) based on CO_2 concentration, stomatal conductance, and water availability. NPP is distributed to the plant compartments green, woody, and resistant pool that are assumed having constant C/N ratios. Dead plant material is assigned to litter pools: The green pool to the green litter pool, representing the more labile fraction of SOM and the wood and resistant pool to the woody litter, representing the more resistant fraction of young SOM. Both litter pools are decomposed to humus, with a fraction being respired and released as CO_2. As the C/N ratio of the humus pool is smaller than the C/N ratio of the litter pools, N is immobilized during this decomposition step. Both processes, the distribution of NPP to the plant C pools and soil decomposition, need N. If the total demand for N exceeds the available N in form of mineral N, both processes are reduced accordingly. Hence, both fluxes, NPP and soil decomposition, are limited by N availability and for both fluxes the model diagnoses the potential flux,

Table 1.
Overview on Simulation Experiments that Are Driven by Data on Climate Forcing, Land-Use Change, and Management[a]

Experiments	Climate forcing	Land use	Management
REF45	RCP4.5	RCP4.5	RCP4.5
REF85	RCP4.5	RCP8.5	RCP4.5
sensNPP	RCP4.5 NPP@PD	RCP4.5	RCP4.5
sensT	RCP4.5 temperature@PD	RCP4.5	RCP4.5
sensM	RCP4.5 moisture@PD	RCP4.5	RCP4.5
H2	RCP4.5	RCP4.5	2 × harvest
FF	RCP4.5	RCP4.5	Fertilizer on forests

[a]The climate forcing is taken from fully coupled MPI-ESM simulations for the RCP4.5 scenario; the land-use change is prescribed according to either the RCP4.5 or the RCP8.5 scenario (Hurtt et al., 2011); in the sensitivity simulations sensNPP, sensT, and sensM, one forcing variable—NPP, temperature, or soil moisture, respectively—is kept at the present-day value (@PD).

and, if N is not sufficient, the actual reduced flux. In the setup applied here, JSBACH considers 11 plant functional types (pft). For each pft there is a set of photosynthetic parameters that represent the photosynthetic capacity under present-day nutrient status (Knorr, 2000). N limitation in JSBACH, therefore, mainly represents the N limitation occurring under enhanced CO_2 concentrations and other changes relative to present-day conditions. In previous C-only simulations with JSBACH, harvested biomass was assigned to a soil litter pool assuming a similar turnover time. However, shuffling harvested biomass back into the soil is not appropriate when considering nitrogen dynamics as this procedure would bias N availability. Hence, for this study, the harvest scheme was adapted such that harvested biomass is removed from the site allowing for a better representation of the effect of harvest on N limitation. JSBACH can be applied in different configurations. One aspect I analyze in this study is the sensitivity of N limitation. Therefore, I choose a configuration where I can disentangle different factors and assess their individual effects. In this setup, the soil–plant system is decoupled from the atmosphere. The sub-model (CBALANCE) is driven by NPP, soil temperature, soil moisture, and leaf area index. For this study, I use the forcing data from a fully coupled MPI-ESM simulation without N dynamics. Hence, NPP used to force the model represents NPP without N limitation and will be reduced according to N demand by soil and plants and N availability. In all simulations conducted in this study, N dynamics are considered. N deposition is prescribed according to the maps from Dentener et al. (2006). In addition, land-use change, dynamic vegetation, and natural disturbances are taken into account (Reick et al., 2013; Schneck et al., 2015; Wilkenskjeld et al., 2013). Those processes are relevant to realize the large-scale afforestation as prescribed in the RCP4.5 scenario and further enable simulation of climate change-induced vegetation shifts such as forest expansion in higher latitudes. In the RCP land-use scenarios, transitions between different natural and anthropogenic land cover types as well as harvest rates are prescribed according to Hurtt et al. (2011).

First, I want to assess the effect of large-scale increase in forest area to a business-as-usual land-use scenario. In the RCP scenarios, both concepts are available. The RCP4.5 scenario is designed as a medium climate change scenario with afforestation due to regrowth of forests on abandoned cropland. The RCP8.5 scenario is a high fossil-fuel emissions business-as-usual scenario. To disentangle the effect of forest cover on C uptake, I compare two simulations using identical climate forcing and differing only in the prescribed land use.

The afforestation scenario “REF45” uses climate forcing from a MPI-ESM simulation for the RCP4.5 scenario, and land-use change according to the RCP4.5. The business-as-usual simulation “REF85” uses identical climate forcing as REF45, but land use according to the RCP8.5 scenario. Hence, both simulations differ only in their land use.

The availability of nitrogen depends on the climatic and biogeochemical conditions in the soil. Anthropogenic climate change will affect those factors by modifications in soil temperature, soil moisture, and carbon input due to changes in NPP. With the chosen model configuration, those factors can be disentangled explicitly and their individual effect can be assessed separately. In the sensitivity analysis, two simulations are compared where one forcing variable (soil temperature, soil moisture, or NPP) changes in one simulation and does not change in the other. These scenarios (sensT, sensM, sensNPP, respectively, see Table 1) are not realistic predictions but model experiments designed to separate one effect. Due to the various couplings and interlinkages, such separations in most cases are not feasible in measurement experiments. To separate the effect of one forcing variable, it was kept at the present day starting value while all other forcing variables were left unchanged in their transient behavior according to the chosen climate scenario. The present-day value was derived as a 10-year mean from 2006 to 2015 from the RCP4.5 MPI-ESM simulation. Table 1 gives an overview on the simulation experiments and Figures 1a–1f shows the changes in the forcing variables NPP, soil temperature, and soil moisture.

To assess the effect of management on C sequestration and N limitation, additional simulations are performed. In the H2 simulation, the harvest rates from the RCP4.5 scenario are doubled. In the FF simulation, fertilizer is applied on forest areas showing N limitation. The amount of fertilizer applied is determined daily during the simulation as the 1.5-fold of the N deficit simulated for forests in the respective grid cell.

3. Efficiency of Large-Scale Afforestation for Carbon Sequestration

C sequestration in this study refers to the C taken up on site, as the difference between CO_2 uptake by NPP and CO_2 loss during soil decomposition. Other processes affecting total C sequestration such as natural disturbances like fires, or the usage of the product pools, are not considered here, as they are not or only indirectly affected by N limitation. However, it needs to be kept in mind that those factors can also change with forest expansion. The CO_2 released during soil decomposition is referred to as SR in the following.

3.1. Comparison to Business as Usual Scenario

The comparison between the REF45 and the REF85 simulation shows the efficiency of large scale afforestation to sequester carbon compared to a business-as-usual land-use scenario. By the end of the 21st century, the forest area in the REF45 simulation is—by 8 Mio km^2 (24.5%)—considerably larger than in the REF85 simulation (Figure 2, Table 2). Those forests play an important role for carbon sequestration in REF45. Cumulated for the simulation period (2006–2099) forests account for 67% of the total global cumulated NPP in REF45 (Table 3). Total global C sequestration calculated as the difference between NPP and SR is higher by approximately 100 Pg C in REF45 compared to that of REF85 (see Table 3). In REF45, forests contribute 82.4% to the global terrestrial C sink.

