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LETTER

Nitrogen and phosphorous limitation reduces the effects of land use change on land carbon uptake or emission

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Abstract

We used an Earth System Model that includes both nitrogen (N) and phosphorus (P) cycling to simulate the impacts of land-use and land-cover change (LULCC) for two representative concentration pathways (RCPs): a reforestation scenario (RCP4.5) and a deforestation scenario (RCP8.5). For each RCP, we performed simulations with and without LULCC using the carbon (C only) mode or including the full C, N and P cycles (CNP). We show, for the first time, that inclusion of N and P cycling reduces both the carbon uptake from reforestation in RCP4.5 and the carbon emission from deforestation in RCP8.5. Specifically, carbon-nutrient interaction reduces carbon uptake in RCP4.5 from 55 Pg C (C only) to 21 Pg C (CNP), or the emissions in RCP8.5 from 72 Pg C (C only) to 56 Pg C (CNP). Most of those reductions result from much weaker responses of net primary production to CO_2 fertilization and climate change when carbon-nutrient interaction is taken into account, as compared to C only simulations. Our results highlight the importance of including nutrient-carbon interaction in estimating the carbon benefit from reforestation and carbon loss from deforestation in a future world with higher CO_2 and a warmer climate. Because of the stronger nutrient limitation, carbon gain from reforestation in the temperate and boreal regions is much less than the carbon loss from deforestation in the subtropical and tropical regions from 2006 to 2100 for the two RCPs. Therefore protecting the existing subtropical and tropical forests is about twice as effective as planting new forests in the temperate and boreal regions for climate mitigation.

1. Introduction

Land-use and land-cover change (LULCC) affects the surface climate by altering the surface albedo, energy balance and its partition between latent and sensible heat fluxes (the biophysical effect) (Boisier *et al* 2012) and by changing the global carbon cycle and atmospheric CO_2 concentration (the biogeochemical effect) Brovkin *et al* (2013). The biophysical effect on global and regional climate has been extensively studied (Pielke *et al* 2011). The biogeochemical effect has only been explored recently as global climate models are expanded to include the interactions between climate change and the carbon cycle (Friedlingstein *et al* 2006, Arora *et al* 2013).

LULCC includes reforestation, deforestation, and land management such as wood harvest and shifting cultivation. Generally, deforestation results in an emission of carbon stored in plant biomass and soils whereas the regrowth of forests on abandoned croplands increases the amount of carbon sequestration on the land (Guo and Gifford 2002). For the historical period (1850–2005) the total CO_2 emission from LULCC was estimated to be 150 ± 80 Pg C, and a similar amount of carbon was also taken up by land biosphere over the same period (Ciais *et al* 2013). Without the increased land carbon uptake, CO_2 emission from LULCC since the 1860s would have led to about 0.3 °C additional warming (Shevliakova *et al* 2013). Reforestation (and the decrease of deforestation) has therefore been advocated as a strategy for mitigating future climate change because converting cropland to forest can significantly increase soil carbon and slow the rate of atmospheric CO_2 increase

(Canadell and Raupach 2008). However it is highly uncertain how effective reforestation will be as a climate mitigation strategy since the rate of carbon accumulation depends on the interaction of nutrient cycles with the carbon cycle and how these interactions will change under future climate conditions (Arneth *et al* 2010).

Previous studies have shown that N and P limitation already constrains the terrestrial carbon uptake and will continue to do so in the 21st century. Although some earlier studies have included the combined effects of LULCC and nutrient cycling (Thornton *et al* 2009, Yang *et al* 2009), the inclusion of carbon-nutrient interactions on the land-use emissions were explicitly analyzed (Jain *et al* 2013, Zhang *et al* 2013) only very recently. When carbon-nitrogen interaction is taken into account, Jain *et al* (2013) simulated higher land-use emissions for the industrial era because nitrogen limitation reduces the net ecosystem carbon uptake by secondary vegetation, but has little effect on the CO_2 emission from the deforested land. As a result, more net CO_2 is emitted under nitrogen limitation than that in their C-cycle only simulation. However, the results by Jain *et al* (2013) are not supported by other studies over the same period (Gerber *et al* 2013, Zhang *et al* 2013). Overall, the inclusion of carbon-nutrient interactions on estimated CO_2 emissions from LULCC remain highly uncertain both in terms of magnitude and sign.

Carbon-nutrient interaction varies regionally. N limitation dominates in temperate and boreal regions and P limitation dominates in the tropics and southern hemisphere (Wang *et al* 2010, Goll *et al* 2012, Zhang *et al* 2013). The projected land use change in the future also has a strong regional variation. In the latest representative concentration pathways (RCP) for the fifth assessment report (AR5) by the Intergovernmental Panel on Climate Change (IPCC), reforestation occurs in the temperate and boreal regions in RCP4.5 scenario, whereas deforestation expands in the tropics and southern hemisphere in RCP8.5 scenario. Given that LULCC is a phenomenon with a clear regional signal, and that N and P limitation affects the land carbon balance in different ways in different regions, it is reasonable to suppose that a spatially explicit representation of the carbon-nutrient interaction under land use change is required for accurately estimating the impact of LULCC on atmosphere-land CO_2 exchange.

Most previous LULCC studies focused on the historical period (Houghton *et al* 2012, Shevliakova *et al* 2013,). How LULCC affects the future carbon cycle and associated climate change has been explored using either highly simplified Earth system model (ESMs) (Sitch *et al* 2005, Strassman *et al* 2008), or simulations based on extreme scenarios of deforestation or reforestation (Bala *et al* 2007). More realistic temporal and spatial LULCC scenarios, such as those used for the Phase 5 of Coupled Model Intercomparison Project (CMIP5), are needed for ESMs for future climate projection (Moss *et al* 2010, Taylor *et al* 2012). For future scenarios, only Brovkin *et al* (2013) have analyzed the impact of LULCC on land carbon storage using a subset of ESM simulations for two net deforestation trajectories compatible to the lowest and highest emission scenarios (RCP2.6 and RCP8.5). However, Brovkin *et al* (2013) did not explore any net reforestation trajectory consistent with the medium mitigation scenario RCP4.5. More importantly, none of their simulations accounted for carbon-nutrient interactions.

