Limitations of nitrogen and phosphorous on the terrestrial carbon uptake in the 20th century

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[1] A climate model, coupled to a sophisticated land model, is used to explore the impact of nitrogen and phosphorous limitations on carbon uptake under increasing atmospheric carbon dioxide concentration, or [CO_2], from 1870 to 2009. Adding nitrogen limitation strongly reduces the capacity of land CO_2 uptake under increasing [CO_2]. The further limitation by phosphorous has a smaller impact on the global uptake of CO_2. However, phosphorous limitation has a strong impact on regional carbon uptake: increasing CO_2 sinks over North America and Eurasia and decreasing sinks over China and Australia. Thus, while the global carbon balance can be resolved with just nitrogen limitation, simulations of continental-scale carbon sinks will need to include the additional limitation of phosphorous through the 20th century.

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1. Introduction

[2] The capacity of the terrestrial surface to absorb CO_2 emitted by human activities is a critical component of how [CO_2] will change in the future. Some modelling results point to the biosphere being able to continue to absorb CO_2 through the 21st century, while others suggest a rapid decline of land uptake in the mid 21st century as the Earth warms [*Friedlingstein et al.*, 2006]. Most of these simulations include the impact of increasing [CO_2] on photosynthesis (the fertilization effect) which likely increases the capacity of plants to absorb CO_2 [*Field et al.*, 1995]. However, the magnitude of the response of photosynthetic carbon uptake to [CO_2] remains quite uncertain, varying from 0.2 Gt C ppm^{-1} to 2.8 Gt C ppm^{-1} among 11 models without nutrient cycles [*Friedlingstein et al.*, 2006].

[3] Globally, nitrogen (N) and phosphorous (P) are the most widespread nutrients limiting plant growth and soil carbon storage [*Vitousek et al.*, 2010]. Evidence from long-term field studies suggests that significant interactions between CO_2 and nitrogen will constrain the terrestrial biosphere's response to [CO_2] in many natural and managed ecosystems [*Luo et al.*, 2004]. Whilst N limitation often dominates in temperate and boreal areas, much of the tropical forest and savannah are P limited [*Aerts and Chapin*, 1999]. Observations also suggest that P limitation can also constrain the response of photosynthetic capacity to leaf N [*Reich et al.*, 2009]. The cycles of N and P differ so substantially in sources and dynamics that their responses to climate and increasing [CO_2] can be quite different [*Vitousek et al.*, 2010].

[4] Recent carbon cycle-climate model simulations with C-N biogeochemistry demonstrate that including N limitation strongly influences the feedbacks of carbon and [CO_2] and could change the sign of the carbon-climate feedback from positive to negative [*Sokolov et al.*, 2008]. The effects of nitrogen limitation were found to reduce the net carbon uptake by global land biosphere by 37% to 74% from pre-industrial period to 2100 in some modelling studies [*Thornton et al.*, 2007; *Zaehle et al.*, 2010a]. Other mass balance estimates indicate that simulations omitting N limitation probably overestimate carbon sequestration under higher [CO_2] and future climate change [*Wang and Houlton*, 2009]. However, no simulations with a carbon-climate model including full C, N and P interactions have previously been reported. It is therefore unclear whether including full C, N and P interactions would lead to significant differences in carbon accumulation at global or regional scales under anthropogenic CO_2 emissions and associated climate changes.

[5] Our paper provides the first estimate of how N and P limit the capacity of the terrestrial system to absorb CO_2. We use a climate model, coupled with a state-of-the art land surface scheme to simulate the climate from 1870 to 2009 using prescribed sea surface temperatures and [CO_2] that reflect the observed record. We explore how N limitation affects the accumulation of carbon and contrast this with the limitations imposed through the interactions of N and P.