3.2. Effect of Nitrogen Limitation of Forests

Hence, the increase in forest area in REF45 compared to that of REF85 (Figure 2) clearly enhances the potential of the terrestrial biosphere to take up C. However, the productivity of forests depends on the availability of N. In the following, I will further investigate how C sequestration of large-scale afforestation is affected by N limitation. Hereby, the difference between the potential and actual NPP (see Section 2) describes the CO_2 that could not be taken up via NPP due to N limitation. By the end of the 21st century, cumulated NPP of forests in REF45 is limited by 272 Pg C (Table 4). However, N limitation not only affects plant productivity in JSBACH, it also reduces soil carbon turnover (see Section 2) and thus SR. Limitation of SR is calculated as the difference between the daily potential and the daily actual SR. This limitation amounts to 177 Pg C during the simulation period. The limitation of both NPP and SR results in a limitation of C sequestration by 96 Pg C (Table 4). Figure 3 shows that both NPP and SR are limited by N availability in the tropics. In the high latitudes, NPP shows a similar magnitude in N limitation as in the tropics, while the limitation in SR is clearly smaller. As both NPP and SR are limited to the same degree in the tropics, N limitation does not affect carbon gain (NPP-SR) here (see Figure 3). However, in high latitudes, the higher limitation in NPP as compared to that in SR shows in the effect on C sequestration. Figure 3 reveals that in some tropical regions, N limitation leads to higher C sequestration. This is the case when SR is limited to a higher degree than NPP, that is, C losses by SR are limited more than C gains by NPP which then leads to higher C sequestration under N limitation. The evolution of N limitation with time shows for NPP an early onset for the tropics, while limitation of NPP in the higher latitudes is increasing more slowly. In the tropics, both NPP and SR show a similar degree of limitation in time and space, which results in a small N limitation of C sequestration in the tropics throughout the simulation period. Limitation of SR in the boreal region increases more slowly than the N limitation of NPP, resulting in a limitation of carbon uptake exceeding the limitation in the tropics, especially from year 2050 onward.

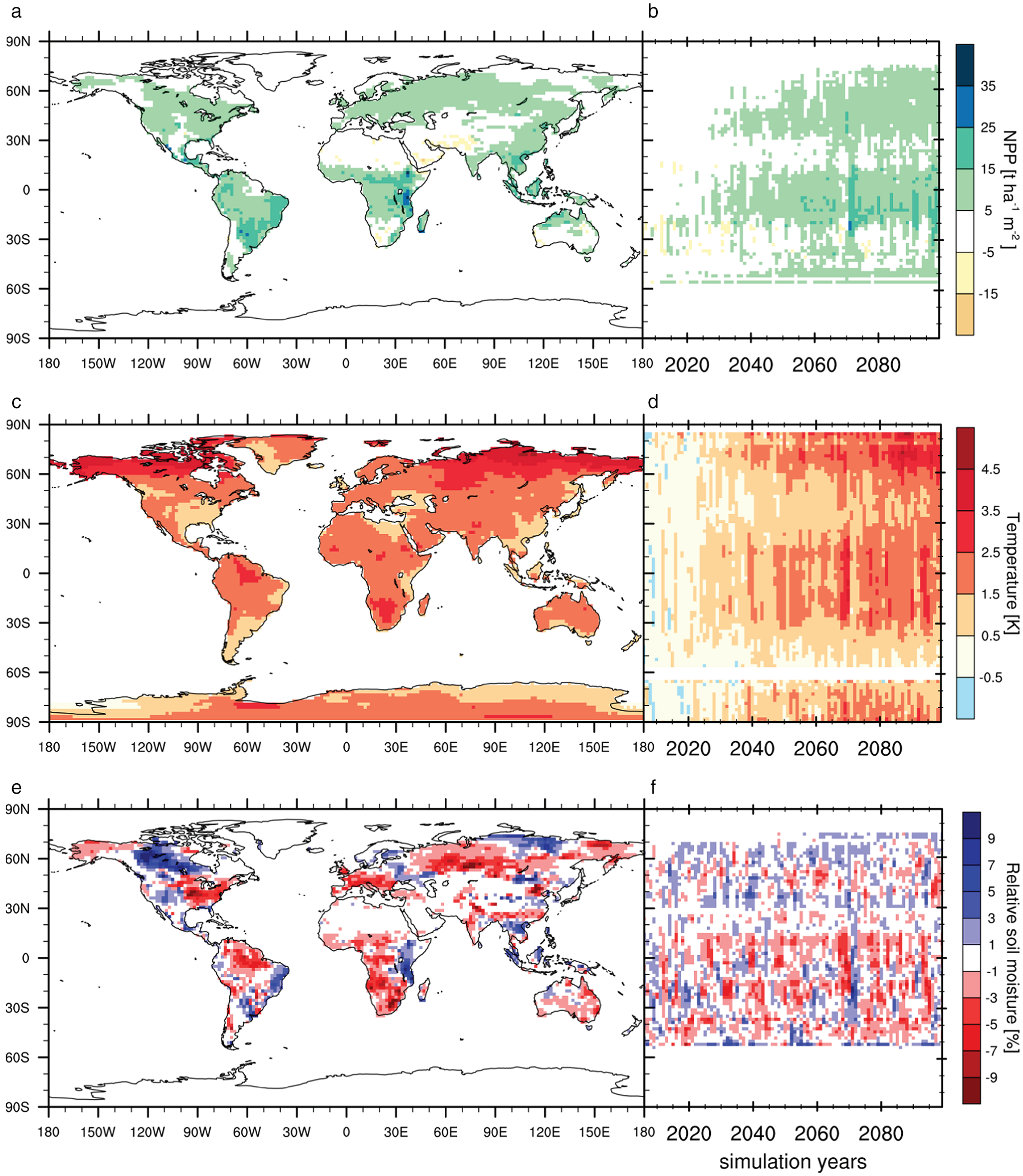

Figure 1. Evolution of forcing data for forest NPP, land surface temperature, and soil moisture content; maps show difference between yearly mean averages of last 10 years (2090–2099) and first 10 years (2006–2015) of the simulation (a,c,e); right-hand side (b,d,f) shows the difference in yearly mean zonal means to beginning of the simulation (2006–2015 average); NPP refers to vegetated area thus being independent of forest area; soil moisture changes were masked for regions with forest NPP smaller than 100 kg C ha^{-1} yr^{-1}.

