Quantifying carbon-nitrogen feedbacks in the Community Land Model (CLM4)

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[1] Recent studies indicate that nitrogen biogeochemistry affects the carbon cycle feedback in climate simulations. We use the Community Land Model version 4 (CLM4) with carbon-only and carbon-nitrogen biogeochemistry to assess the influence of nitrogen on the land carbon budget for 1973–2004. Carbon-only simulations show that the carbon gain from increasing atmospheric CO2 (the concentration-carbon feedback) is four times greater than the warming-induced carbon loss (the climate-carbon feedback) over the period 1973–2004. Nitrogen reduces both feedbacks compared with carbon-only biogeochemistry. The decrease in the concentration-carbon feedback is three times greater than the effect on the climate-carbon feedback. Thus, the influence of nitrogen on the CLM4 concentration-carbon feedback is of greater importance for near-term climate change simulations than its effect on the climate-carbon feedback. Furthermore, the land use carbon flux greatly exceeds these carbon-nitrogen biogeochemical feedbacks. Citation: Bonan, G. B., and S. Levis (2010), Quantifying carbon-nitrogen feedbacks in the Community Land Model (CLM4), Geophys. Res. Lett., 37, L07401, doi:10.1029/2010GL042430.

1. Introduction

[2] Coupled carbon cycle-climate models show that rising atmospheric CO2 concentration increases land carbon uptake by stimulating plant productivity (the concentration-carbon feedback), diminished by carbon loss with warmer temperature (the climate-carbon feedback) [Friedlingstein et al., 2006; Plattner et al., 2008]. In the linear analysis framework of Friedlingstein et al. [2006]

\[ \Delta C_L = \beta_L \Delta C_A + \gamma_L \Delta T_L \]  

(1)

where \( \Delta C_L \) is the change in land carbon (Pg C) over some time interval, \( \beta_L \) is the land carbon sensitivity to CO2 (Pg C ppm\(^{-1}\)), \( \Delta C_A \) is the change in atmospheric CO2 (ppm), \( \gamma_L \) is the land carbon sensitivity to temperature (Pg C K\(^{-1}\)), and \( \Delta T_L \) is the change in land temperature (K). Model intercomparison finds \( \beta_L > 0 \) (i.e., negative concentration-carbon feedback with respect to \( C_A \)) and \( \gamma_L < 0 \) (i.e., positive climate-carbon feedback with respect to \( C_A \)) [Friedlingstein et al., 2006; Plattner et al., 2008]. The concentration-carbon feedback has a greater effect on land carbon storage than the climate-carbon feedback and is the dominant uncertainty [Gregory et al., 2009].

[3] This interpretation of the terrestrial carbon cycle is formed from models that do not include carbon-nitrogen biogeochemistry. Two carbon cycle-climate model simulations of future climate change with carbon-nitrogen biogeochemistry find that nitrogen decreases \( \beta_L \) and changes \( \gamma_L \) from negative to positive [Sokolov et al., 2008; Thornton et al., 2009]. Limited mineral nitrogen availability restricts the increase in plant productivity from the concentration-carbon feedback. Conversely, warming increases decomposition of organic material and nitrogen mineralization, stimulating plant productivity. Other carbon-nitrogen simulations for the twentieth and twenty-first centuries similarly find that \( \beta_L \) decreases and carbon loss with warming decreases when nitrogen is included, but that \( \gamma_L \) remains negative [Zaehle et al., 2010a, 2010b]. Thus, the role of nitrogen to change the climate-carbon feedback from positive (\( -\gamma_L \)) to negative (\( +\gamma_L \)) is unclear, as is the relative importance of \( \beta_L \) and \( \gamma_L \) to the overall land carbon budget.