Here, we present the first study of CO_2 emissions from deforestation or CO_2 uptake from reforestation on the projected global carbon cycle using an ESM that includes both N and P limitation on land. We examine, in particular, the impact of LULCC for the 21st century using two contrasting land use projections compatible with RCPs used for IPCC AR5. These RCPs differ in terms of their radiative forcing (approximating an increase in global forcing of ~4.5 and 8.5 W m^{-2} respectively). However, they also contrast in how LULCC is prescribed (figure 1(a)). RCP 4.5 represents a reforestation scenario where forest cover recovers from $\sim 47 \times 10^6$ km^2 in 2006 to $\sim 51 \times 10^6$ km^2 in 2100. RCP 8.5 is a deforestation scenario where forest cover falls to 43×10^6 km^2 in 2100. There are changes in total crop area (figure 1(b)) which mirror the changes in total forest area and change in total grass area that vary largely in terms of the timing of changes (figure 1(b)). The area of afforestation in RCP4.5 is similar to the area of deforestation in RCP8.5. We therefore examine the impact of these two LULCC scenarios on the global carbon budget in carbon-only (C-only) simulations and in simulations including N and P cycling (CNP). Our aim is to how much carbon-nutrient interaction will affect the global and regional-scale impact of LULCC on the future terrestrial carbon budget.

2. Methods

We used a climate model Mk3L (Phipps *et al* 2011) coupled with a land surface model, CABLE (Wang *et al* 2011) and a global biogeochemical model CASA-CNP (Wang *et al* 2010). CABLE simulates the temporal evolution of heat, water and momentum fluxes at the surface as well as the biogeochemical cycles of carbon, nitrogen and phosphorus in the land system. Both Mk3L and CABLE have been extensively evaluated (Abramowitz *et al* 2008, Phipps *et al* 2011, Wang *et al* 2011). The Mk3L model has been further examined by exploring the 20th century carbon balance and their uncertainties under N and P limitation (Zhang *et al* 2011, Exbrayat *et al* 2013). By including transient LULCC in Mk3L, the influences of N and P cycling on historical terrestrial carbon uptake and land use carbon emissions were explored in our

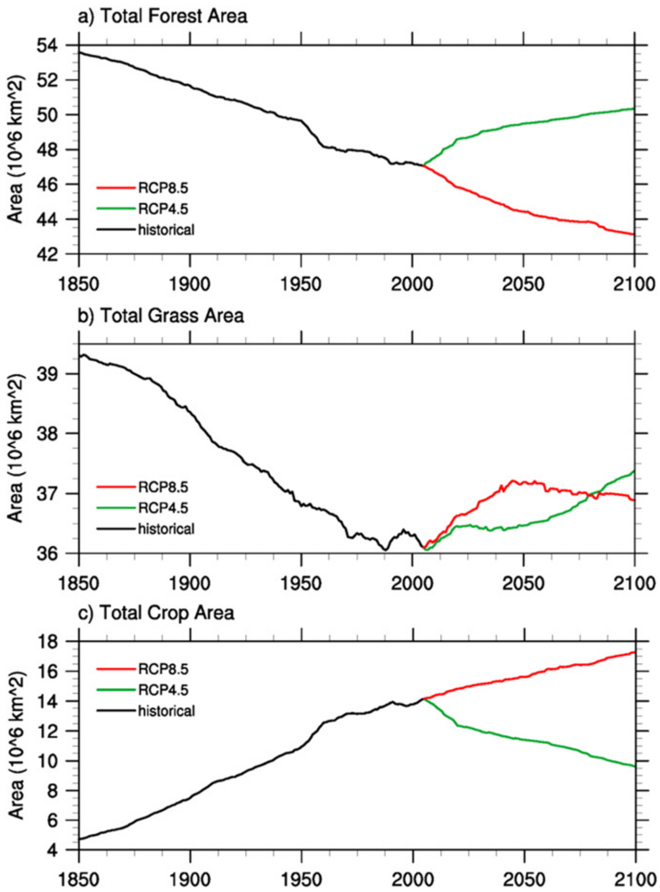

Figure 1. CMIP5 global historical and RCP land cover changes in land area (10^6 km^2). Note that the *y*-axis scale is different for each panel. The top panel shows total forest area, the middle panel shows total grass area and the lower panel shows total crop area.

earlier study (Zhang *et al* 2013) who found that nutrient-carbon interaction reduced the estimated net CO_2 emission from land use and land use change from 1850 to 2005 by 33 Pg C or 25%.

In this study we used the land cover changes (Hurtt *et al* 2011) interpreted by Lawrence *et al* (2012) for the historical and the RCP periods from 2006 to 2100. To investigate the potential impact of LULCC over the 21st century, land cover trajectories for RCP 4.5 and RCP 8.5 are used because of the large reforestation and deforestation activities in these two scenarios (figure 1). Globally the total forested area increases by 7% in the reforestation scenario (RCP4.5) or decreases by 8% in the deforestation scenario (RCP8.5) from 2006 to 2100. Regionally, the area fractions of forests and grasslands increase while the area fraction of cropland decreases in eastern USA, Europe and Africa for RCP4.5. The area fraction of forests decreases and the area fractions of grassland or cropland increase in the tropics and southern subtropical and temperate regions for RCP8.5 (see figure 2).