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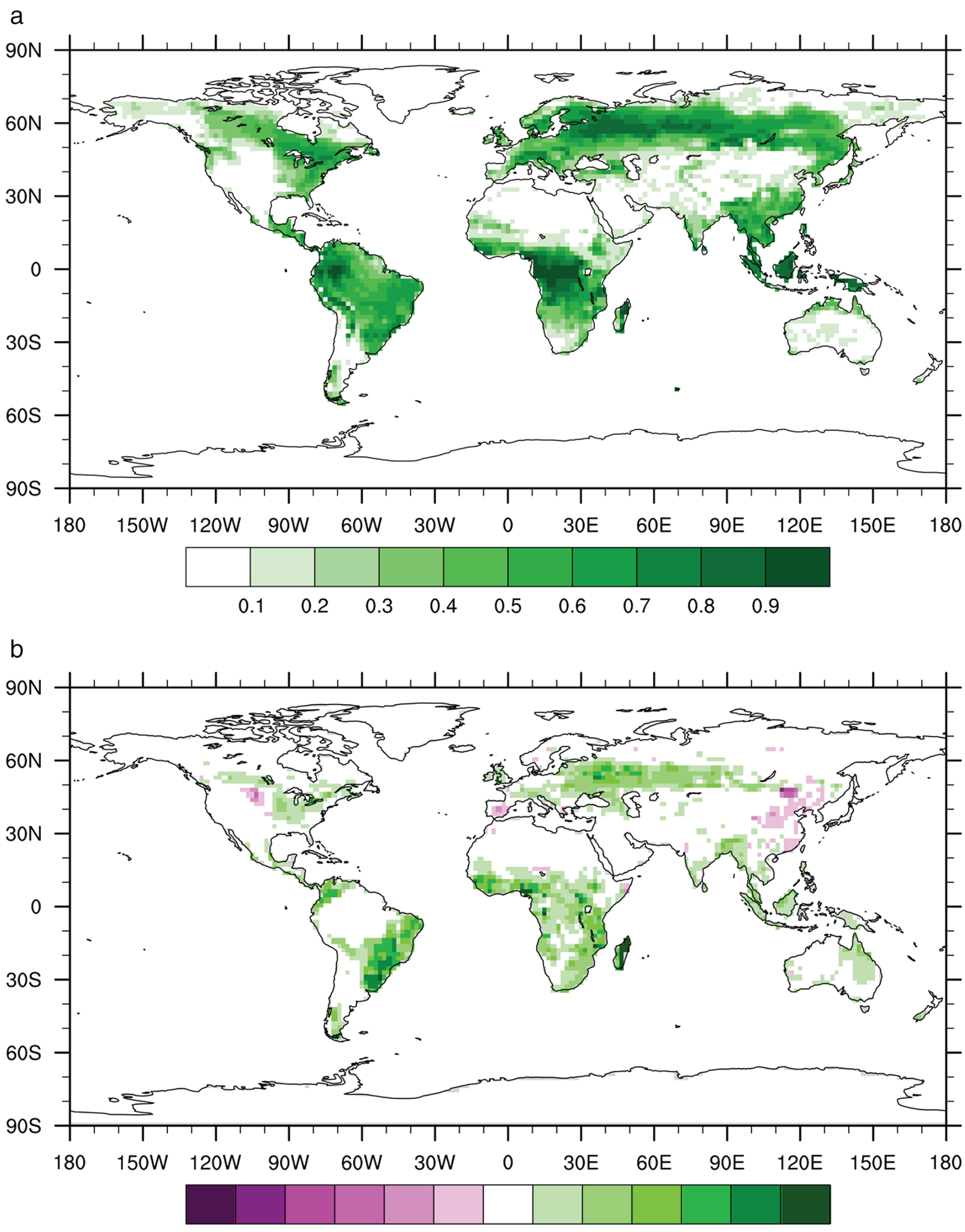

Figure 2. Forest cover in the REF45 simulation (a) and difference in forest cover to the REF85 simulation (REF45-REF85) (b) for the end of the simulation period.

3.3. Effect of Climate on Nitrogen Limitation

N limitation is influenced by many factors and the onset of N limitation in different regions can be driven by different causes. In this section, I will have a deeper look into how climate forcing affects N limitation regionally and in time.

Keeping temperatures at present-day values increases N limitation of NPP and SR to 424 Pg C and 280 Pg C, respectively, until 2099 (Table 4). Due to the higher N limitation NPP and SR are smaller in sensT than in REF45. This difference amounts to 181 Pg C for NPP and to 174 for SR (Table 3). Particularly N limitation of SR shows a similar spatial and temporal pattern as the change in temperature (Figures 1 and 4). The effect

Table 2.
Changes in Forest Area to REF45 Simulation

	Difference in forest area to REF45 in 2099(10^6 km^2)	Forest area 2099(10^6 km^2)
REF45		42.56
REF85	−8.54	34.02
sensT	−0.95	41.61
sensM	0.16	42.72
sensCO2	−0.57	41.99
FF	1.00	43.56
2H	0.10	42.66

Table 3.
Cumulated C Fluxes for the 21st Century for NPP, Soil Respiration (SR), and C Sequestration (Cseq)

	NPP (Pg C)	SR (Pg C)	Cseq (Pg C)
Global total cumulated C fluxes			
REF45	7627	6514	1113
REF85	7239	6230	1009
Global forest cumulated C fluxes			
REF45	5132	4214	918
Differences in cumulated C fluxes to REF45 for forests			
sensT	−182	−174	−8
sensM	14	27	−13
sensNPP	−454	−256	−198
H2	33	−33	66
FF	208	118	90

Table 4.
Cumulated Reduction in C Fluxes Due to N Limitation for Forests

	NPP (Pg C)	SR (Pg C)	Cseq (Pg C)
REF45	273	177	96
sensT	424	280	144
sensM	242	135	107
sensNPP	104	65	39
H2	227	147	80
FF	60	33	27

of warming on N limitation of NPP is largest in the tropics. N limitation effects NPP in the tropics and in higher latitudes, while SR is mainly reduced in the tropical region. This indicates that rising temperatures in the boreal zone stimulate plant growth to a larger extent than soil C turnover. Hence, the demand for N by plants is higher than the demand by soil processes in high latitudes. In sensT the lack of warming reduces the forest areas up to approximately 1 Mio km^2 by 2099. Temperature affects forest expansion in both the tropics and the extratropics. NPP is to a large extent limited by N in the tropics when temperatures are kept at present-day values. The effect of temperature on N limitation shows a smaller magnitude in the boreal zone. In contrary, keeping temperature at present day affects forest expansion in the boreal zone more than that in the tropics. Hence, temperature increase affects forest expansion twofold: By reducing N limitation in both the tropics and extratropics due to higher mineralization and by causing more favorable conditions for forest growth in the higher latitudes.

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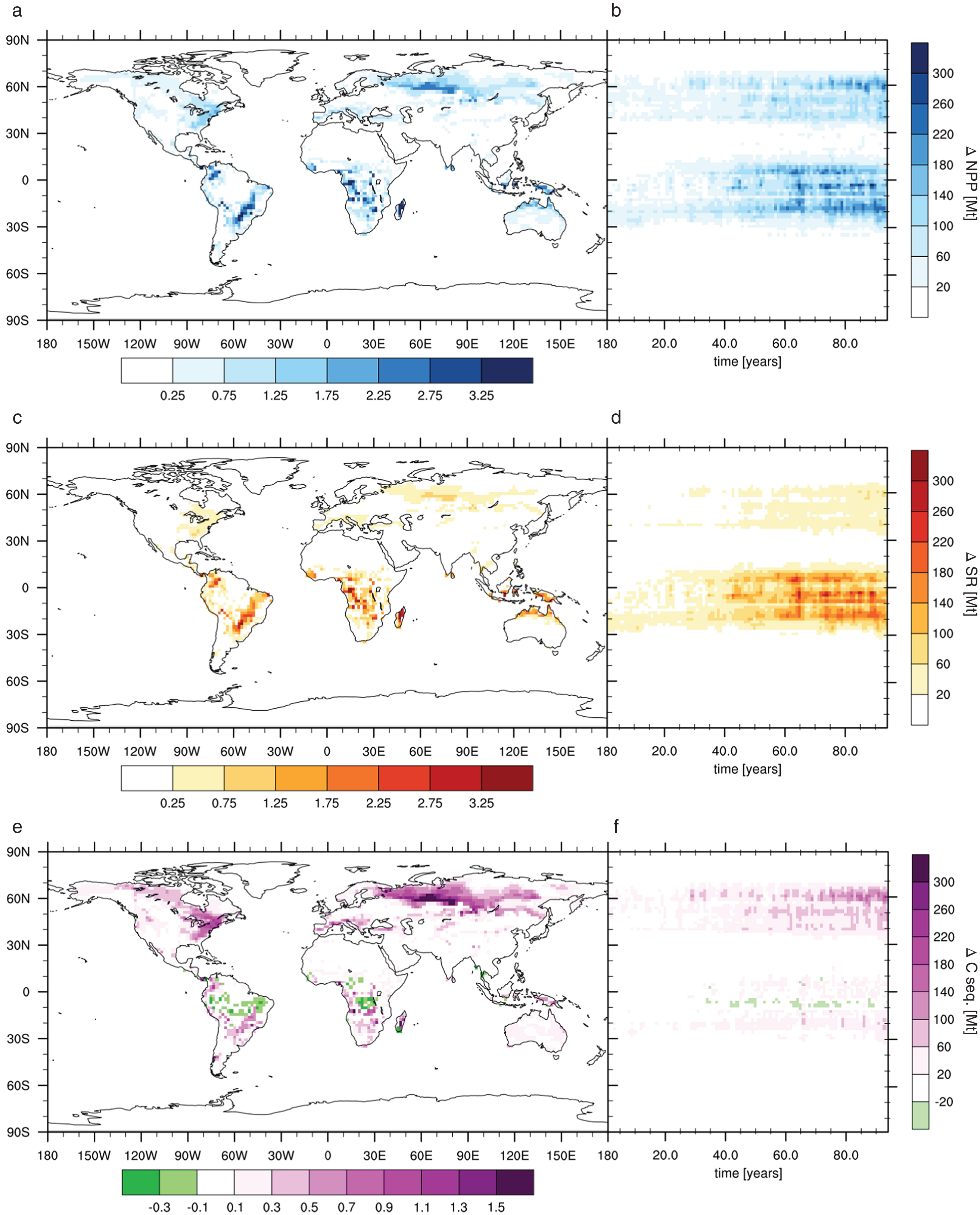