[4] Here, we report simulations using the Community Land Model version 4 (CLM4) for the late twentieth century forced with historical meteorology, CO2 concentration, atmospheric nitrogen deposition, and land use change. The CLM4 is the updated land component of the Community Climate System Model [Collins et al., 2006] and provides the terrestrial carbon flux for carbon cycle-climate simulations. As one of the few models with carbon-nitrogen biogeochemistry, it is imperative to understand the influence of carbon-nitrogen dynamics relative to carbon-only dynamics. Thornton et al. [2007] used an earlier version of the model in carbon-only and carbon-nitrogen simulations to examine the influence of nitrogen on \( \beta_L \) and Thornton et al. [2009] contrasted a carbon-nitrogen simulation with the Friedlingstein et al. [2006] carbon-only simulations. In this study, we quantify the influence of nitrogen on \( \beta_L \) and \( \gamma_L \), as well as terms from nitrogen deposition and land use change, to identify aspects of the terrestrial carbon cycle most affected by the CLM4 carbon-nitrogen biogeochemistry.

2. Model Experiments and Analyses

[5] The CLM4 succeeds CLM3.5 [Oleson et al., 2008; Stöckli et al., 2008], with revised hydrology and snow models, organic soils, and a 50 m deep ground column. The distribution of plant functional types (PFTs) is modified to reduce a high grass bias in forested regions. These changes increase soil moisture variability and produce drier soils, reducing the CLM3.5 deficiency of excessively wet and unvarying soil moisture. Additional improvements include higher snow cover, cooler soil temperature in organic-rich soils, and lower albedo for forests and grasslands.

[6] The CLM4 includes carbon-nitrogen biogeochemistry with prognostic carbon and nitrogen in vegetation, litter, and
Table 1. Annual Mean Forcings (Land Only) for Control and Experiment Simulations*  

<table>
<thead>
<tr>
<th>Simulations</th>
<th>Atmospheric CO₂, ( C_4 ) (ppm)</th>
<th>Temperature, ( T_L ) (K)</th>
<th>N Deposition, ( \text{NTg N yr}^{-1} )</th>
<th>Cropland, ( \left(10^3 \text{ km}^2\right))</th>
<th>Wood Harvest, ( \left(10^3 \text{ km}^2\text{ yr}^{-1}\right))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>328.6</td>
<td>280.8</td>
<td>48.5</td>
<td>14.0</td>
<td>0</td>
</tr>
<tr>
<td>Experiments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1973–77</td>
<td>331.0</td>
<td>280.9</td>
<td>51.2</td>
<td>14.1</td>
<td>0.14</td>
</tr>
<tr>
<td>2000–04</td>
<td>372.8</td>
<td>281.8</td>
<td>63.9</td>
<td>15.2</td>
<td>0.22</td>
</tr>
<tr>
<td>Change</td>
<td>41.8</td>
<td>0.9</td>
<td>12.7</td>
<td>1.1</td>
<td>0.08</td>
</tr>
</tbody>
</table>

*Forcings are constant for control simulations and vary with time for experiment simulations. Shown are the 1973–1977 and 2000–2004 means and the temporal change. Simulations have a 2.5° (longitude) by 1.9° (latitude) resolution.

Soil organic matter [Thornton et al., 2007, 2009; Randerson et al., 2009]. Vegetation is represented by leaf, fine root, respiring and non-respiring stem and coarse root, and storage pools. Leaf phenology is simulated for evergreen, seasonal deciduous, and stress-deciduous plants. The heterotrophic model represents coarse woody debris, three litter pools, and four soil organic matter pools. A prognostic fire model simulates wildfire. Transient land cover change and wood harvest are implemented from annual datasets. The model diagnoses the change in PFT area and adjusts carbon pools for mass conservation. For example, when PFT area decreases, lost mass is distributed among litter, wood products, and a land cover conversion flux that is released immediately to the atmosphere. A portion of the wood carbon is transferred to product pools released to the atmosphere with 10 year and 100 year lifespans. Harvesting is similarly implemented except that it does not change PFT composition and instead removes a specified fraction of the vegetation mass.