2. The Carbon-Climate Coupled Model

[6] We use the CASACNP model [*Wang et al.*, 2010] coupled to the CSIRO Mk3L climate system model [*Phipps et al.*, 2011]. CASACNP is a global biogeochemical model of C, N and P cycles for the terrestrial biosphere designed for use in a global climate model. To simulate the simultaneous feedbacks of carbon and nutrient cycles to the environment drivers, CASACNP was coupled to the Community Atmosphere Biosphere Land Exchange model (CABLE). CABLE calculates the temporal evolution of CO_2, radiation, heat, water and momentum fluxes at the surface and has been thoroughly evaluated [*Abramowitz et al.*, 2008; *Wang et al.*, 2011].

[7] The CSIRO Mk3L is a computationally efficient coupled atmosphere-sea ice-ocean climate model, suitable for studying climate variability and change on millennial time-scales [*Phipps et al.*, 2011]. The atmosphere model uses 18 vertical layers, and has a spatial resolution of 5.6°latitude

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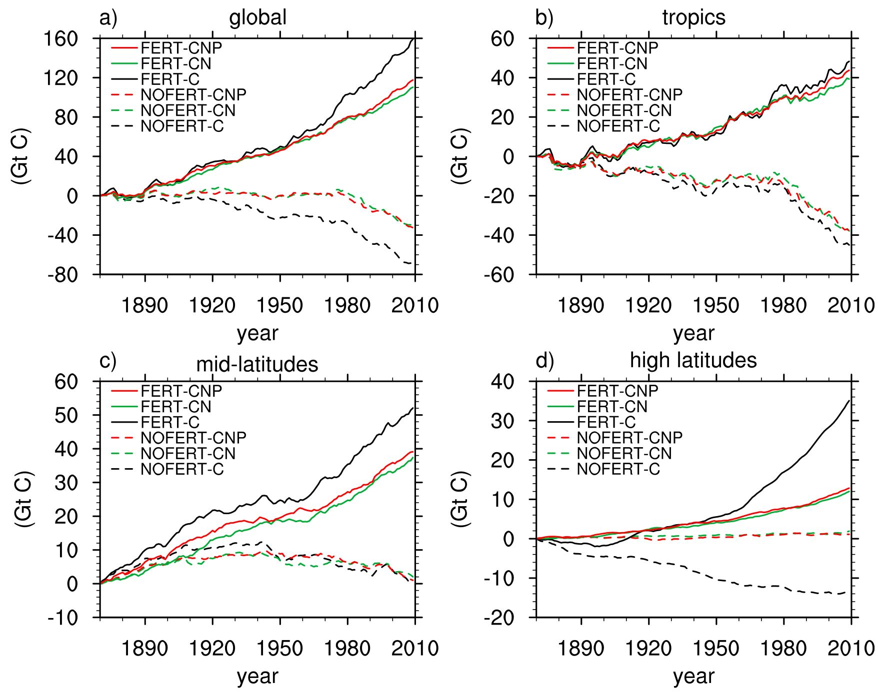

Figure 1. Trends in terrestrial carbon (Gt C) for (a) global land; (b) tropical regions (22°S–22°N); (c) Northern Hemisphere mid-latitudes (29°N–51°N); and (d) Northern Hemisphere high latitudes (51°N–90°N). Solid lines are with CO_2 fertilization enabled, dashed lines are with CO_2 fertilization ignored.

and 3.2°longitude. In this study, the ocean is prescribed using AMIP II monthly sea surface temperature (SST) data from 1870 to 2009 [*Taylor et al.*, 2000]. The historical [CO_2] data [*MacFarling Meure et al.*, 2006] is used to force atmosphere and land surface models separately.

3. Experiments

[8] To evaluate the effects of N and P on terrestrial carbon under CO_2 fertilization, we undertook two sets of experiments. In the "FERT" case, [CO_2] increased according to observations from 1870 to 2009 with impacts on the global climate captured by the climate model. The photosynthetic effects of an increase in [CO_2] are simulated in CABLE using the two-leaf canopy model [*Wang and Leuning*, 1998] while the biogeochemical effects of an increased carbon uptake on net ecosystem carbon storage are modelled by CASACNP. In the "NOFERT" case, the same experiment was run except the land biosphere was exposed only to the [CO_2] representing 1870 (288 ppm).

