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Key Points:
- Allowable emissions with N and P limitations on land are simulated in an ESM
- N and P limitations reduce allowable CO_2 emissions used in RCPs of the IPCC AR5

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Nitrogen and phosphorous limitations significantly reduce future allowable CO_2 emissions

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Abstract Allowable CO_2 emissions are the emissions of CO_2 allowed in order to follow a prescribed atmospheric CO_2 concentration pathway. Allowable emissions depend on the uptake rates by the land and ocean and carbon-climate interaction. Few Earth System Models used for estimating allowable emissions include nitrogen limitation on land, and none include phosphorus. We provide the first estimate of how nitrogen and phosphorus limitations alter the allowable emissions between 2006 and 2100 for two representative concentration pathways (RCPs). We show that nutrient limitations on land have little influence on ocean carbon uptake but reduce the land carbon uptake and allowable emissions by 69 Pg C (21%) for RCP2.6 and by 250 Pg C (13%) for RCP8.5 by 2100, as compared with the emissions estimated using integrated assessment models. We therefore demonstrate the importance of nutrient limitations in estimating future CO_2 emissions to achieve the climate change limits implied by RCPs.

1. Introduction

To assess the effects of different climate mitigation policies on future climate projection, integrated assessment models (IAMs) are used to generate time-evolving atmospheric CO_2 concentrations, or representative concentration pathways (RCPs) that are consistent with different climate scenarios [*Meinshausen et al.*, 2011; *Riahi et al.*, 2011; *Van Vuuren et al.*, 2011]. These RCPs are used to drive Earth System Models (ESMs) to predict future climate change for the fifth assessment (AR5) by the International Panel on Climate Change (IPCC) using a well-defined simulation protocol [*Taylor et al.*, 2012]. ESMs simulate the interactions between the carbon cycle and climate, as well as time evolution of climate, carbon pools in the land biosphere and in the ocean [*Friedlingstein et al.*, 2006; *Jones et al.*, 2013]. By mass balance, the allowable emission for each RCP is calculated as the sum of the changes in atmospheric CO_2 and land and ocean carbon pools. However, only two ESMs used in the IPCC AR5 include nitrogen (N) limitation and none include phosphorus (P) limitation. Given the critical relevance of land-based natural sinks of carbon to future atmospheric CO_2 concentrations [*Denman et al.*, 2007; *Friedlingstein et al.*, 2006] and the impact of N and P limitations on these sinks [*Bonan and Levis*, 2010; *Goll et al.*, 2012; *Sokolov et al.*, 2008; *Thornton et al.*, 2009; *Zaehle et al.*, 2010; *Zhang et al.*, 2011], establishing whether N and P limitations significantly affect the allowable emissions for RCPs used in IPCC AR5 is urgent.

Globally, N limitation commonly dominates temperate and boreal areas, while much of the tropical forests and savannah ecosystems are P limited [*Aerts and Chapin*, 2000]. There is also strong field evidence that nutrient limitation reduces the carbon uptake by different land ecosystems [*Van Groenigen et al.*, 2006; *LeBauer and Treseder*, 2008]. Previous studies using ESMs found that N limitation reduced the global carbon uptake by the land biosphere from 2000 to 2100 by up to 40% [*Sokolov et al.*, 2008; *Thornton et al.* 2009]. Including P limitation will further reduce the simulated rate of land carbon uptake over the same period, as shown in an off-line study using a land surface model [*Goll et al.* 2012]. However, offline simulations do not account for the interrelated biophysical and biogeochemical feedback between the atmosphere, land, and ocean on the simulated climate, and climate variation, and this in turn exerts global and regional bias in predicting future carbon uptakes [*Denman et al.* 2007]. To date, no ESM simulations have been performed to assess the impact of N and P limitations on allowable emissions. It therefore remains unknown how N or P limitation affects CO_2 mitigation policies under different RCPs.

Here we use an ESM, which includes N and P limitations on the land carbon, to demonstrate that the reduction in land carbon uptake due to nutrient limitation reduces future allowable emissions used to

Table 1. Comparison of the Simulated Historical Changes in the Total Land (ΔC_l) and Ocean (ΔC_o) Carbon Pools, and Diagnosed Carbon Emissions in Pg C From This Study With Other Estimates From 1850 to 2005[a]

1850–2005	C-Only	CN	CNP	Observational Estimate
ΔC_l	225 ± 3	136 ± 3	85 ± 1	135 ± 84[e]
ΔC_o	116 ± 1	116 ± 1	118 ± 1	135 ± 25[d]
Emissions	541 ± 11[b]	452 ± 11[b]	403 ± 11[b]	470 ± 80[c]