[7] A carbon-only version of the model was created assuming nitrogen saturation [Thornton et al., 2007]. We adjusted the nitrogen-saturated gross primary production (GPP) so that annual GPP for an 1850 carbon-only simulation was comparable to an 1850 carbon-nitrogen simulation (Text S1 and Table S1 of the auxiliary material). [8] A carbon-only and a carbon-nitrogen simulation were spun up for 1850 conditions (land cover, atmospheric CO₂, and nitrogen deposition) followed with a transient simulation for 1850–1972 to provide initial conditions for 1973 and subsequent forcing experiments for 1973–2004 (Table S2 of the auxiliary material). A 57 year (1948–2004) meteorological dataset is available to force the model in offline simulations uncoupled from a climate model [Oleson et al., 2008]. A repeating 25 year subset (1948–1972) was used for the 1850 spinup. The simulations for 1850–1972 used the same repeating 25 year meteorology, but CO₂ concentration, nitrogen deposition, wood harvest, and land cover change for 1850–1972. Subsequently, the 1973–2004 meteorology was used in simulation experiments for 1973–2004. The initial 1973 land carbon obtained from the 1850–1972 simulations was ∼50 Pg C (3%) greater for the carbon-only simulation than for the carbon-nitrogen simulation.

[9] Atmospheric CO₂ concentration was specified as by Randerson et al. [2009]. Atmospheric nitrogen deposition was based on that of Lamarque et al. [2005], as implemented previously [Thornton et al., 2007, 2009; Randerson et al., 2009] but with updated fluxes and includes NH₃ in addition to NOₓ. Nitrogen deposition over land for 1860 (∼19 Tg N yr⁻¹) and 1990 (∼63 Tg N yr⁻¹) are comparable to that of Galloway et al. [2004] (1860, 17 Tg N yr⁻¹; 1990, 64 Tg N yr⁻¹). Annual land cover change and harvest area were derived from the University of New Hampshire version 1 Land–Use History A (LUHa.v1) historical dataset based on that of Hurt et al. [2006]. Between 1973–1977 and 2000–2004, annual temperature over land increased by 0.9°C, atmospheric CO₂ increased by 41.8 ppm, the area rate of nitrogen deposition increased by 12.7 Tg N yr⁻¹, the area in cropland increased by 1.1 × 10⁶ km², and the annual rate of wood harvest increased by 0.08 × 10⁶ km² yr⁻¹ (Table 1).

[10] Using initial conditions obtained at the end of the carbon-only and carbon-nitrogen 1850–1972 simulations, we performed three sets of simulations for 1973–2004 using: (i) the carbon-only implementation of the model (denoted C); (ii) the carbon-nitrogen model while holding nitrogen deposition constant (CN); and (iii) the carbon-nitrogen model with transient nitrogen deposition (CN̂dep).

[11] For each model configuration, seven 32 year simulations individually examined the various forcings over 1973–2004 (Table S2 of the auxiliary material): CTRL, a control simulation without harvest/land cover change and with atmospheric CO₂, meteorology, and nitrogen deposition held constant (Table 1); CONC, as in CTRL but with transient atmospheric CO₂ forcing; CLIM, as in CTRL but with climate change from the transient meteorology; and CONC × CLIM, as in CTRL but with transient CO₂ and meteorological forcing. With CONC, CLIM, and CONC × CLIM performed again with transient harvest/land cover change for 1973–2004, we have the 7-member CN experiment. We repeated the 7-member experiment with transient nitrogen deposition for 1973–2004 (CN̂dep) and with carbon-only biogeochemistry (C).

[12] Our analysis focuses on land carbon (vegetation, coarse woody debris, litter, and soil organic matter). We use the notation ΔC_L to denote the temporal change in carbon, defined as the difference in mean land carbon for the years 2000–2004 and the mean for 1973–1977 (27 year difference). We use the notation ΔΔC_L to denote the departure in ΔC_L between two experiments. The concentration-carbon (\( \beta_L \)) and climate-carbon (\( \gamma_L \)) parameters are diagnosed from the difference in ΔC_L between simulations:

\[
\beta_L = \frac{\Delta \Delta C_L^{\text{CONC}}}{\Delta C_A} = \frac{C_L^{\text{CONC}} - C_L^{\text{CTRL}}}{C_A}
\]