[9] For model spin-up, 10 years of daily meteorological forcing and gross primary production (GPP) were obtained from an equilibrium simulation using SST and [CO_2] conditions for 1870. We ran CASACNP off-line to stable states for each of the carbon only (C), carbon and nitrogen limited (CN) and carbon, nitrogen and phosphorous limited (CNP) cases using the daily forcing repeatedly. The resulting initial conditions were then used for the spin-up of the coupled model for pre-industrial initial conditions until both climate and biogeochemical pools reach a steady state. Multiple transient simulations were then performed for the model states after performing spin-up using observed historical changes in [CO_2] and SST for the period 1870–2009. All pool sizes and major carbon fluxes for the first and last 2 decades are presented in the auxiliary material.[1]

[10] We used a fixed global vegetation map with the dominant plant function types characterized in CABLE-CASACNP from the land cover data for the year 2005 from *Hurtt et al.* [2006]. Nutrient inputs were specified at 1990s levels according to *Wang et al.* [2010]; thus human induced changes in N and P deposition and fertilization from the pre-industrial period were not considered in this study.

4. Results

[11] Figure 1 shows the net accumulation of carbon over land through the 20th Century. Without CO_2 fertilization, the global C stores decline over the 20th century (Figure 1a). This decline depends critically on nutrient limitation: it is ~70 Gt C for the carbon only simulation or ~30 Gt C for the simulations including N and P limitations. In contrast, if CO_2 fertilization is included, nutrient (N or NP) limitation reduces the net carbon uptake by land from ~160 Gt C (FERT-C) to ~120 Gt C (Figure 1a). At a global scale, NP limitation in our model increases the land carbon uptake by ~10 Gt C by 2009, compared with the simulation with N limitation only.

[12] Figure 1 highlights very different regional-scale responses of land carbon accumulation to climate. Without CO_2 fertilization, both net primary production (NPP) and heterotrophic respiration (Rs) from 1870 to 2009 decrease in the tropics, increase at mid-latitudes, and change very little or decrease at high latitudes (see Figures S1 and S2 in the auxiliary material). When nutrient-carbon interactions are

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL049244.