Figure 3. Changes in NPP, SR, and C sequestration due to N limitation of the REF45 simulation: Averaged for the last 10 years (maps on left side: a,c,e); evolution of reduction in C fluxes with time shown as zonal sums on right side (b,d,f).

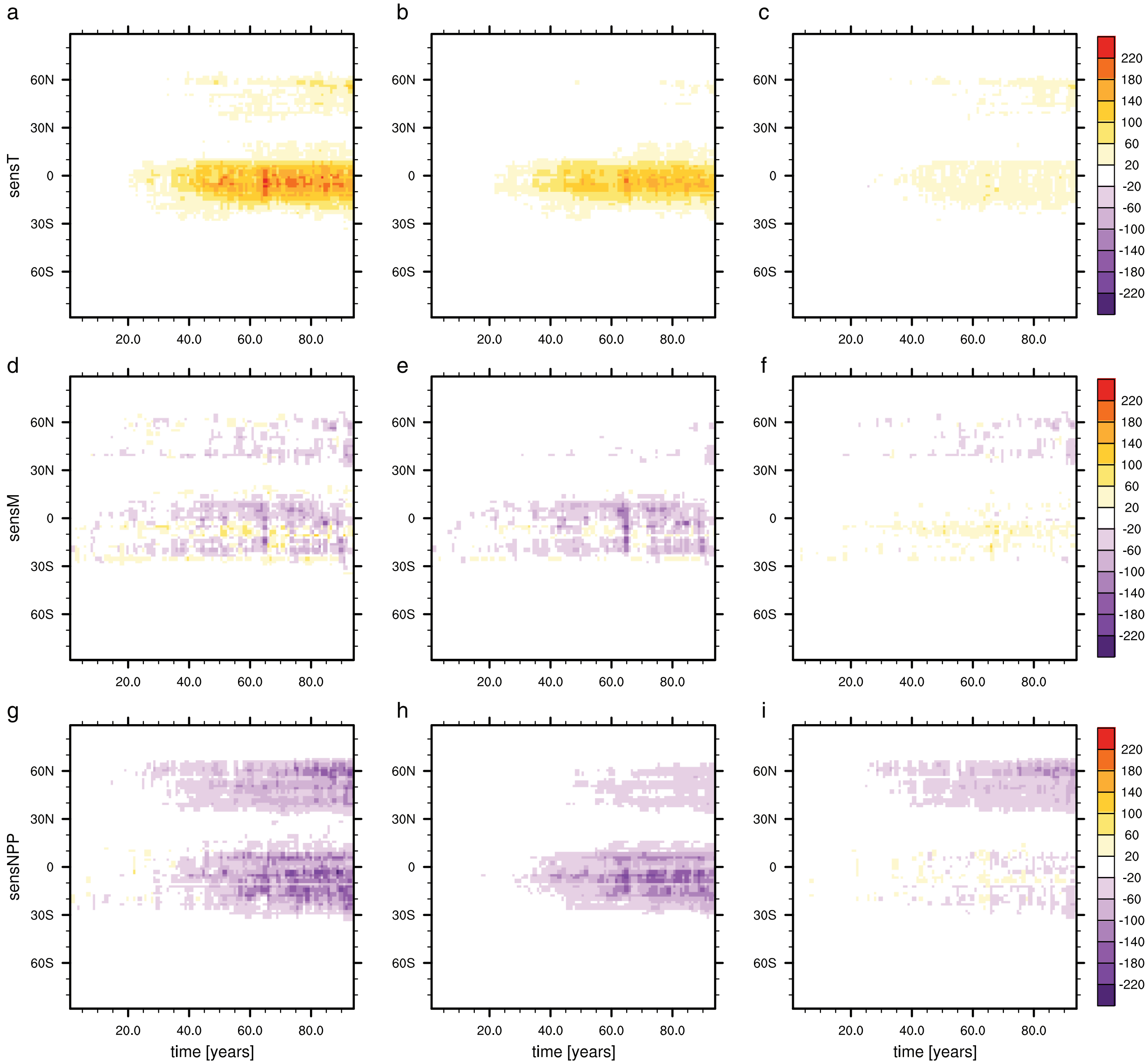

Figure 4. Differences to REF45 simulation in reductions of C fluxes (Mt yr^{-1}) due to N limitation; Shown are zonal sums for NPP (left: a,d,g), SR (middle: b,e,h), and C sequestration (right: c,f,i), for sensT-REF45 (first row: a,b,c), sensM-REF45 (second row: d,e,f), and sensNPP-REF45 (third row: g,h,i).

Keeping NPP at present-day values (sensNPP) reflects a simulation without CO_2 fertilization effect on productivity. In addition, it reflects a simulation without enhanced productivity in northern latitudes due to warming. In this simulation, the effect on N limitation is of opposite direction as in the sensT simulation. Having no CO_2 fertilization in general reduces the demand for N and thus also the effect of N limitation on productivity. Regarding NPP, N limitation is reduced in both the tropics and the extratropics in similar magnitude, with the reduction being slightly stronger in the tropics (Figure 4). The change in N limitation of SR from REF45 to sensNPP shows a similar pattern as for NPP, however, at smaller magnitude. Especially in the boreal region, net C exchange without CO_2 fertilization shows less N limitation compared to REF45. In the tropics however, higher N limitation of C sequestration is simulated. The total reduction in NPP due to N limitation is smaller by 169 Pg C in sensNPP compared to REF45. Reduction of SR is diminished by 112

Pg C when CO_2 fertilization is not considered. As potential NPP is not increasing in sensNPP, productivity and SR are smaller than those in REF45 (Table 3), and limited less by N (Table 4). Globally, forest expansion in sensNPP is smaller than in REF45, while in boreal regions there are more forests in sensNPP than in REF45 (Figure 5, Table 2).