[a]One standard deviation of our model estimate calculated from the five members of ensemble is also shown.
[b]Emission for each of three model simulations is calculated as $\Delta C_l + \Delta C_o + \Delta C_a$, where ΔC_a is the atmospheric CO_2 increase from 284.7 ppm in 1850 to 378.8 ppm in 2005, or 200 Pg C.
[c]Total CO_2 emission is calculated as the sum of emissions from fossil fuel burning and land use change. From 1850 to 2005, the total amount of fossil fuel CO_2 emission is 314 Pg C [*Andres et al.*, 2011] and the total amount of CO_2 emission from land use change is 155 Pg C [*Houghton*, 2008]. The uncertainty calculated as one standard deviation for fossil fuel CO_2 burning is assumed to be 5% of the total emission for fossil fuel CO_2 burning from 1850 to 2005, or 16 Pg C [*Canadell et al.*, 2007]. Based on the recent evidence for 1960–2008 [*Arora and Boer*, 2010], we assumed that uncertainty of CO_2 emission from land use change for 1850–2005 is 50% of the total emission or 78 Pg C, which is larger than the 30% of the emission as assumed by *Canadell et al.* [2007] for 1960–2005.
[d]The change in ocean carbon (ΔC_o) and its uncertainty are taken from *Khatiwala et al.* [2009] but reduced by 5 Pg C to account for the slightly less storage in the ocean up to 2006 rather than 2008 as given in their study.
[e]ΔC_l is calculated as $E - \Delta C_a - \Delta C_o$. The uncertainty of ΔC_a relates to the uncertainty of atmospheric CO_2 during preindustrial times and is assumed to be 11 Pg C [*MacFarling Meure et al.*, 2006].

determine a RCP. The land model can run with carbon cycle alone (C only); carbon and nitrogen (CN); or carbon, nitrogen, and phosphorus (CNP) cycles. The difference in the carbon uptake between CN and C only or CNP and CN simulations represents the effects of N or P limitations, respectively. We use the simulated land and ocean carbon accumulation rates since 1850 to diagnose the allowable emissions for each of three simulations (C only, CN, or CNP). These were then compared with the emissions estimated by the IAMs used to generate RCP2.6 and RCP8.5.

2. Methods

We used the ESM Mk3L-COAL that couples a global climate model, Mk3L [*Phipps et al.*, 2011], with a global biogeochemical model Carnegie-Ames-Stanford Approach of carbon, nitrogen, and phosphorus cycles, CASA-CNP [*Wang et al.*, 2010] in the Community Atmosphere Biosphere Land Exchange (CABLE) [*Mao et al.*, 2011; *Wang et al.*, 2011], and an ocean carbon model [*Matear and Hirst*, 2003].

The ocean biogeochemical model can simulate the global ocean carbon cycle [*Khatiwala et al.*, 2009] and anthropogenic carbon uptake by the ocean [*Matsumoto et al.*, 2004] realistically. CASA-CNP includes three plant, three litter, and three soil pools for the cycling of C, N, and P elements, respectively. *Wang et al.* [2012] and *Zhang et al.* [2013] provided details explaining how nutrient limitations are represented in CASA-CNP. Further details are also provided in supplementary Text S2. The geographic variations of nutrient limitations, major biogeochemical fluxes, and pools on land under present climate conditions are simulated well [*Wang et al.*, 2010] and consistent with earlier ecological studies [*Hedin*, 2004] and field observations at different latitudes [*LeBauer and Treseder*, 2008]. Evaluation using results from free-air CO_2 experiments also showed that CABLE with NP limitation satisfactorily reproduced the observed response of photosynthetic carbon uptake to rising CO_2 [*De Kauwe et al.*, 2013]. The coupled model has been used to assess historical land carbon uptakes and CO_2 emissions from land use changes and compared well with other independent estimates [*Zhang et al.*, 2011, 2013].