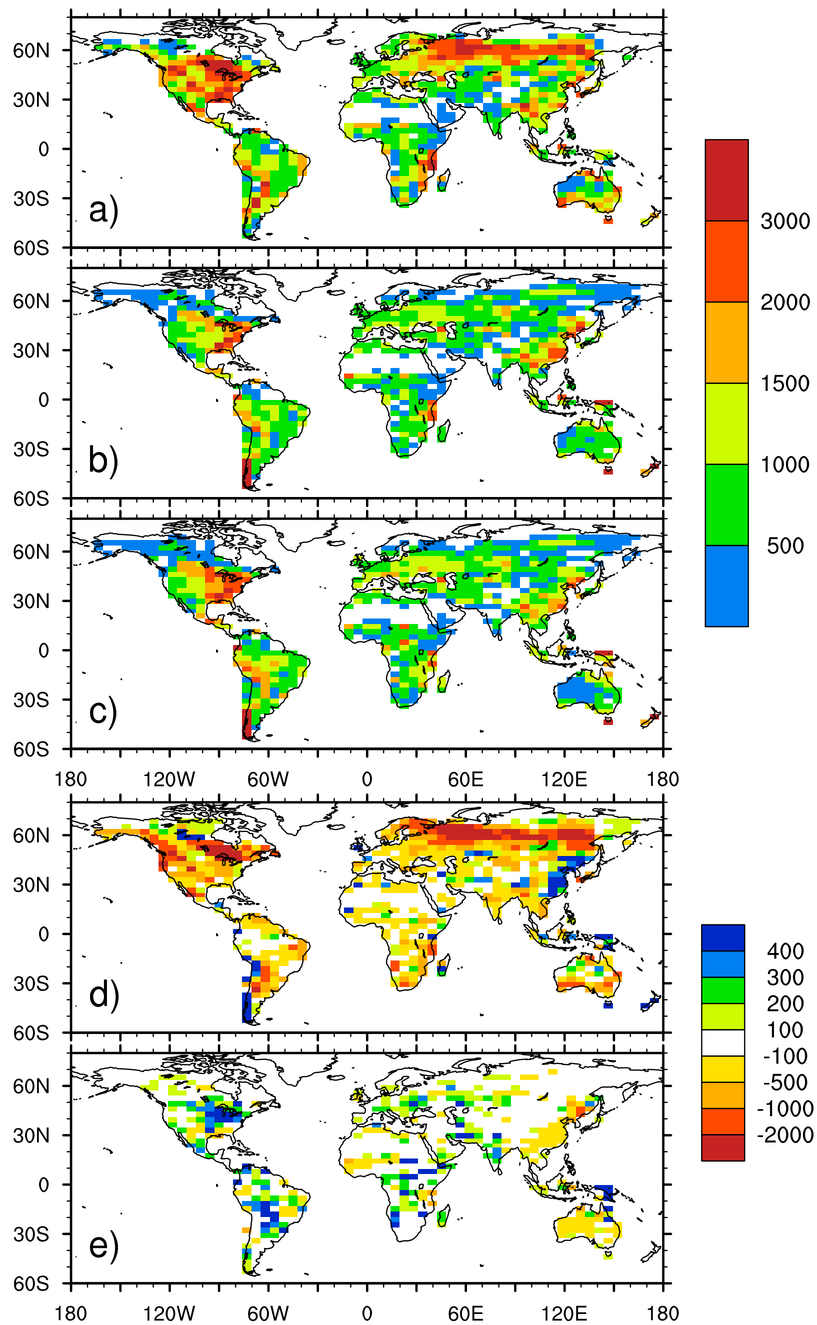

Figure 2. Net terrestrial carbon accumulation (gC/m^2) for (a) carbon only; (b) limited by N; and (c) limited by NP; (d) the differences between the N-limited simulation and the carbon only simulation; (e) the differences between the NP-limited simulation and the N-limited. Each quantity is averaged over a decade (1870–1879 or 2000–2009). Note the non-uniform scale in Figures 2d and 2e.

included, the estimated amount of carbon loss by 2009 is decreased for the tropics (Figure 1b) and high latitudes (Figure 1d), but is changed very little in the mid-latitudes (Figure 1c). The loss of carbon from warming, as estimated in the carbon only simulation, is entirely suppressed in the N-limited and NP-limited simulations in the high latitudes (Figure 1d). When the CO_2 fertilization is considered, the relative impact of nutrient-carbon interaction on land carbon accumulation is weakest in the tropics and strongest in the high latitudes. Adding P limitation in our model generally results in higher estimates of carbon accumulation in all three regions, and the difference is largest in the tropics (about 5 Gt C) by 2009.

[13] The large-scale results shown in Figure 1 hide important regional details. Figure 2a shows the carbon accumulation for the FERT-C simulation, in which carbon accumulates over virtually all regions. The increase ranges from <1000 gC/m^2 over most of the tropics to >2000 gC/m^2 over much of North America and the mid- and high-latitudes of Eurasia. Carbon accumulation increases in the mid- and high latitudes and decreases in the tropics under rising surface temperature (see Figures S3 and S4 in the auxiliary material,

other experiments have similar patterns as Figures S3 and S4). The impact of adding N limitation is profound over the northern-hemisphere high latitudes with carbon accumulation decreasing from >2000 gC/m^2 to between 500–1000 gC/m^2 (Figure 2b). This is best shown in Figure 2d, which shows the difference in carbon accumulation from 1870s to 2000s as a result of N limitation in our model. Note that N limitation does not always reduce carbon accumulation (e.g., eastern China).