To simulate the effects of LULCC on terrestrial carbon cycle, harvest is invoked at the end of each model year, and the harvested biomass of herbaceous vegetation is deposited into litter pools. For woody PFTs, only the deforested biomass in wood, or harvested wood is collected for human use, the deforested biomass in leaves and roots are transferred to litter pools. Harvested wood is partitioned equally among three anthropogenic pools characterized by their turnover rates: fuel wood (1 year^{-1}), paper and paper products (0.1 year^{-1}) and wood products (0.01 year^{-1}), similar to Zhang *et al* (2013). Our model has no explicit representation for primary or secondary forest, or the wood harvest without LULCC. In the case of crop abandonment, natural vegetation is specified to re-grow from the time of agricultural abandonment. For simplicity, we used the time-invariant nitrogen deposition reflecting 1990s condition from Dentener (2006) and dust phosphorous deposition reflecting 1990s conditions from Mahowald *et al* (2008) in all simulations.

The atmosphere model was forced by annual CO_2 concentrations from the CMIP5 database from 1850 through to 2005. From 2006, yearly CO_2 concentrations representing RCP 4.5 and RCP 8.5 were used through to 2100. The ocean sea surface temperatures (SSTs) were prescribed using monthly SSTs simulated by CSIRO-Mk3.6 (Rotstayn *et al* 2010, Rotstayn *et al* 2012) for the CMIP5 experiments associated with the same CMIP5 CO_2 time series from 1850 to 2100. For model spin-up, we forced Mk3L repeatedly with

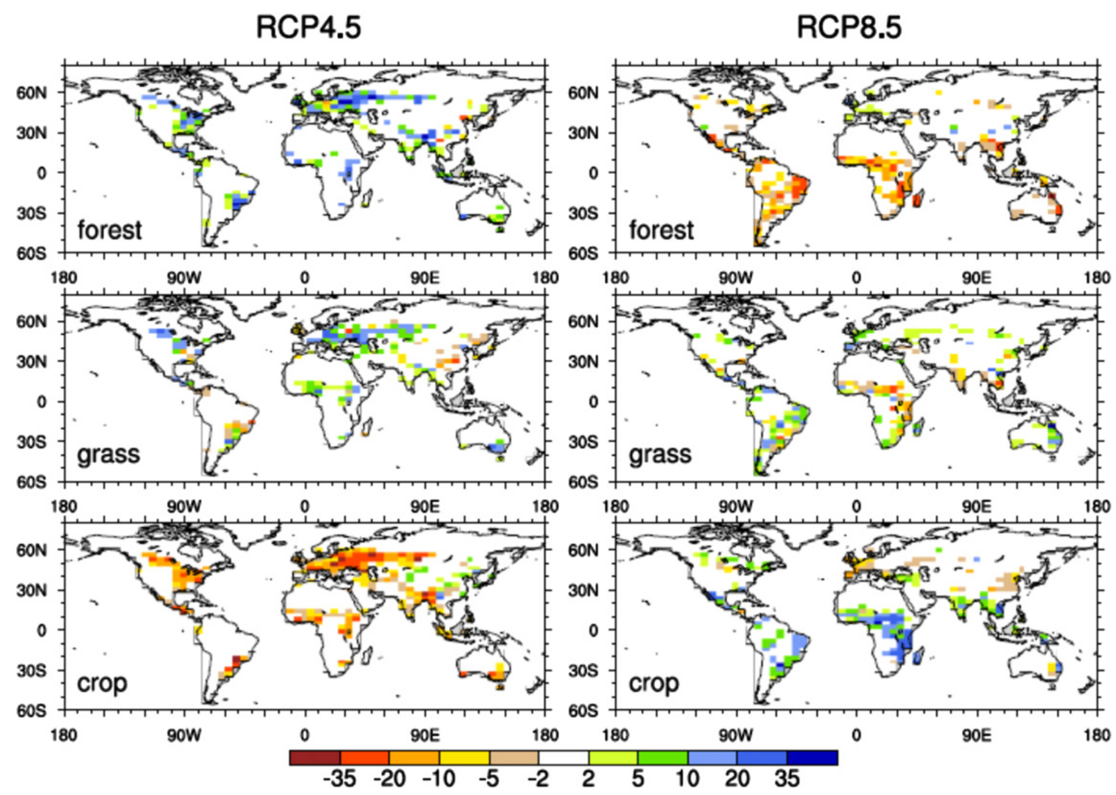

Figure 2. Fractional changes in coverage of woody (top), grass (middle) and crop (bottom) plant functional types (PFTs) for RCP4.5 (left) and RCP8.5 (right) from 2006 to 2100.

Table 1. List of simulation experiments conducted.

Experiment	Configuration	
	Land use configuration	*Nutrients*
CTL-C	Constant at 2006 through to 2100	No nutrient limitation
CTL-CNP	Constant at 2006 through to 2100	Limited by nitrogen and phosphorous
LUC-C	Changing according to RCP	No nutrient limitation
LUC-CNP	Changing according to RCP	Limited by nitrogen and phosphorous

SSTs from Mk3.6 for 1850–1879 to stable states for the carbon cycle only (C), carbon, nitrogen and phosphorous cycles (CNP) cases under conditions of CO_2 and land cover in 1850. 200 year preindustrial control simulations under spin-up conditions repeatedly using the SSTs from 1850 to 1979 were then performed before forward model integration from 1850 to 2100. An ensemble of three historical simulations is initialized at 10 years intervals from the last 30 years of 200 years control simulation under the pre-industrial condition for each of the C and CNP cases using land cover changes from 1850 to 2005. The differences among three ensemble members are quite small (<1%), therefore only the means of ensemble simulations are presented here.

To evaluate the impacts of carbon-nutrient interaction on LULCC in the 21st century, we performed two sets of experiments for each of the C and CNP ensembles from 2006–2100 (see table 1). In the LUC experiment, the model was run using the land use change and CO_2 data for the reforestation (RCP 4.5) or deforestation (RCP 8.5) scenario from 2006 to 2100. In the CTL experiment, the same simulations were run except the vegetation distribution was kept constant after 2005. Because the initial carbon pool sizes in 2005 are the same for C-only or CNP simulations, but are different between C-only and CNP simulations, the differences in the changes in total carbon pool size between the LUC and CTL simulations at time t after 2005 represent the effect of LULCC on accumulated net atmosphere-land CO_2 exchange, or F_{LUC}. The difference in the estimated F_{LUC} using C-only or CNP simulation represents the effect of carbon-nutrient interaction. This is further explained in the next section.