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1Auxiliary materials are available in the HTML. doi:10.1029/2010GL042430.
or

\[ \beta_L = \frac{\Delta C_L^{CONC × CLIM} - \Delta C_L^{CLIM}}{\Delta C_L^{CTRL}} \]  

(2b)

and

\[ \gamma_L = \frac{\Delta C_L^{CLIM}}{\Delta T_L} = \frac{\Delta C_L^{CTRL} - \Delta C_L^{CTRL}}{\Delta T_L} \]  

(3a)

or

\[ \gamma_L = \frac{\Delta C_L^{CLIM} - \Delta C_L^{CTRL}}{\Delta T_L} \]  

(3b)

[13] Equations (2) and (3) are applied to the C, CN, and CN_{ndep} simulations; (2b) and (3b) include the interaction of CO\textsubscript{2} and climate. The difference between simulations removes background carbon trends from the non-equilibrium initial conditions. For comparison, we performed additional simulations using equilibrium initial conditions for 1973. Estimates of \( \beta_L \) and \( \gamma_L \) from these simulations were nearly identical to the non-equilibrium estimates.

[14] Using the CONC \times CLIM simulations, the contributions of CO\textsubscript{2}, climate change, nitrogen deposition, and harvest/land cover change to carbon accumulation are assessed from the linear equation

\[ \Delta C_L^t = \Delta C_L^{HIST} + \Delta C_L^{CONC} + \Delta C_L^{CLIM} + \Delta C_L^{NDEP} + \Delta C_L^{HLCC} \]  

(4)

where \( \Delta C_L^{HIST} \) is the background carbon trend from the non-equilibrium initialization (assessed from the CTRL simulations without forcing) and \( \Delta C_L^{CTRL} \) is the carbon accumulation due to CO\textsubscript{2} (CONC), climate change (CLIM), nitrogen deposition (NDEP), and harvest/land cover change (HLCC), diagnosed as the difference in \( \Delta C_L \) between appropriate simulations: \( \Delta C_L^{CONC} \) and \( \Delta C_L^{CLIM} \) are defined by equations (2b) and (3b); \( \Delta C_L^{NDEP} \) is the difference in \( C_L^{CONC × CLIM} \) between the CN_{ndep} and CN simulations; and \( \Delta C_L^{HLCC} \) is the difference in \( \Delta C_L^{CONC × CLIM} \) between the simulations with and without harvest/land cover change.

3. Results

[15] The C and CN_{ndep} carbon budgets for 1973–2004 are consistent with those of Le Quéré et al. [2009]. In the carbon-only CONC \times CLIM simulation, the 32 year mean land use emission is 1.8 Pg C yr\(^{-1}\) and the land sink is 2.5 Pg C yr\(^{-1}\) in the CN_{ndep} simulation, the land use emission is 1.8 Pg C yr\(^{-1}\) and the land sink is 1.8 Pg C yr\(^{-1}\). [Le Quéré et al. 2009] reported the land use emission over 1973–2004 is 1.5 Pg C yr\(^{-1}\), and the land sink, from five terrestrial carbon models (all without nitrogen), is 2.4 Pg C yr\(^{-1}\). Their atmospheric growth rate derived with these land fluxes (plus fossil fuel emission and ocean sink) underestimates the observed atmospheric growth rate by 0.4 Pg C yr\(^{-1}\), likely due to an overestimated land sink [Le Quéré et al., 2009]. If the residual were included in the land sink, the land uptake would be 2.0 Pg C yr\(^{-1}\). The 32 year mean C and CN_{ndep} land sinks are within this uncertainty. The simulated annual land sink is strongly correlated with Le Quéré et al.’s [2009] time series for 1973–2004. The correlation is greater for the C simulation (\( r = 0.86 \)) than for the CN_{ndep} simulation (\( r = 0.73 \)). Other aspects of the C and CN_{ndep} simulations are consistent with current estimates of the global carbon cycle, though soil carbon is low (Table S3 of the auxiliary material).

