Background

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

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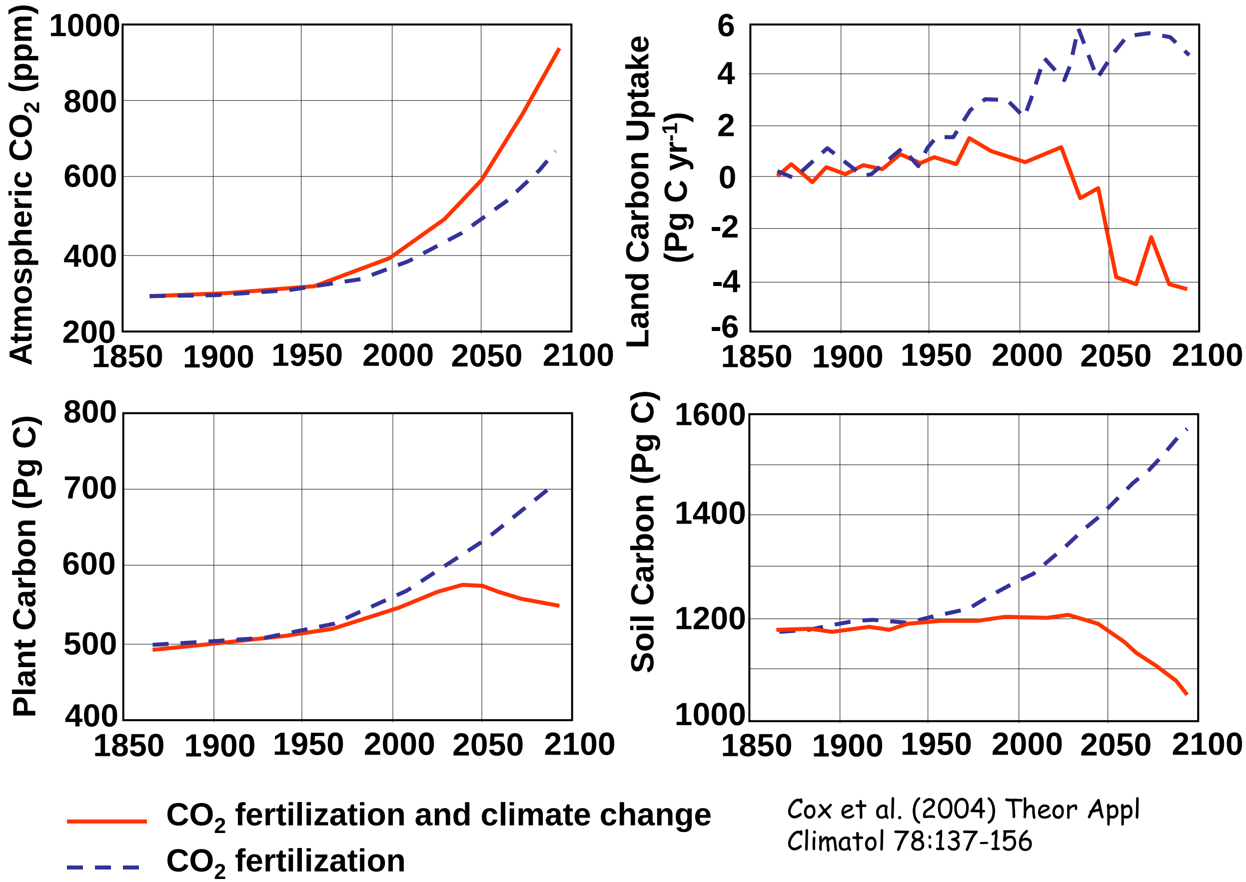
- N cycle reduces the capacity of the terrestrial biosphere to store carbon (CO_2 fertilization) and changes sign of carbon cycle-climate feedback from positive to negative. The CO_2 fertilization effect is larger than the climate feedback effect.
- Uncertainty in land use flux may be greater than the N-cycle feedback.