3. Effect of carbon-nutrient interaction on atmosphere-land CO_2 exchange

As explained in Zhang *et al* (2013), the effect of LULCC on net atmosphere-land CO_2 exchange (f_{LUC}) at time t

can be estimated as

$$f_{\mathrm{LUC}}(t) = f^{*}_{\mathrm{NBP}}(t) - f_{\mathrm{NBP}}(t), \quad (1)$$

where f^{*}_{NBP} and f_{NBP} represent the atmosphere-land CO_2 exchange for a land point with or without LULCC, respectively; and are calculated as

$$f^{*}_{\mathrm{NBP}}(t) = \frac{\mathrm{d}c^{*}_{V}}{\mathrm{d}t} + \frac{\mathrm{d}c^{*}_{L}}{\mathrm{d}t} + \frac{\mathrm{d}c^{*}_{S}}{\mathrm{d}t} + \frac{\mathrm{d}c^{*}_{P}}{\mathrm{d}t} = f^{*}_{\mathrm{GPP}} - r^{*}_{V} - r^{*}_{L} - r^{*}_{S} - f^{*}_{P} \quad (2)$$

and

$$f_{\mathrm{NBP}}(t) = \frac{\mathrm{d}c_{V}}{\mathrm{d}t} + \frac{\mathrm{d}c_{L}}{\mathrm{d}t} + \frac{\mathrm{d}c_{S}}{\mathrm{d}t} + \frac{\mathrm{d}c_{P}}{\mathrm{d}t} = f_{\mathrm{GPP}} - r_{V} - r_{L} - r_{S} - f_{P}, \quad (3)$$

where c^{*}_{V}, c^{*}_{L}, c^{*}_{S} and c^{*}_{P} and represent carbon pool sizes in vegetation biomass, litter, soil and wood product of a land point with LULCC, respectively; c_V, c_L, c_S and c_P are carbon pool sizes in vegetation biomass, litter, soil and wood product of that land point without LULCC. f^{*}_{GPP}, r^{*}_{V}, r^{*}_{L}, r^{*}_{S} and f^{*}_{P} represent gross primary production, autotrophic plant respiration, litter respiration, heterotrophic soil respiration and decomposition of wood product of a land point with LULCC, respectively; and corresponding fluxes for that land point without LULCC are represented similarly but without star as superscript in equation (3).

The accumulated effect of LULCC on atmosphere-land CO_2 exchange since time $t = 0$ is given by

$$F_{\mathrm{LUC}}(t) = \int_0^t f_{\mathrm{LUC}}(\tau)\,\mathrm{d}\tau = \left(c^{*}_{V}(t) - c_{V}(t)\right) + \left(c^{*}_{L}(t) - c_{L}(t)\right) + \left(c^{*}_{S}(t) - c_{S}(t)\right) + \left(c^{*}_{P}(t) - c_{P}(t)\right). \quad (4)$$

Here we assume $c^{*}_{V} = c_V$, $c^{*}_{L} = c_L$, $c^{*}_{S} = c_S$ and $c^{*}_{P} = c_P$ at $t = 0$ or year 2005, therefore $f_{\mathrm{LUC}}(t = 0) = 0$. We use the sign convention that a negative value for a net carbon emission from land to atmosphere and a positive value for a net carbon uptake by land from atmosphere.

Equation (4) shows that F_{LUC} at time t can be computed from the differences in the sizes of plant, litter, soil organic carbon and wood product pools as simulated by two separate runs with Mk3L+CABLE: one with LULCC and the other without.

Because carbon-nutrient interaction affects carbon flux rather than pool size directly, to help interpret our simulation results, we can also calculate F_{LUC} as a function of the changes in the accumulated carbon fluxes. That is:

$$F_{\mathrm{LUC}} = \underbrace{\Delta F_{\mathrm{NPP}} - \Delta F_{W} - \Delta F_{L}}_{\Delta c_V} + \underbrace{\Delta F_{L} - \Delta R_{H}}_{\Delta c_L + \Delta c_S} + \underbrace{\Delta F_{W} - \Delta F_{P}}_{\Delta c_P} \quad (5)$$

or

$$F_{\mathrm{LUC}} = \Delta F_{\mathrm{GPP}} - \Delta R_{V} - \Delta R_{H} - \Delta F_{P} = \Delta F_{\mathrm{NPP}} - \Delta R_{H} - \Delta F_{P}, \quad (6)$$

where ΔF_{NPP} is the difference in the accumulated net primary production with and without LULCC, and $\Delta F_{\mathrm{NPP}} = \Delta F_{\mathrm{GPP}} - \Delta R_{V}$. ΔF_{W} and ΔF_{L} are the differences in the accumulated total carbon from wood harvest and litter fall between the simulations with and without LULCC, respectively. All other terms on the right-hand side of equation (6) are as defined in equations (9)–(12) in Zhang *et al* (2013).

Effect of nutrient limitation on the estimated F_{LUC}, or ΔF_{LUC}, can be estimated as

$$\Delta F_{\mathrm{LUC}} = F^{C}_{\mathrm{LUC}} - F^{\mathrm{CNP}}_{\mathrm{LUC}} = \Delta\Delta F_{\mathrm{NPP}} - \Delta\Delta R_{H} - \Delta\Delta F_{P}, \quad (7)$$

where F^{C}_{LUC} and $F^{\mathrm{CNP}}_{\mathrm{LUC}}$ represent the accumulated atmosphere-land CO_2 exchange from LULCC estimated using Mk3L with C only or CNP simulation, respectively; and $\Delta\Delta F_{\mathrm{NPP}}$, $\Delta\Delta R_H$ and $\Delta\Delta F_P$ represent the difference in ΔF_{NPP}, ΔR_H and ΔF_P between the CNP and C-only simulations, respectively.