[16] Estimates of \( \beta_L \) in the C simulations vary little (Table 2, 0.93 Pg C ppm\(^{-1}\) multi-simulation mean). The C and CN_{ndep} simulations reduce \( \beta_L \) to 0.25 Pg C ppm\(^{-1}\) (Table 2, multi-simulation mean). The C and CN_{ndep} estimates are similar because our differencing from the appropriate CN and CN_{ndep} simulations removes the influence of increasing nitrogen deposition. The additional nitrogen deposition increases \( \Delta C_L \) in CN_{ndep} by 5.3 Pg C compared with the CN \( \Delta C_L \) (\( \Delta C_L^{NDEP} = 5.3 \) Pg C). When this extra carbon is included in the estimate, \( \beta_L \) increases to 0.37 Pg C ppm\(^{-1}\) (Table 2).

[17] The C simulations have a positive climate–carbon feedback (\( \gamma_L < 0 \)). The \( \gamma_L \) is slightly changed by HLCC (Table 2, \(- 11.5 \) Pg C K\(^{-1}\) multi-simulation mean). The CN and CN_{ndep} simulations reduce carbon loss with climate change, i.e., \( \gamma_L \) increases (Table 2, \(- 0.2 \) Pg C K\(^{-1}\) multi-simulation mean).

[18] Table 3 summarizes the terms in equation (4) (given here as annual fluxes) for the C and CN_{ndep} CONC \times CLIM simulations. The linear analysis provides a good approximation for \( \Delta C_L \). The carbon trend from non-equilibrium initialization (\( \Delta C_L^{HIST} \)) is large and results from historical transient forcing. In the C simulation, carbon accumulation from the concentration–carbon feedback (\( \Delta C_L^{CONC} = 1.43 \) Pg C yr\(^{-1}\) is 3.8 times greater than carbon loss from the

### Table 2. \( \beta_L \) and \( \gamma_L \) Calculated for Carbon-Only and Carbon-Nitrogen Simulations\(^a\)

<table>
<thead>
<tr>
<th>( \beta_L ) (Pg C ppm(^{-1}))</th>
<th>Without HLCC</th>
<th>With HLCC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Constant Climate</td>
<td>Climate Change</td>
</tr>
<tr>
<td>C</td>
<td>0.94</td>
<td>0.94</td>
</tr>
<tr>
<td>CN</td>
<td>0.24</td>
<td>0.25</td>
</tr>
<tr>
<td>CN_{ndep}</td>
<td>0.25</td>
<td>0.26</td>
</tr>
<tr>
<td>( \Delta C_L^{NDEP} )</td>
<td>0.37</td>
<td>0.38</td>
</tr>
</tbody>
</table>

\( \gamma_L \) (Pg C K\(^{-1}\))

<table>
<thead>
<tr>
<th></th>
<th>Constant CO\textsubscript{2}</th>
<th>Increasing CO\textsubscript{2}</th>
<th>Increasing CO\textsubscript{2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>-11.7</td>
<td>-11.7</td>
<td>-11.0</td>
</tr>
<tr>
<td>CN</td>
<td>-0.7</td>
<td>-0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>CN_{ndep}</td>
<td>-0.9</td>
<td>-0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>( \Delta C_L^{NDEP} )</td>
<td>4.8</td>
<td>5.9</td>
<td>6.0</td>
</tr>
</tbody>
</table>

\(^a\) Responses are calculated without and with harvest/land cover change \((HLCC)\). \( \beta_L \) is calculated with constant climate \((equation (2a))\) and with climate change \((equation (2b))\). \( \gamma_L \) is calculated with constant CO\textsubscript{2} \((equation (3a))\) and with increasing CO\textsubscript{2} \((equation (3b))\). Analyses are for carbon-only simulations \(C\) and carbon–nitrogen simulations with constant nitrogen deposition \(CN\) and transient nitrogen deposition \(CN_{ndep}\). Data for \(CN_{ndep}\) are shown without and with the carbon gain from nitrogen deposition \((\Delta C_L^{NDEP})\).
human activities.