[14] At the global scale, the carbon accumulation under NP limitation is very similar to N limitation (Figure 2c) and the pattern of differences between the carbon only simulation and the NP-limited simulation are broadly similar to those in Figure 2d. However, P limits carbon accumulation non-uniformly. Figure 1 shows that the global impact of adding P limitation in our model is small relative to including N limitation only. However, Figure 2e shows geographically coherent regional variations in carbon accumulation when both N and P limitations are included in our model. As compared with N limitation only, adding P limitation will reduce the carbon accumulation by 100 to 500 g C m^{-2} over most parts of Australia and south-east Asia, but increase the carbon accumulation by >200 g C m^{-2} over the eastern United States, tropics and sub-tropics of South America, Europe, southern Africa and parts of the Middle East where P is likely more limiting than N on productivity.

5. Discussion and Conclusions

[15] Our results confirm earlier studies that N limitation reduces the response of land carbon uptake to increased [CO_2] and the response of land carbon loss to climate changes [*Sokolov et al.*, 2008; *Bonan and Levis*, 2010; *Zaehle et al.*, 2010b]. As compared with the C only simulation, our model estimates that N limitation reduces the carbon accumulation on land during 1870 to 2009 by 40 Gt C, which is higher than the estimated reduction of 19 Gt C by *Zaehle et al.* [2010b] for 1860–2002, but much lower than the estimated reduction of 162 Gt C by *Thornton et al.* [2007] for 1850 to 2000. Without CO_2 fertilization, soil warming increases soil mineralization and nutrient availability in the mid- and high latitudes, therefore NPP increases (see Figures S1 and S2 in the auxiliary material). This nutrient-stimulated positive response of NPP to warming results in the high latitudes becoming a small carbon sink, compared to a large carbon source without nutrient effects. In the tropics, the relative effect of nutrient limitation is quite small, because of the fast soil turnover rate and relatively low sensitivity of soil mineralization to warming at high temperature. Our simulated response of net carbon accumulation to warming is similar to *Zaehle et al.* [2010a, 2010b], but much smaller than that by *Sokolov et al.* [2008] for the high latitudes or by *Thornton et al.* [2007] for the tropics.

[16] Our results on how P limitation affects carbon accumulation provide the first evidence of how land carbon accumulation responds to P limitation. Globally, including P limitation in our model results in higher estimates of carbon accumulation than if only N limitation is modeled. That increase is ~10 Gt C (Figure 1a) but increases of 5 Gt C (tropics), 2 Gt C (mid-latitudes) and 1 Gt C (high latitudes) indicate a consistent response where NP limitation increases carbon accumulation, as compared to N limitation only. However, NP limitation of carbon accumulation generates regional differences that deviate substantially from the effects of N limitation only. Both N and P limitation can reduce the CO_2 fertilization response, but the reduction under P-limited conditions is more gradual than that under N-limited conditions because of the slower turnover of P in the ecosystem. When NPP is co-limited by N and P initially, increasing [CO_2] can shift the system towards more P limitation, Because of the slower response of P limitation to increasing [CO_2], carbon accumulation will be greater than that under N-limited condition. This is the case for the regions of North America, South America, Europe and southern Africa, where the increase in carbon accumulation is commonly between 200 and 400 g C m^{-2} and locally >500 g C m^{-2}. By contrast, NP limitation reduces carbon accumulation by 100 to 500 g C m^{-2} over Australia and eastern China. These two regions are P-limited, hence increasing [CO_2] will exacerbate P limitation, and reduce NPP and carbon accumulation. Therefore the estimated net carbon accumulation will be smaller if P limitation is included. This is consistent with field observations [*van Groenigen et al.*, 2006]. Our results point to large regional errors in simulating carbon accumulation if only N limitation is included in our global model.

[17] Our results are limited to increases in [CO_2] and associated climate changes observed through the 20th century. It is conceivable that the limitation of N with P will change as [CO_2] increases more rapidly through the 21st century, or as warming accelerates. To first order and at the global scale, however, terrestrial carbon accumulation is strongly limited by N. Here we show that there are large negative and positive deviations from a picture suggested by considering only a global average [*Pitman et al.*, 2011]. More studies are needed to confirm our findings, as the uncertainties in our model can be large, particularly the representation of P cycle. Our results point out that if results are to be interpreted at continental and finer scales, climate models that resolve CO2 fertilization in simulations of the 20th century will need to include both N and P limitation.

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