The global effect of keeping soil moisture at present-day conditions is small. Cumulated for the 21st century, NPP is higher by 14 Pg C and SR by 27 Pg C in sensM compared to REF45 (Table 3). When soil moisture conditions are kept at their starting value, regionally, N limitation of NPP is both higher and smaller in sensM compared to REF45, however, regions with lower N limitations prevail (Figure 4) leading to a reduction in cumulated limitation. Soil respiration shows a clear decrease and C uptake an increase in N limitation in sensM compared to those in REF45 (Table 4). The difference in C sequestration between sensM and REF45 is larger than the difference between sensT and REF45. Hence, in the simulations, changes in soil moisture affect NPP and SR less than changes in temperature, but those changes result in a larger difference in C uptake than for the sensT simulation. Compared to sensT and sensNPP, keeping soil moisture at present-day values shows a rather small effect on global forest expansion (Table 2). However, regionally, both decreasing and increasing forest cover compared to REF45 are visible and mirror the pattern of soil moisture change (Figure 1) for some regions. Those regional trends show a similar magnitude than for the sensT and sensNPP experiments and compensate when calculating the zonal and global sums (Figure 5).

3.4. Effect of Management on Nitrogen Limitation

Doubling harvest leads to an increase in NPP and a decrease in SR (Table 3) and reduces N limitation of NPP, SR, and C uptake, see Table 4. N limitation of NPP is reduced in both tropics and boreal zone to a similar magnitude, however, more regions show a reduction in N limitation in boreal zone than in the tropics. Soil respiration shows a similar reduction in N limitation as NPP, however, only in the tropics. N limitation of C sequestration in the boreal zone is higher in REF45 than that in H2. In the tropics, some years show higher N limitation of C sequestration with higher harvest. Due to the reduction in N limitation in the boreal region, forest expansion is higher in H2 compared to that of REF45. However, this increase in forest expansion overrides only late. In the first 40–50 years of the simulation, forest expansion is smaller in H2 as that in REF45, in the following 20 years both increase and decrease of forests from REF45 to H2 are simulated and only in the last 30 years increase in forest area dominates. In the tropics, some latitudinal bands show a decrease in forests in H2 compared to that in REF45. The comparison of the total global forest area at the end of the simulation between H2 and REF45 reveals a marginal difference, while regionally the magnitude is comparable to the other experiments.

The second management option analyzed is fertilizer application aiming at reduction of N limitation. As we saw, both, C uptake by NPP as well as C release by SR, are limited by N. Hence, with fertilizer application both fluxes will be higher. In the simulation with added fertilizer N limitation of both NPP and SR are reduced to 60 and 33 Pg C, respectively (Table 4). In the tropics, both increase and decrease in N limitation of C sequestration are simulated (Figure 6). Increased forest expansion with fertilizer is particularly simulated for higher latitudes (Figure 7). NPP increased by 208 Pg C and C sequestration by 91 Pg C (Table 3). The well-known side effect of fertilizer application is the enhanced release of N_2O. Hence, for climate mitigation, the benefits regarding C sequestration achieved by applying fertilizer can be compensated partly by increased N_2O emissions. The total amount of fertilizer applied on forests in FF over the simulation period is 4.782 Pg N. The IPCC (2007) recommends an emission factor (EF) of 1.0% for N_2O emissions from mineral fertilizer. The IPCC (1997) recommended a factor of 1.25%. Studies on the EF of N_2O hint that the IPCC underestimates the EF. Davidson et al. (2007) for instance found an EF of 2.5% and Crutzen et al. (2008) found a range of 3.5%–4.5%. Considering a minimum EF of 1.0% and a maximum EF of 4.5%, and conversing N_2O emissions to CO_2-equivalents with a GWP of 289, the N_2O emitted due to fertilizer application is in a range of 12.2–54.9 Pg C CO_2-equivalents, corresponding to 12%–54% of the achieved C sequestration.

4. Discussion

4.1. Potential of Afforestation to Sequester Carbon

The total forest area by the end of the 21st century in REF45 (42.5 Mio km^2) differs from the one in Sonntag et al. (2016) (47–48 Mio km^2) found for the RCP4.5 land-use scenario with the MPI-ESM. In their study the authors consider a business as usual climate and no limitation due to nutrients. Hence, forest areas differ

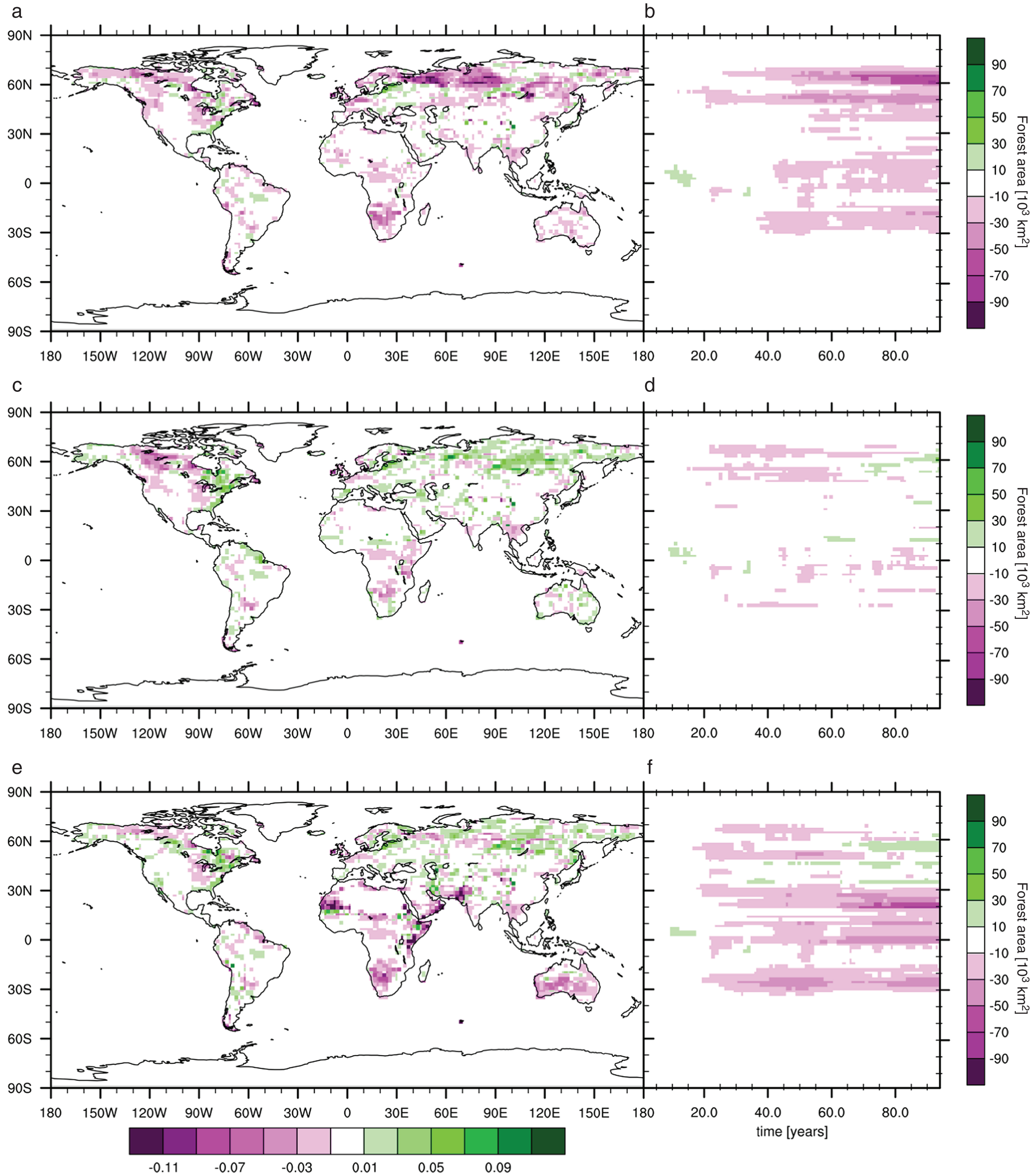

Figure 5. Differences in forest cover to REF45 simulation: sensT-REF45 (a,b), sensM-REF45 (c,d), sensNPP-REF45 (e,f); left side shows cover fractions and right side shows zonal sums of forest area.