4. Discussion

[20] The carbon-only simulations show that the gain in land carbon from the concentration-carbon feedback is almost four times greater than the loss in carbon from the climate-carbon feedback (Table 3). Gregory et al. [2009] found a similar four-fold difference in the magnitude of these two feedbacks. Our analyses additionally show that the decrease in the concentration-carbon uptake due to carbon-nitrogen biogeochemistry is almost three times greater than the reduction in the climate-carbon loss (Table 3). Zaehle et al. [2010a] similarly found that nitrogen reduces the concentration-carbon uptake and climate-carbon loss in the ORCHIDEE-CN (O-CN) model, with a seven-fold greater effect on the concentration-carbon feedback than on the climate-carbon loss.

[21] Analyses of carbon cycle-climate simulations without carbon-nitrogen biogeochemistry suggest that carbon-only models overestimate land carbon uptake from rising atmospheric CO₂ [Wang and Houlton, 2009]. Our carbon-only βL cannot be directly compared with other estimates obtained with larger CO₂ forcing over the twentieth and twenty-first centuries. In our simulations, carbon-nitrogen biogeochemistry reduces the concentration-carbon feedback compared with carbon-only simulations. The 73% reduction in βL due to nitrogen (Table 2) is similar to that of Thornton et al. [2007] using an earlier version of the model, but is greater than the 19% [Jain et al., 2009], 50% [Zaehle et al., 2010a], and 58% [Sokolov et al., 2008] reductions found with other models. The CN_ndep simulations compared with the CN simulations represent a nitrogen fertilization experiment. The additional nitrogen increases land carbon uptake, and βL increases by ~50% (Table 2). This suggests that the simulated nitrogen constraints on plant productivity are strong, noted also by Randerson et al. [2009] in a comparison with free-air CO₂ enrichment experiments.

[22] Coupled carbon cycle-climate simulations find that carbon-nitrogen biogeochemistry reduces the climate-carbon feedback loss [Sokolov et al., 2008; Thornton et al., 2009]. Our simulations for 1973–2004 show similar decreased land carbon loss due to warming when nitrogen is included in the model (Table 2). Other models also find that inclusion of nitrogen stimulates land carbon uptake and decreases the climate-carbon feedback loss during the 1990s [Jain et al., 2009; Zaehle et al., 2010b]. In the O-CN model, the effect of nitrogen on this feedback is much less than the effect on the concentration-carbon feedback [Zaehle et al., 2010a]. In our simulations, the effect of nitrogen on the climate-carbon feedback is generally less than that on the concentration-carbon feedback, except in some regions of the tropics (Figures 1c and 1f).

[23] We find small difference in global land carbon uptake between the carbon-only and carbon-nitrogen simulations, similar to those of Jain et al. [2009] and Zaehle et al. [2010a, 2010b]. The carbon-nitrogen and carbon-only land sinks for 1973–2004 are within the observational uncertainty [Le Quéré et al., 2009]. Represented as a 27 year annual flux, the net carbon accumulation differences by ~0.75 Pg C yr⁻¹ (Table 3). The dominant term is the land use flux (~1.92 Pg C yr⁻¹). The fluxes associated with nitrogen are smaller: ~1.04 Pg C yr⁻¹, concentration-carbon; 0.38 Pg C yr⁻¹, climate-carbon; and 0.19 Pg C yr⁻¹, nitrogen deposition. The importance of nitrogen for climate simulations may, however, increase with larger CO₂ and temperature perturbations such as expected by 2100.