Mk3L-COAL was spun-up under preindustrial atmospheric CO_2 (284.7 ppm) until the simulated climate became stable (the linear trend of global mean surface temperature over the last 400 years of the spin-up $<$0.015 K per century) for each of the three configurations of the land biogeochemical component (C, CN, and CNP). The climate and sizes of land biogeochemical pools from the last 50 years of spin-up, at 10 year intervals, were used as initial conditions for five ensemble simulations of the 1850 to 2100 period for each land model configuration. We average the five simulations since differences were quite small between individual ensemble members (Tables 1 and 2). For each simulation, the model was run using the atmospheric CO_2 for 1850 to 2005 and then using the atmospheric CO_2 from the lowest (RCP2.6) or highest (RCP8.5) emission scenario for the 2006 to 2100 period as provided by the Coupled Model Intercomparison Project Phase 5 (CMIP5, http://cmip-pcmdi.llnl.gov/cmip5/; Figure S1a). The vegetation distribution [*Lawrence et al.*, 2012] remained unchanged at 1850 over the simulation period. We thus diagnosed total anthropogenic emissions

Table 2. For the 2006 to 2100 Period, the Increase in Land (ΔC_l) and Ocean Carbon (ΔC_o) Storage Along With the Diagnosed Total Emissions in Pg C[a]

	C-Only	CN	CNP	IAM
RCP2.6				
ΔC_l	197 ± 2	124 ± 3	72 ± 1	-
ΔC_O	146 ± 1	151 ± 1	152 ± 1	-
Emissions	432 ± 2	364 ± 3	313 ± 1	382
RCP8.5				
ΔC_l	425 ± 4	267 ± 5	138 ± 1	-
ΔC_O	393 ± 1	397 ± 0	399 ± 1	-
Emissions	2001 ± 4	1847 ± 5	1720 ± 1	1970

[a]Total diagnosed emissions are calculated as $\Delta C_l + \Delta C_o + \Delta C_a$, where ΔC_a is the increase in atmospheric CO_2 over the same period. ΔC_a increased by 89 Pg C for RCP2.6 and 1183 Pg C for RCP8.5. For comparison, the allowable emissions used in the Integrated Assessment Model (IAM) to compute the RCPs are also given under the IAM column. One standard deviation of our model estimate calculated from the five members of ensemble is also shown.

including CO_2 from both fossil fuel combustion and land use changes. We used the spatially explicit estimates of nitrogen deposition for 1990s [*Dentener et al.*, 2006] over the simulation period.

To account for possible drift in the simulated climate and carbon pools, control simulations of the three land carbon models (C, CN, and CNP) with the atmospheric CO_2 held constant at 284.7 ppm were performed over the 1850 to 2100 period. Drifts in climate and carbon pool sizes were small (< 0.015°C/century and 5 Pg C/century) and were subtracted from the simulated change in carbon pools or fluxes as presented in this study. The simulated increases in global surface temperatures agree well with historical observations and CMIP5 model ensembles for the two future RCPs (Figure S1b and Table S1). The sensitivities of land or ocean carbon to increasing atmospheric CO_2 concentration or climate change are evaluated in supplementary Text S1 and Table S2.

3. Results

Figure 1 shows the simulated net annual carbon uptake by ocean and land biospheres since 1850. The changes in ocean carbon uptake rates (Figure 1a) are largely driven by different atmospheric CO_2 pathways (Figure S1a) with negligible differences between different model simulations due to indirect impact of land nutrient states on ocean climate in the concentration-driven simulations. Over land, although the carbon fluxes into the surface roughly follow the changes of atmospheric CO_2, their magnitudes are significantly reduced by N and P limitations (Figure 1b). Note that while atmospheric CO_2 keeps increasing for RCP8.5, the terrestrial carbon uptake starts to level off in the last decades of this century because CO_2 emission from respiration from warming exceeds the CO_2 uptake increase by CO_2 fertilization. The ocean and land carbon accumulations for historical and future RCPs are summarized in Tables 1 and 2. By 2005, the simulated land uptakes for CN or CNP are within the range of independent estimates (135 ± 85 Pg C) while the C-only simulation is higher. The ocean uptakes estimated by our model agree well with observations (135 ± 25 Pg C) [*Khatiwala et al.*, 2009] (Table 1). From 2006 to 2100, the carbon accumulated on land is reduced by 37% due to N limitation or 63% due to both N and P limitations, as compared to C-only simulation (197 Pg C) by our