4. Results

The simulated changes in total land carbon, and its three components (vegetation, litter+soil and wood product) from 2006 to 2100 are shown in table 2 for each of the eight simulations. If the total land carbon in 2100 is less than that in 2006, the land is a net CO_2 source. Change in total carbon pool size for each simulation depends on three factors: concentration pathways (RCP4.5 or RCP8.5) and associated climate change, LULCC and carbon-nutrient interaction. For both RCPs with or without LULCC, the size of the vegetation carbon pool increases, while total carbon in wood product decreases from 2006 to 2100 for all eight simulations. The global litter+soil carbon decreases, relative to the C-only simulations, for both RCPs if carbon-nutrient interaction is considered. If nutrients are not included, the global soil carbon increases under RCP4.5, but decreases under RCP8.5 from 2006 to 2100 (see table 2).

For RCP4.5, both LUC-C and LUC-CNP experiments as described in table 1 simulated a continuous land carbon increase over the period 2006–2100 (see figure 3(a)). For RCP8.5, the land sink peaks around 2080 and then declines through to 2100 (figure 3(a)). These changes are largely driven by the increase of atmospheric CO_2 and land surface warming (Friedlingstein *et al* 2006). Inclusion of N and P limitation strongly suppressed land carbon accumulation on

Table 2. Changes in vegetation carbon, litter and soil carbon or carbon in the harvested wood product, or total land biosphere carbon (total) from 2006 to 2100, and accumulated CO_2 emission or uptake due to land use change over the same period (F_{LUC}). Positive values are for carbon uptake by land biosphere and negative values for carbon emission from land biosphere. The unit is Pg C for all numbers.

	Vegetation	Litter + soil	Wood product	Total	FLUC
			RCP4.5		
CTL-C	92	21	−14	99	
LUC-C	129	36	−11	154	55
CTL-CNP	58	−16	−12	30	
LUC-CNP	77	−16	−10	51	21
			RCP8.5		
CTL-C	129	−4	−14	111	
LUC-C	64	−23	−2	39	−72
CTL-CNP	83	−44	−12	27	
LUC-CNP	31	−58	−2	−29	−56

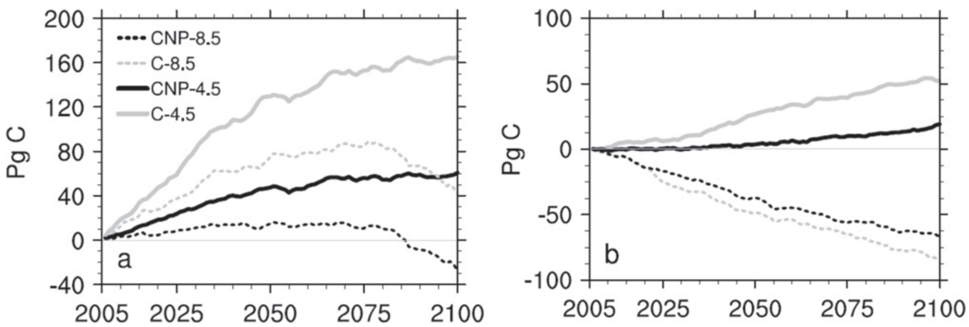

Figure 3. (a) Changes in total land carbon store in Pg C/year including LULCC and (b) the accumulated carbon emissions/additional uptake in Pg C due to LULCC (differences of land carbon uptake between LUC and CTL simulations) for RCP 4.5 and RCP 8.5 from 2006–2100 (all units in Pg C). Positive value represents a carbon uptake by land biosphere from atmosphere and vice versa.

both natural and disturbed lands, resulting in a total decrease of land carbon uptake ('LUC-CNP' minus 'LUC-C') by 103 (51 – 154 = −103) Pg C for RCP4.5 or 68 (−29 – 39 = −68) Pg C for RCP8.5 from 2006 to 2100. In contrast to all other seven simulations, LUC-CNP for RCP8.5 simulates a net carbon source (−29 Pg C, figure 3(a)) because the increase in vegetation carbon is less than the respiration loss of carbon from litter and soil (table 2).

By comparing the LUC and CTL simulations, agriculture abandonment and reforestation as in RCP4.5 leads to a net carbon uptake, while expanded deforestation leads to a net carbon emission in RCP8.5 (figure 3(b)). Including N and P limitation in our model reduces both the carbon uptake associated with RCP4.5 from 55 Pg C (C-only) to 21 Pg C and the carbon emission associated with RCP8.5 from 72 Pg C (C-only) to 56 Pg C from 2006 to 2100.

To understand the effect of nutrient-carbon interaction on the estimated atmosphere-land CO_2 exchange from LULCC, we aggregate all land types into three broad categories: forest, crop and grass type including shrub and tundra, and then divide the total carbon pool changes by the components of the carbon stores in vegetation, litter+soil and wood product for each of three land types. We then identify the land type that is most sensitive to nutrient-carbon interaction and the underlying mechanism.

Results in table 3 show that the forest biomass carbon change is the largest contributor to the estimated net carbon uptake from reforestation (RCP4.5) or net carbon emission from deforestation (RCP8.5) for both C-only and CNP simulations.

For RCP4.5, reforestation results in a net carbon uptake of 66 Pg C by forests and 7 Pg C by grasslands, and a net carbon loss of 19 Pg C from croplands from 2006 to 2100 for the C-only simulation (see table 3). Nutrient carbon interaction, as quantified by the difference between CNP simulation and C-only simulation, reduces net carbon uptake by forests from 66 to 36 Pg C, but has relatively small effect on the net carbon uptake by grasslands or emission by croplands.