[24] The CLM4 is not fully consistent with our understanding of carbon-nitrogen interactions. Tropical forests are thought to not be nitrogen-limited [Vitousek, 1984; Vitousek and Sanford, 1986; Martinelli et al., 1999; Cleveland and Townsend, 2006]. The simulated relative reduction in concentration-carbon uptake due to nitrogen is least in the tropics, but some tropical areas have enhanced climate-carbon uptake with nitrogen (Figure 1). The geographic similarity of the carbon-only and carbon-nitrogen simulations suggests that the CLM4 carbon biogeochemistry, rather than the nitrogen cycle, imposes a fundamental control on the concentration-carbon and climate-carbon feedbacks. In par-

Table 3. Carbon Budget Terms (Pg C yr⁻¹) in Equation (4)^

<table>
<thead>
<tr>
<th>Simulation</th>
<th>ΔC_L</th>
<th>ΔC_C</th>
<th>ΔC_JSTH</th>
<th>ΔΔC_L</th>
<th>ΔΔC_C</th>
<th>ΔΔC_JSTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.62</td>
<td>0.62</td>
<td>1.54</td>
<td>1.43</td>
<td>0.37</td>
<td>0.00</td>
</tr>
<tr>
<td>CN_ndep</td>
<td>−0.13</td>
<td>−0.11</td>
<td>1.22</td>
<td>0.38</td>
<td>0.01</td>
<td>0.19</td>
</tr>
<tr>
<td>CN_ndep − C</td>
<td>−0.75</td>
<td>−0.73</td>
<td>−0.32</td>
<td>−1.04</td>
<td>0.38</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Terms are reported as the 27 year flux. ΔC_L is from the CONC × CLIM simulations with harvest/land cover change. ΔC_C is from equation (4). ΔC_JSTH is the carbon trend from the CTRL simulation without forcing (carbon-only CTRL for C simulations; CN CTRL for CN_ndep simulations). Other terms represent ΔC_ndep for CO₂ concentration (CONC), climate change (CLIM), nitrogen deposition (NDEP), and harvest/land cover change (HLCC). Also shown is the difference CN_ndep − C. Positive/negative terms represent the flux out of the atmosphere.
ticular, tropical areas show the greatest sensitivity to CO$_2$ and climate change in both the C and CN$_{ndep}$ simulations. Additionally, nitrogen reduces the climate-carbon gain in arctic ecosystems, in contrast to other studies [Zaehle et al., 2010a, 2010b].

5. Conclusions

[25] Carbon-nitrogen biogeochemistry simulated by the CLM4 for 1973–2004 decreases the concentration-carbon uptake and lessens the climate-carbon loss compared with carbon-only biogeochemistry. The nitrogen-related decrease in land carbon uptake from increasing atmospheric CO$_2$ is three times greater than the nitrogen-related reduction in land carbon loss from warming. This suggests that while warmer temperature may stimulate nitrogen mineralization and as a result increase plant productivity, thereby introducing a biogeochemical feedback not considered with carbon-only biogeochemistry, our incomplete understanding of CO$_2$ fertilization effects on plant productivity remains a key gap for carbon cycle simulations. Other studies suggest a similar conclusion [Zaehle et al., 2010a].

Figure 1. $\Delta \Delta C_L^{CONC}$ and $\Delta \Delta C_L^{CLIM}$ (g C m$^{-2}$) for (a and d) C simulations and (b and e) CN$_{ndep}$ simulations. (c and f) Difference CN$_{ndep}$ − C. Data are from the simulations shown in Table 3.
Our conclusions are limited to the forcings applied to the model (Table 1), and larger CO$_2$ and climate change such as may occur by the end of the twenty-first century may yield different inference. However, the late twentieth century warming is comparable to that expected for the early twenty-first century [Meehl et al., 2007]. We suggest, therefore, that for near-term climate change simulations the influence of carbon-nitrogen biogeochemistry on the concentration-carbon feedback, not the climate-carbon feedback, is a key uncertainty.

Moreover, land use is a large forcing of the carbon budget over the late twentieth century. Future trajectories of land use and land cover change driven by socioeconomic needs and societal responses to climate change will undoubtedly affect the carbon cycle. If trends for the late twenty-first century hold for the twenty-first century, uncertainty in projections of future land use and land cover change may impact carbon cycle-climate simulations more than feedbacks associated with other terrestrial biogeochemical processes.

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References