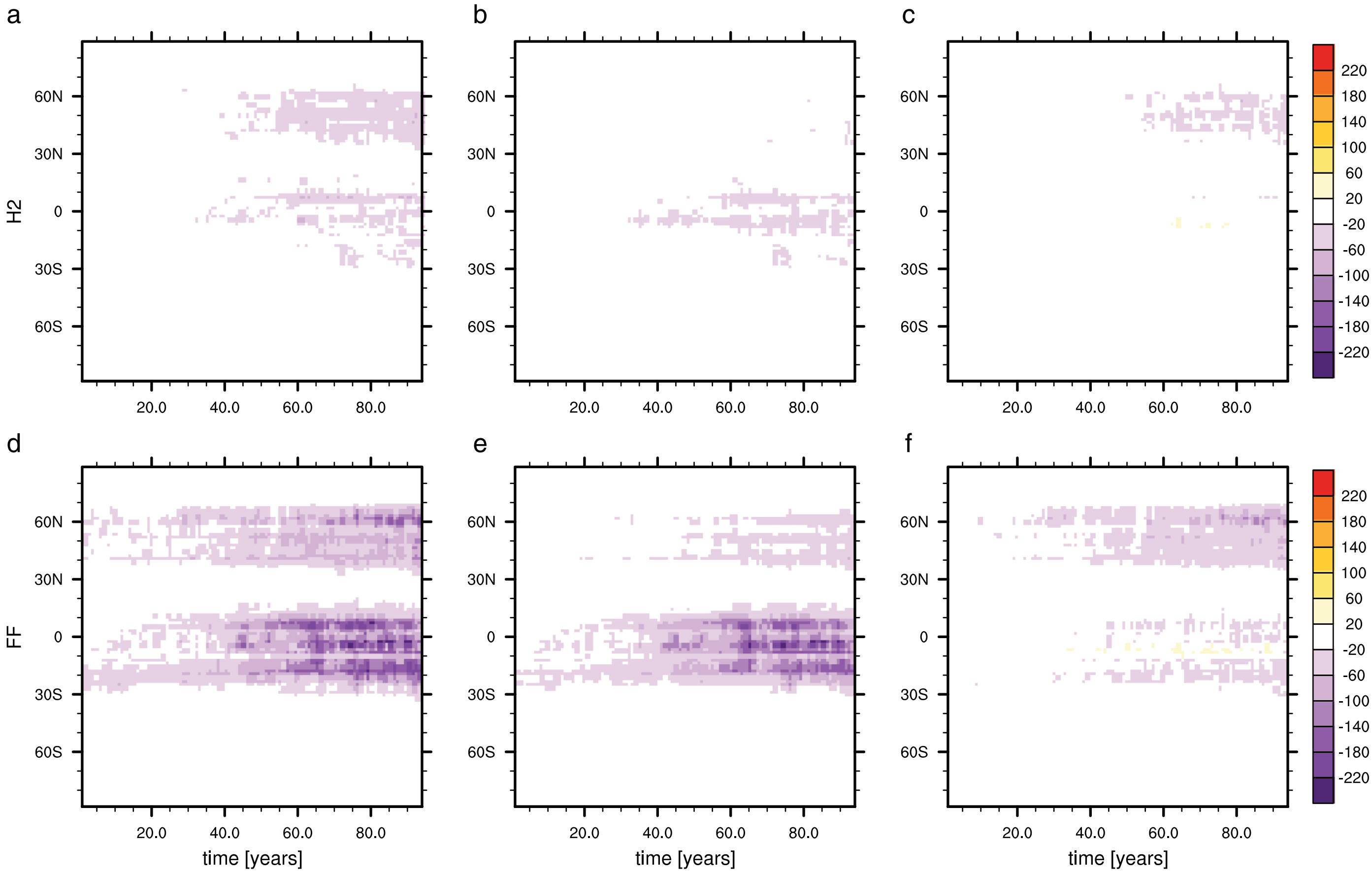

Figure 6. Differences to REF45 simulation in reductions of C fluxes (Mt yr^{-1}) due to N limitation; Shown are zonal sums for NPP (left: a,d), SR (middle: b,e), and C sequestration (NPP-SR) (right: c,f), for H2-REF45 (a,b,c) and FF-REF45 (d,e,f).

due to the different climate and the consideration of N limitation, which reduces both the expansion of the forested areas as well as the productivity of the established forests in REF45. In REF45, N limitation reduces C sequestration by forests by 96 Pg C being approximately 100% of the C sequestered in REF45 compared to REF85 and 50% of the number found by Sonntag et al. (2016). The limiting effect of N availability to sustain enhanced plant growth under CO_2 fertilization has been found in free-air concentration enrichment (FACE) experiments (e.g., Ainsworth & Long, 2005; De Graaff et al., 2006; Leakey et al., 2009; Norby et al., 2010; Oren et al., 2001) and has been addressed in modeling studies (e.g., Goll et al., 2012; Zaehle et al., 2014). However, those investigations did not explicitly consider large-scale afforestation. Studies on future land-use change including N limitation do not quantify the effect of N limitation explicitly (Stocker et al., 2014) or focus on anthropogenic land-use changes and do not address boreal forest expansion due to climate change (Meiyappan et al., 2015; Wang et al., 2015). Those studies diagnosed the effect of N limitation via changes in total C pools or changes in total emissions from LULUC and did not further investigate the effect on NPP and soil decomposition separately. In this study, I find that particularly the influence of N availability on SR is a crucial factor to assess the implications of N dynamics on C sequestration. In JSBACH, N limitation leads to a reduction in SR, while N addition increases SR by offsetting N limitation and by increasing input of C into the soil. This effect shows due to the concept in JSBACH of coupling soil N and C pools. When C is decomposed from soil pools with higher C/N ratios to the humus pool having a small C/N ratio, additional mineral N is needed and immobilized. Hence, the effect of N addition on soil decomposition depends on the concept applied in the model. Addition of C and N to the soil has been found to enhance SR more than adding C or N alone (Allen & Schlesinger, 2004; Gallardo & Schlesinger, 1994). N addition has also been found leading to a decrease in soil decomposition; however, only when N is not a limiting factor (Janssens et al., 2010). Sillen and Dieleman (2012) found that moderate N addition enhances decomposition under CO_2 fertilization in managed grassland. Chen et al. (2016) showed that SR increases with N application