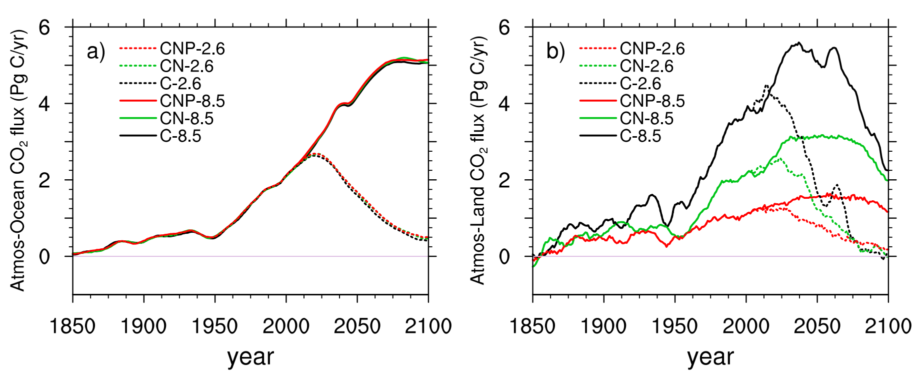

Figure 1. The simulated net annual carbon uptake of (a) the ocean and (b) the land in Pg C yr^{-1} for RCP2.6 (dashed curves) and RCP8.5 (solid curves). All rates are smoothed using 10 year running average.

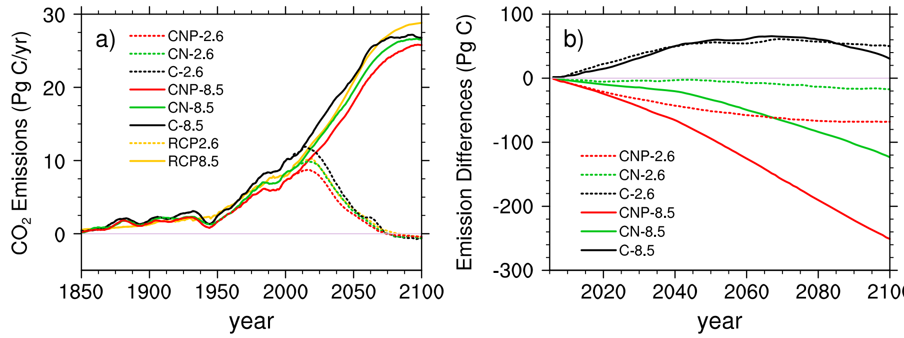

Figure 2. (a) Ten year running mean averages of the diagnosed and prescribed annual CO_2 emissions for RCPs 2.6 and 8.5; the prescribed emissions (yellow lines) are the allowable emissions determined by the IAM for the two RCP scenarios. (b) Ten year running mean of the differences between the cumulative diagnosed and prescribed emissions. In Figures 2a and 2b, green and red lines show results from the C, CN, and CNP simulations, respectively, with the solid lines representing RCP8.5 and dashed lines representing RCP2.6.

model under RCP2.6. Under RCP8.5, the carbon accumulated on land is reduced by 37% due to N limitation or 68% due to NP limitation, as compared to C only simulation (425 Pg C) by our model (see Table 2).

To examine the impact of nutrient limitation on allowable emissions, we diagnose emissions in our simulations as the sum of changes of CO_2 in the atmosphere, land, and ocean carbon (Figure 2a). For most of the simulation period, the diagnosed emissions projected by the C-only simulation are higher than those from IAM estimates except for the high-end RCP8.5 scenario over the last three decades, while the allowable emissions under N or NP limitation as estimated by our ESM are smaller than those from the IAMs. For the historical period (1850–2005), an independent estimate of CO_2 emission is 470 ± 80 Pg C (Table 1). This is similar to our diagnosed emission for CN (452 Pg C) and is 71 Pg C lower than the C simulation and 67 Pg C higher than the CNP simulation. Given the relatively large uncertainty in the estimated CO_2 emissions from land use from 1850 to 2005 [*Arora and Boer*, 2010], all three diagnosed emissions from our simulations are within the range of estimates from inventories (Table 1).

From 2006 to 2100, we define the emission corrections as the differences between the diagnosed from our simulations and those from the IAMs to generate the RCPs (Figure 2b). While IAMs may account for past N limitation on land carbon uptake via calibration, increasing N limitation under higher CO_2 and P limitation are not included. For the C only simulation, the emission correction is positive, or the cumulative emission is 50 Pg C for RCP2.6, and 31 Pg C for RCP8.5 more than respective estimate of emissions by IAMs for the future period (Table 2). However, adding N or NP limitation changes the sign of emission corrections to meet a given RCP. Under the RCP2.6 scenario, the emission correction is −18 Pg C (−5%) for CN or −69 Pg C (or −18%) for CNP. Under the RCP8.5 scenario, the emission correction is −123 Pg C (−6%) for CN or −250 Pg C (or −13%) for CNP.