The effect of nutrient carbon interaction on estimated net carbon uptake from reforestation can be explained by the changes in major carbon fluxes in each of three land types. For forests, reforestation increases NPP by 197 Pg C, of which 147 Pg C is exported as litter input to litter and soil pool, and 11 Pg C is exported from wood harvest (see figure 4). Vegetation biomass therefore increases by 39 Pg C from 2006 to 2100 for C-only. Those increases are mainly driven by the strong CO_2 fertilization effect on NPP in the C-only simulation and the expansion of forest area. When nutrient carbon interaction is taken into account, as in CNP simulation, the CO_2 fertilization effect on NPP is much reduced (99 Pg C only), and

Table 3. Differences in the carbon pools of forest, grass, crop or total land biosphere carbon (Total) in vegetation ($\Delta c_V = c_V^* - c_V$), soil and litter ($\Delta c_L + \Delta c_S = c_L^* + c_S^* - c_L - c_S$) or wood product ($\Delta c_P = c_P^* - c_P$) pools due to reforestation or deforestation from 2006 to 2100 (positive value for an increase in pool size and negative value for a decrease in pool size from 2006 to 2100). The unit is Pg C for all the numbers.

Carbon pool change	'LUC-C'-'CTL-C'				'LUC-CNP'-'CTL-CNP'			
	Forest	Grass	Crop	Total	Forest	Grass	Crop	Total
				RCP4.5				
Δc_V	39	1	−3	37	21	2	−3	19
$\Delta c_L + \Delta c_S$	25	6	−16	15	13	4	−17	0
Δc_P	2	0	0	3	2	0	0	2
$\Delta c_V + \Delta c_L + \Delta c_S + \Delta c_P$	66	7	−19	55	36	6	−20	21
				RCP8.5				
Δc_V	−68	2	2	−64	−55	2	2	−51
$\Delta c_L + \Delta c_S$	−28	5	5	−18	−24	4	4	−16
Δc_P	11	0	0	11	10	0	0	10
$\Delta c_V + \Delta c_L + \Delta c_S + \Delta c_P$	−85	7	7	−71	−69	6	6	−57

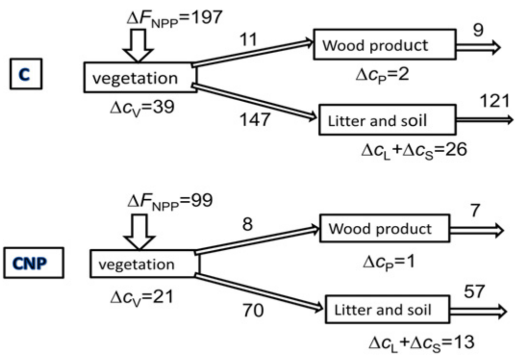

Figure 4. Differences (LUC-CTL) in the accumulated fluxes of net primary production (ΔF_{NPP}), and pool sizes due to reforestation for forests for C-only simulation or CNP simulation. Differences in the accumulated fluxes from vegetation to litter+soil carbon pool, or to wood product pools are also stated besides the arrows in the figure.

increases in NPP increase and litter input to litter and soil pool are only half as much as those in C-only simulation. As a result, the vegetation biomass only increases by 21 Pg C in CNP simulation, or 18 Pg C less than that in C-only simulation. Changes in forest biomass are quite small for both C-only and CNP simulation, because changes in NPP are largely balanced out by the changes in litter fall fluxes. Effect of nutrient limitation on net carbon balance of grasslands and croplands are relatively small (table 3).

Deforestation, as in RCP8.5, reduces the forest biomass by 68 Pg C for C-only simulation, and 55 Pg C for CNP simulation. This difference contributes to over 90% of the difference in the estimated net CO_2 emission from deforestation between C-only and CNP simulations. Deforestation increases all carbon pools in grasslands and croplands from 2006 to 2100, largely due to the increases in their areas from 2006 to 2100, and varies very little between C-only and CNP simulations (see table 3).

The effect of carbon-nutrient interaction on the estimated CO_2 emission from deforestation can also be explained by the different responses to CO_2 fertilization and climate between C-only and CNP simulations. Due to strong CO_2 fertilization, vegetation biomass in C-only simulation accumulates much faster, therefore the forests (before harvest) have greater biomass than those in the CNP simulation. As a consequence, more vegetation biomass is lost in the C-only simulations at harvest than in the CNP simulation (see table 3).

As a result of deforestation, the total area of grasslands and croplands increase from 2006 to 2100. The simulated increases in all major accumulated carbon fluxes in grasslands and croplands result from the increases in their areas and the effect of CO_2 fertilization on accumulated NPP. Due to stronger CO_2 fertilization in C-only simulation, in comparison to CNP simulations, increases in the accumulated NPP in C-only simulation for grasslands and croplands are higher than those in the CNP simulation. Due to the fast turnover rate of carbon in grassland and cropland, most of the increases in accumulated NPPs are lost by respiration. As a result, net carbon uptake by grassland and croplands together only increases by 14 Pg C for C-only simulation and 12 Pg C for CNP simulation.

Since both LULCC and carbon-nutrient interactions vary regionally, their effects on land carbon uptake also vary significantly from region to region. Figure 5 shows the impact of atmospheric CO_2 concentration increase and land surface warming without LULCC on net biosphere production (NBP) from 2006 to 2100. NBP is here defined as the change of the amount of carbon in plant, litter, soil and wood product. The temperate forests in eastern USA and middle northern latitudes and boreal forests in Russian become a carbon sink, while the tropical forest in south America, Africa and Australia, and subtropical forests in China become a carbon source for both RCPs. The magnitudes of the carbon sinks or sources without including carbon-nutrient interaction (see figures 5(a) and (c)) are up to three times higher those with including carbon-nutrient interaction for most regions except part of central Africa and southern China from 2006 to 2100 (see figures 5(b) and (d)).