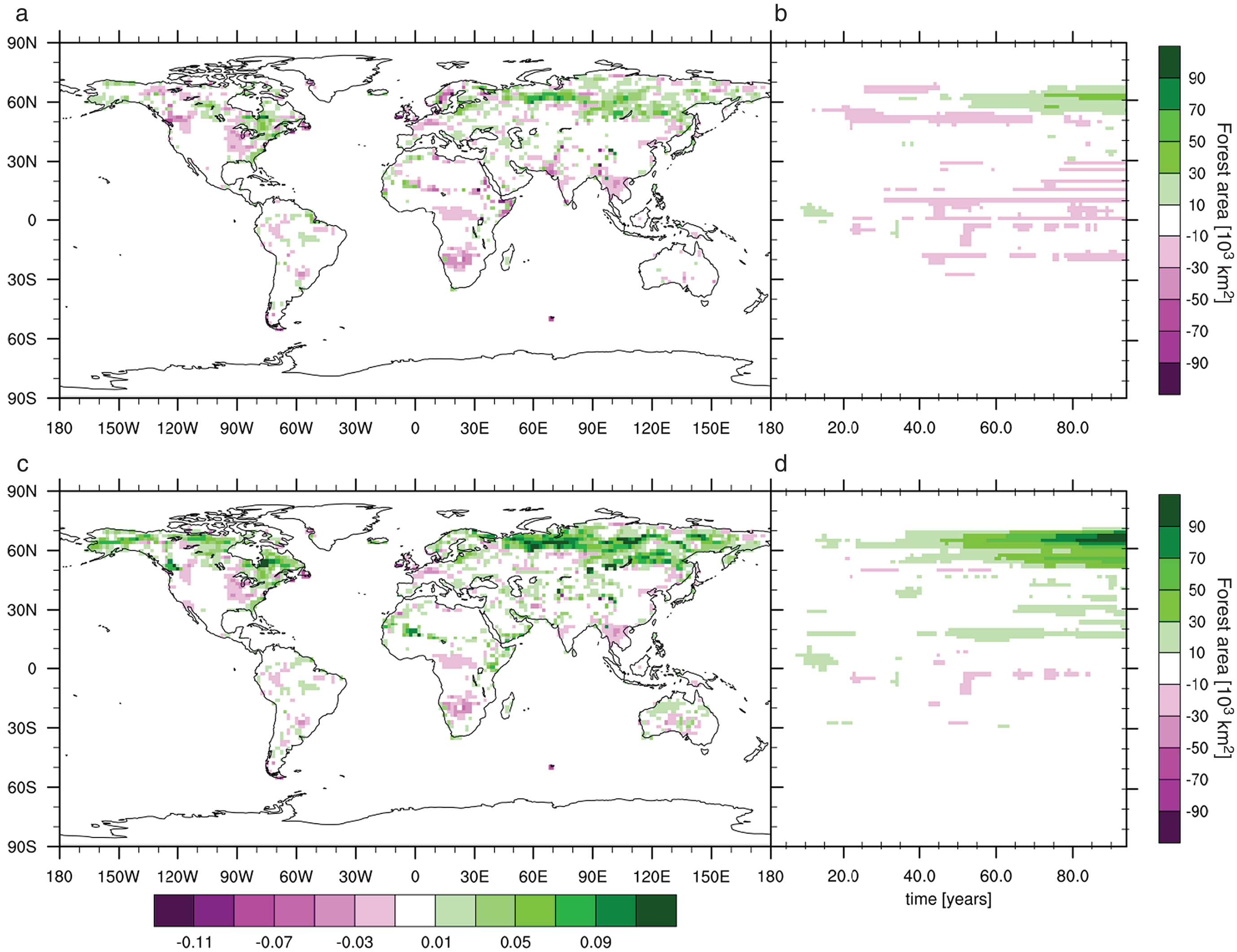

Figure 7. Differences in forest cover to REF45 simulation: H2-REF45 (a,b) and FF-REF45 (c,d); left side shows cover fractions and right side shows zonal sums of forest area.

for grassland on degraded soils being prone to N limitation. Hence, reduction in soil decomposition with N limitation and respective increase with fertilizer addition as was simulated in this study can be expected under CO_2 fertilization.

Especially in the tropical and boreal region the interplay between N limitation of NPP and SR drives N limitation of C sequestration differently in JSBACH. As both NPP and SR are limited equally by N availability, C sequestration is not affected in the tropics, while in the boreal region higher limitation of NPP compared to SR leads to a reduction in C sequestration. It seems that in the boreal region, temperatures are despite warming too low to enhance soil decomposition at the same rate as NPP. In agreement with this study, Goll et al. (2012) found that N limitation does not affect C sequestration in the tropics but becomes relevant in the boreal region under CO_2 fertilization. However, the authors did not analyze N limitation of NPP or SR explicitly, and therefore concluded that N limitation does not occur in the tropics.

In general, tropical ecosystems are prone to phosphorous limitation due to the highly weathered soils (Cusack et al., 2016; Goll et al., 2012). The fast turnover and the relative high N losses suggest that at present day, tropics are not limited by N availability. However, even though the N status of tropical ecosystems is generally high, N limitation can occur at microsites and hamper soil C turnover (Cusack et al., 2016; Parton et al., 2007). Van der Sleen et al. (2015) found that there is no increase in tropical tree growth due to CO_2 fertilization up to now; the authors focus on water use efficiency, but state in addition that nutrient limitation can be an important aspect. Due to the lack of FACE studies in the tropics, knowledge on the behavior of tropical ecosystems under future CO_2 fertilization is scarce. Davidson et al. (2007) and Nagy et al. (2016) found that regrowing secondary forest in the tropics shows a similar N limitation as temperate forests, particularly during the first decades, and is overruled by P limitation later on. Cusack et al. (2016) conclude in their review on tropics under global change that compared to other relevant factors, changes in the future nutrient cycling responses inherit highest uncertainty. They gathered for instance information on studies suggesting that P availability in the tropics is likely to increase under CO_2 fertilization. This indicates that N limitation can become a more relevant factor in the tropics under future climate change. Particularly under the RCP4.5 scenario considered in this study, tropical forests expand onto abandoned cropland, that is, on nutrient depleted soils, raising the probability of nutrient limitation. Hence, N limitation in the tropics can become more relevant under climate change conditions than usually assumed. FACE experiments so far have been carried out only in extratropical regions. Conclusions from FACE or modeling experiments on temperate regions cannot necessarily be extended to the tropics (Hickler et al., 2008) showing the need for FACE experiments in the tropics. For future tropical FACE studies, it will be important to include soil borne CO_2 emissions. Measuring or modeling changes in NPP alone can lead to wrong conclusions regarding C sequestration and its regulation by N limitation.

In this study, N limitation of NPP and SR is quantified as the cumulated difference between the daily potential fluxes and the due to N limitation reduced fluxes. This differs to an approach of comparing a simulation without N dynamics ("C-only") to a simulation with N dynamics to determine the effect of N limitation. This latter approach is suitable to assess the implications of including N dynamics in models (e.g., Thornton et al., 2007) and has also been applied for JSBACH (Goll et al., 2012). In contrast, the focus of this study lies on the sensitivity of N limitation on factors that can change daily. Hence, N limitation in this study is diagnosed by comparing daily fluxes, and not, as it was done in previous studies, by comparing C stocks. Other factors determining the total C sequestration such as shifts in fire regime or fate of harvested biomass are not considered here explicitly as they are beyond the scope of this study.

Land-use changes not only affect C sequestration, but also the biogeophysical properties, such as reflectivity and latent heat flux. Those factors can offset the positive effect of additional CO_2 uptake, particularly in higher latitudes, by reducing the reflectivity of the surface (Bala, 2007; Bathiany et al. 2010) and need to be considered for a more comprehensive assessment.