4. Discussion and Conclusions

N and P limitations on land in our ESM led to systematically lower land carbon uptake. This implies greater reductions in human CO_2 emissions than assumed in the IAMs used to generate the RCPs. Since the IAMs are calibrated to C^4MIP models that do not include nutrients [*Friedlingstein et al.*, 2006], our results demonstrate that ignoring the N and P limitations in those ESMs will overestimate total allowable CO_2 emissions for both low and high emission scenarios. In addition, there is significant uncertainty in allowable emissions diagnosed by recent AR5 ESMs. This uncertainty is dominated by projections of land carbon change, which has diverse response to changes in CO_2, climate, and land use [*Jones et al.*, 2013]. NP limitation reduces the sensitivity of land carbon uptake to atmospheric CO_2 by 79% or climate warming by 35% as simulated in our model. This is consistent with *Arora et al.* [2013] who showed that the inclusion of N cycle processes in two land carbon components out of 11 AR5 ESMs reduces the magnitude of the sensitivity to both CO_2 and climate (Tables S1 and S2). Since N and P act to limit the responses of land carbon cycle to changes in CO_2, climate, and land use [*Gerber et al.*, 2013; *Zhang et al.*, 2013], including N and P limitations in ESMs will likely reduce the large intermodel uncertainty.

By including both N and P limitations, our results point to strong N limitation in the midlatitude and high latitude (Figures S2a and S2c), consistent with earlier modeling results with C-N interactions [*Sokolov et al.*, 2008;

Thornton et al., 2009; *Zaehle et al.*, 2010]. The simulated strong P limitation and weak N limitation in the tropics (Figures S2b and S2d) agrees with the current understanding of global P limitation [*Hedin*, 2004; *Goll et al.*, 2012] but is different from the results by *Thornton et al.* [2009] achieved using only N limitation. The geographic pattern of nutrient limitations results from low net N mineralization rate at high latitudes, where soil temperature is low and the soil C:N ratio is high, and low level of labile soil P at low latitudes associated with highly weathered soil (further discussions in supplementary Text S2; see Tables S3 and S4, the hemispherical N and P budgets). Thus, omitting P processes in the model could lead to misrepresentation of the impacts of nutrient limitation on tropical carbon uptake under future climate change.

Our results are affected by several sources of uncertainty. By holding N deposition at the 1990s' level, land carbon uptake under nutrient limitations can be underestimated, while the effect of increasing N deposition rates on the magnitude of global ($<$10 Pg C) and regional land carbon accumulation over the 21st century is marginal [*Goll et al.*, 2012; *Zaehle et al.*, 2010]. In terms of omitting land use change in our experiments, we diagnosed total anthropogenic emissions including the CO_2 emissions from land use change. Our recent study [*Zhang et al.* 2013] using Mk3L-COAL estimated that CO_2 emission from land use change from 1850 to 2005 was 130 Pg C for C only simulation or 97 Pg C for CNP simulation. Interactions of NP limitation and land use change therefore have a relatively small effect on total allowable emissions over the historical period. From 2006 to 2100, it was estimated that the CO_2 emission from land use change is about 60 Pg C for RCP2.6 and 55 Pg C for RCP8.5 by the IAMs. This is much smaller than the effects of NP limitation on land carbon uptake (125 Pg C for RCP2.6 and 287 Pg C for RCP8.5).

We note that the uncertainty of the magnitude of nutrient limitation in our ESM simulation is difficult to quantify. Sensitivity studies have shown high uncertainty of NP limitation on plant production ($>$15%) due to leaf C:N:P parameterization for some shrublands, grassland, and savannah in CASA-CNP [*Wang et al.* 2010]. The temperature dependence of microbial decomposition is another major uncertainty in simulating the C and nutrient cycles in our model [*Exbrayat et al.*, 2013]. However, both studies show that the carbon estimates between the C-only, CN, and CNP simulations are significantly different from each other. Our conclusion that N and P limitations reduce future allowable emissions is therefore likely to be robust, but the exact scale of this reduction requires further study, in particular on the stoichiometric parameters and mechanisms governing ecosystem carbon responses to future anthropogenic forcing [*Thomas et al.*, 2013].

In conclusion, this is the first study to quantify the effects of N and P limitations on the allowable emissions using an ESM simulating land and ocean CO_2 exchanges to the atmosphere and physical climate simultaneously in RCPs used for IPCC AR5. Ignoring N and P limitations in the IAMs used to develop the RCPs leads to an overestimate of how much CO_2 can be absorbed by the land biosphere. To achieve a given RCP, a greater reduction in human CO_2 emissions than assumed in the IAMs used to generate the RCPs is required. Our results therefore demonstrate that including N and P limitations implies either the necessity of deeper reductions in anthropogenic CO_2 emissions than previously assumed or acceptance of greater global warming.

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