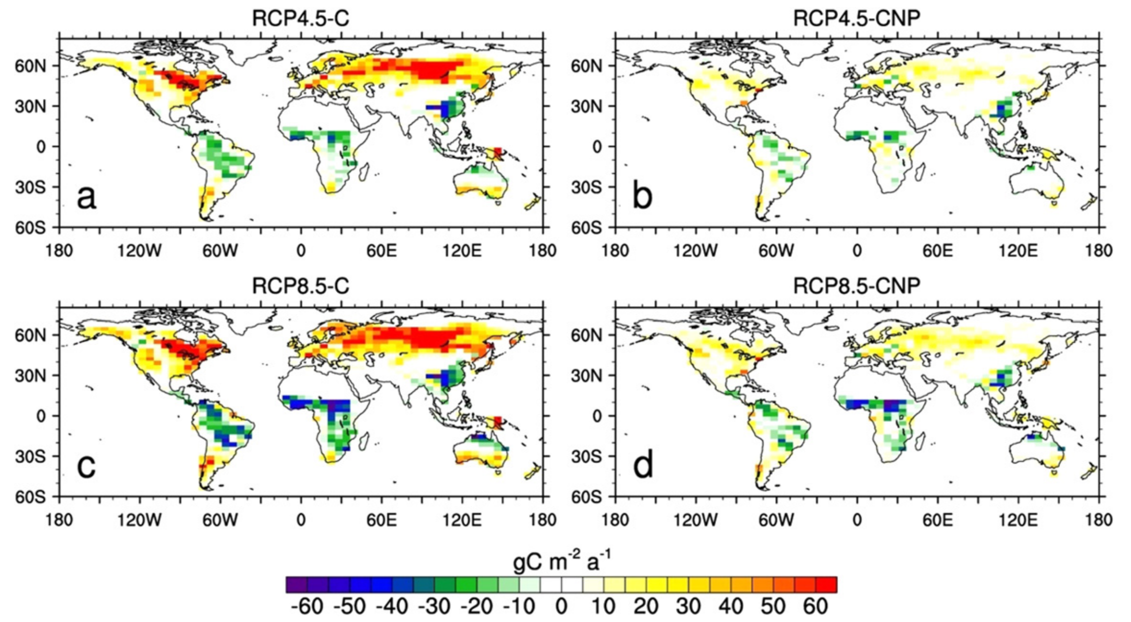

Figure 5. Average annual net biosphere production (NBP) for RCP4.5 and RCP8.5 (2006–2100) excluding LULCC. Panels (a) and (c) omit carbon-nutrient interaction, panels (b) and (d) include limitation by nitrogen and phosphorous. All quantities are in g C m^{-2} a^{-1}. Positive values represent a net carbon uptake by land biosphere.

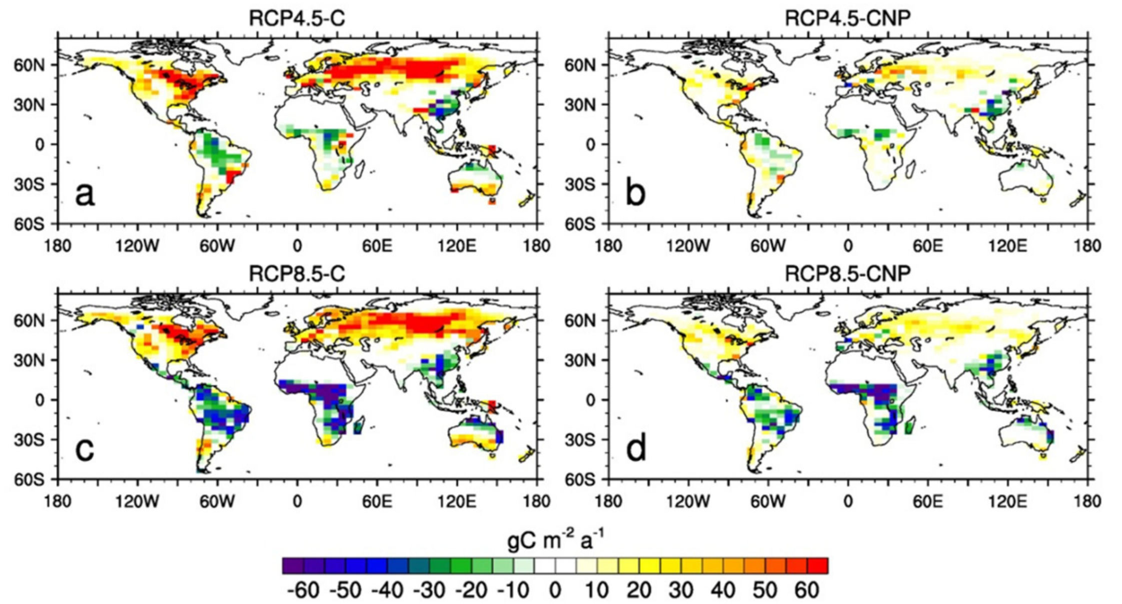

Figure 6. Average annual net biosphere production (NBP) for RCP4.5 and RCP8.5 (2006–2100) including LULCC. Panels (a) and (c) omit carbon-nutrient interaction, panels (b) and (d) include limitation by nitrogen and phosphorous. Positive value represents a net carbon uptake by land biosphere. NBP is calculated as the change of carbon pools in plant, litter, soil and wood product.

If LULCC from 2006 to 2100 is included in addition to changes in atmospheric CO_2 and climate, the simulated global pattern of carbon sinks and sources as shown in figure 6 is quite similar to that without LULCC (see figure 5). Therefore, a large fraction of these changes in NBP or the global pattern of carbon sinks and sources from 2006 to 2100 are not related to LULCC, but are substantially a biogeochemical response to changes in the climate and atmospheric CO_2, a response which masks the signal of LULCC.