4.2. Effect of Climate on Nitrogen Limitation

The higher N limitation under sensT, that is, with temperatures kept at present day, compared to the REF45 simulation, where temperature increases, shows the stimulating effect of temperature rise on N released during mineralization. Especially in the boreal zone, warming and the implied decrease in N limitation triggers forest expansion. In the sensT simulation potential NPP is identical to REF45, that is, plant productivity in sensT triggers the same forest expansion as in REF45, but is limited by restricted N availability compared to REF45. This is also obvious from the comparison between sensNPP and REF45. Forest expansion in the boreal zone is larger in sensNPP, despite smaller NPP values. In REF45, higher NPP values augment N limitation leading to less forest expansion compared to sensNPP. As warming is identical in both simulations, N mineralization is triggered in both sensNPP and REF45.

Highest effect of warming on N limitation is simulated for the tropical region. For the tropics Cusack et al. (2016) found in their review that warming is likely to trigger N mineralization.

As there is no measurement study looking at the effect of warming on N limitation under CO_2 fertilization for the tropics, it is difficult to judge whether this prediction is realistic. Studies under present-day ambient CO_2 concentration cannot be used as a reference, as present-day N status of ecosystems is likely to change under climate change.

The global mean changes in soil moisture are small and the effect of soil moisture changes on N limitation are small compared to other forcings. Soil moisture is directly affected by precipitation and evapotranspiration and thus depends on the climate and the vegetation. The present-day soil moisture values in sensM therefore represent not only the climatic condition but also the vegetation cover. Vegetation cover impacts the energy fluxes at the surfaces, which is beyond the scope of this study. For the sensitivity analysis, I assume that the changes in soil moisture reflect a realistic range of possible changes. Globally the changes in soil moisture affect NPP and SR little; however, they induce a larger effect on C sequestration than changes in soil temperature, despite a much larger effect of warming on NPP and SR. Hence, for a comprehensive understanding of the effects of climate changes on the C cycle, be it under N limitation or not, it is important to look at changes in NPP, in soil decomposition, and the resulting net effect for C uptake. Particularly for soil moisture it seems to be important to look at regional changes as those regional signals compensate when calculating global or zonal diagnostics.

4.3. Effect of Management on Nitrogen Limitation

Frequent removal of biomass leads to a reduction in N limitation in the H2 simulation due to reduced N demand by soil decomposition. This is counterintuitive to the hypothesis that frequent removal of nitrogen would lead to higher N limitation. In the model, soil pools are described with constant C/N ratios and the soil C pool with the highest resistance (humus) has the smallest C/N ratio. Therefore, N is needed for the decomposition process from more labile C pools with higher C/N ratio to humus. This coherence is also described by Manzoni et al. (2008). Meaning that with higher soil C content, more N is immobilized, and with lower soil C content, as seen with increased harvest, less N is immobilized. With unchanged N inputs, this leads to higher N availability in the model.

Frequent removal of both C and N can also lead to degradation in available N. In meta-analysis both a decline in soil C due to harvest (Nave et al., 2010; Olsson et al., 1996) and no clear effect of harvest on soil C or N (Johnson & Curtis, 2001; Olsson et al., 1996) have been concluded. In those studies, the main factors for the effect of harvest on soil C and N were found to be the harvest method, particularly residue management, forest type, and soil type. For a comprehensive assessment of the impact of harvest on C and N turnover in an afforestation and CE context, all those processes need to be considered. C sequestration assessed in this study refers to the difference between NPP and soil decomposition. However, for a more detailed analysis of the impact of harvest on climate change, the fate of the harvested biomass and potentials for fossil fuel substitution need to be considered in addition.

From forests, mainly woody biomass with high C/N ratio is harvested and in the H2 experiment removal of C has a more drastic impact on N limitation than removal of N. The possibility of higher N limitation of soil decomposition under CO_2 fertilization has been discussed earlier. Hence, the harvest simulation indicates that particularly frequent removal of biomass with high C/N ratio and subsequent depletion in soil C can lead to improved N status.

Improving the N status of forests is the intension when applying fertilizer. As expected, NPP increases with fertilizer application, however, the increase in C uptake by NPP is partly offset by simultaneous increase in SR and additional emissions of N_2O. The effect of N inputs on soil processes is often neglected and only the stimulating effect on plant growth is assessed (e.g., Thomas et al., 2009). Zhou et al. (2016) found a range of 5.8%−31.5% offset of C sequestration by N_2O emissions for rubber plantations replacing tropical rain forests, which is similar to the range found in this study by applying lower and upper limits for the N_2O EF. Hence, fertilizer application is a method to trigger for instance boreal expansion of forests that would otherwise be hampered by N limitation; however, the gain in C sequestration can be offset to a large part by emitted N_2O.

5. Conclusions

In this study, I show that large-scale afforestation is a measure to enhance terrestrial C sequestration, also when considering N limitation. However, N limitation reduces the potential of afforestation to sequester C drastically, especially by hampering boreal forest expansion. I find that in particular soil processes are a crucial factor influencing the effect of N limitation on C sequestration and its sensitivity to climate and management. Warming for instance leads to higher N availability by enhancing mineralization, thus triggering boreal forest expansion. However, as not only NPP is stimulated but also SR, the effect of warming on C gain is small. A similar compensation happens in the tropics. Here, both NPP and SR are limited by N such that a limitation does not get obvious for C uptake. Increased harvest of forests has shown to be beneficial for C uptake by reducing soil C turnover and thus the demand of soil decomposition for N alleviating limitation. Fertilizer application enhanced C sequestration but can induce large compensating effects by stimulating SR and enhancing N_2O emissions from soil.

Future estimates of terrestrial C sink consider boreal forest expansion which might be limited by N availability. Furthermore, dispersal rates of forests and thus their migration rates are likely to be overestimated by models (Davis & Shaw, 2001; Svenning & Skov, 2004) such that the contribution of boreal expansion to C uptake is likely to be smaller than expected.

The overall conclusions from this study to a large extent depend on the model setup. In this study, soil decomposition can be limited by N availability due to the different C/N ratios of the soil C pools. In models pursuing a similar approach, simulations will likely show a similar effect of N limitation. Field and lab experiments indicate that under CO_2 fertilization, limitation of soil decomposition is to be expected, but there is no clear evidence. Hence, this study does not claim to provide realistic predictions. Instead, it aims at analyzing the interplay between C and N dynamics for afforestation and the sensitivity to different forcings from a qualitative perspective. It further highlights the importance of a careful interpretation of simulation results, keeping in mind the influence of the concept pursued by the model.

Due to the compensating effects of NPP and SR for C uptake, N limitation cannot be diagnosed comprehensively by analyzing changes in C stocks only. With this study, I want to highlight the importance of taking into account soil decomposition for both modeling and observational experiments. The effect of N limitation and N addition on soil decomposition is crucial as it can offset the C gain from enhanced NPP under CO_2 fertilization. Field and lab experiments on that aspect, as well as an intercomparison between models following different approaches to represent soil processes, would be beneficial for a better understanding of future changes. Particularly for the tropics, such investigations are still scarce.

This study focuses on the effect of future forest expansion for C sequestration considering N limitation. Large-scale afforestation is discussed in a climate engineering context as a measure to increase the terrestrial C sink. This study shows that drawbacks related to N dynamics are to be expected.

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