Figures 6(a) (RCP 4.5) and (c) (RCP 8.5) shows a very large (>50 g C m^{-2} y^{-1}) carbon sink, or positive NBP in the Northern mid-latitudes and a loss of carbon, or negative NBP −20 to −50 g C m^{-2} y^{-1}) in the tropics and Southern subtropics in C-only simulations. When carbon-nutrient interaction is included in our model, the mean annual NBP from 2006 to 2100 for the carbon sink regions at the northern mid-latitude is reduced to 10–30 g C m^{-2} y^{-1} (figures 6(b), (d)), and the rate of carbon loss simulated in the

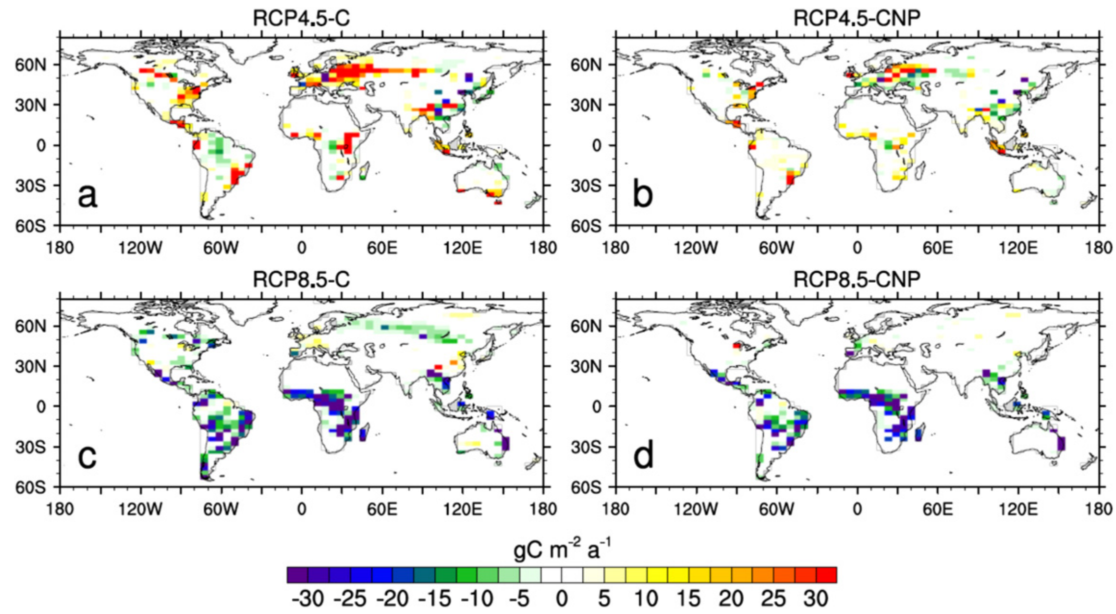

Figure 7. Average annual CO_2 uptake for RCP4.5 or emission for RCP8.5 from land use and land use change from 2006 to 2100. Panels (a) and (c) omit carbon-nutrient interaction or ('LUC_C'-'CTL_C'), panels (b) and (d) include limitation by nitrogen and phosphorous ('LUC_CNP'-'CTL_CNP'). Each panel is calculated as the difference between the corresponding panels in figures 6 and 5. Positive value represents a net carbon uptake by land.

tropics also is much lower for most regions in both RCP4.5 and RCP8.5.

The CO_2 emission from LULCC is estimated as the difference between figure 6 with LULCC and figure 5 without LULCC. The LULCC embedded in the RCP4.5 scenario (reforestation, figure 5(a)) leads to increases in carbon sequestration over the eastern US and Europe (figure 6(a)). These increases in carbon sequestration remain visible under nutrient limitation (figure 7(b)) but are smaller in magnitude and spatial extent.

The tropical deforestation in South America, Africa and Asia embedded in RCP8.5 induces a large loss of carbon (figure 7(c)), which is the largest and most coherent signal on CO_2 emissions and on changes in NBP from LULCC. This LULCC impact in the tropics is only weakly reduced by carbon-nutrient interaction (comparing figures 7(c) and (d)). Therefore nutrient carbon interaction has much greater impact on carbon uptake from afforestation in the middle and high latitudes than on CO_2 emission from deforestation in the tropics and the Southern Hemisphere.

5. Discussion and Conclusions

At the global scale, the reduction in the net carbon uptake by the terrestrial surface due to carbon-nutrient interaction has been shown previously for different historical and future simulations (Sokolov *et al* 2008, Thornton *et al* 2009, Zaehle *et al*2010, Zhang *et al* 2011, 2013, Goll *et al* 2012). However, our results, by combining nitrogen and phosphorous limitation with two future RCP LULCC projections are *the first* to demonstrate that carbon-nutrient interaction reduces both the benefits of reforestation and the cost of deforestation in terms of the global terrestrial carbon balance. From 2006 to 2100, carbon-nutrient interaction reduces the amount of carbon sequestered from reforestation in RCP4.5 by 62%, and the CO_2 emission from deforestation in RCP8.5 by 22% globally. Therefore limitation by nitrogen and phosphorus on land carbon uptake significantly reduces the previously estimated the effectiveness of crop abandonment and reforestation as a climate mitigation strategy (House *et al* 2002, Canadell and Raupach 2008).

Globally the increase in forest area in the reforestation scenario (RCP4.5) is similar to the decrease in forest area in the deforestation scenario (RCP8.5) from 2006 to 2100 but the geographic locations of the forest area change are quite different. Most of the afforestation takes place in the temperate and boreal regions, whereas most deforestation is in the tropics and the Southern Hemisphere. Our study finds that the net carbon emission from deforestation is about twice as much as the net carbon uptake from reforestation from 2006 to 2100. This is because vegetation biomass change is the largest contributor to the estimated change in net land carbon balance from LULCC, and the biomass density in the tropical and subtropical forests is much higher than that in temperate and boreal regions. Therefore it is much more effective for climate mitigation to protect existing tropical and subtropical forests than planting trees in temperate and boreal regions where tree growth is slower and is more strongly limited by nutrient than in the tropical and subtropical regions.

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