Prevailing modeling paradigm

CO_2 fertilization enhances carbon uptake, diminished by decreased productivity and increased soil carbon loss with warming



Cox et al. (2004) Theor Appl Climatol 78:137-156

$\Delta C_L = \beta_L \, \Delta C_A$ — $\beta_L > 0$: concentration-carbon feedback (Pg C ppm^{-1})

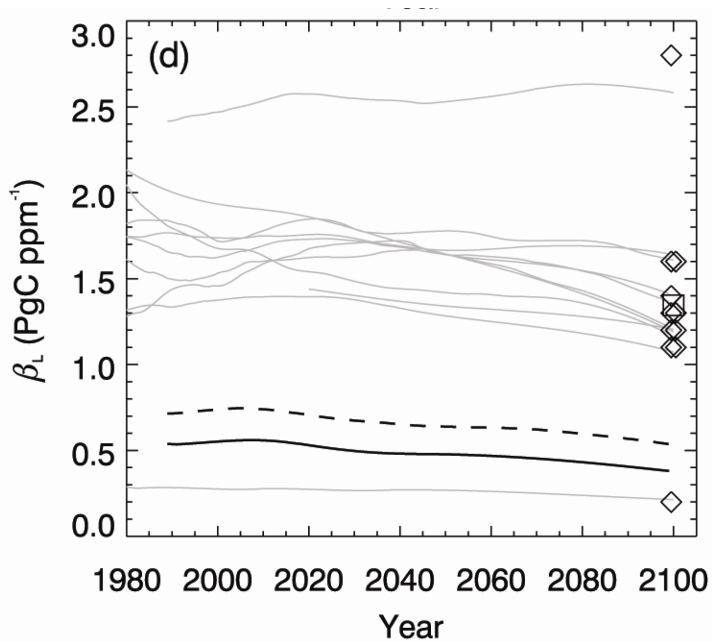
$\Delta C_L = \beta_L \, \Delta C_A + \gamma_L \, \Delta T$ — $\gamma_L < 0$: climate-carbon feedback (Pg C K^{-1})

Carbon-nitrogen interactions

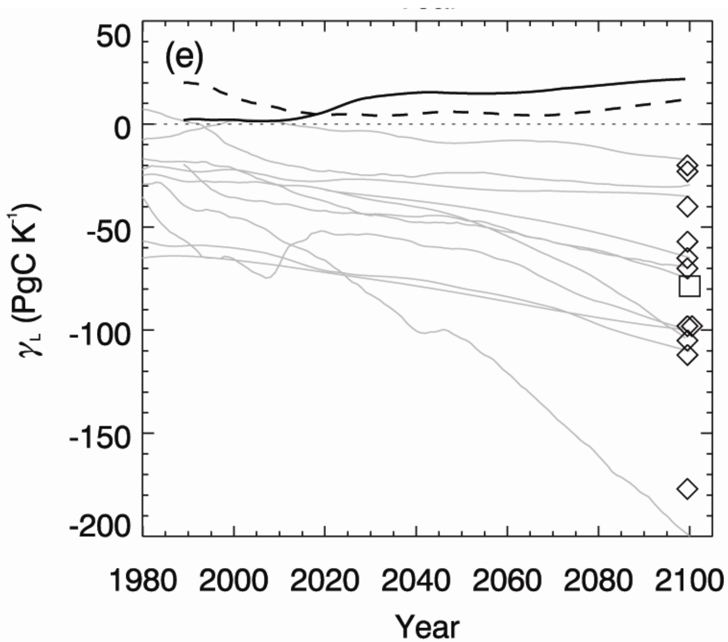
Reduces concentration-carbon feedback (β_L)
- Nitrogen limitation reduces the CO_2 fertilization gain in productivity

Changes sign of climate-carbon feedback (γ_L)
- Greater N mineralization with warming stimulates plant growth

Sokolov et al. (2008) J Climate 21:3776-3796
Thornton et al. (2009) Biogeosci 6:2099-2120



Land biosphere response to CO_2



Land biosphere response to temperature

Thornton et al. (2009) Biogeosci 6:2099-2120

Thick solid line is with preindustrial nitrogen deposition
Thick dashed line is with anthropogenic nitrogen deposition
Thin gray lines are C4MIP models

Model simulations

Offline carbon-only and carbon-nitrogen simulations, 1973-2004

(1) 1850 spin-up
- 1850 land cover, atmospheric CO_2, and nitrogen deposition
- Meteorology uses repeating 25–year subset (1948–1972)
- C-only Vcmax multiplied by time-invariant PFT-specific factor f(N) so that annual GPP matches C-N GPP

(2) Transient simulation for 1850–1972
- Historical atmospheric CO_2, nitrogen deposition, land cover and harvest
- Meteorology uses repeating 25–year subset (1948–1972)

(3) Forcing experiments for 1973–2004
- Historical meteorology, atmospheric CO_2, nitrogen deposition, land cover and harvest
- Initial conditions for 1973 obtained from 1850-1972 transient simulation
- The initial 1973 land carbon is 50 Pg C (3.3%) greater for C-only than the C–N initial condition

Model simulations

Three sets of simulations for 1973–2004:

- **C-only**
- Carbon–nitrogen, constant nitrogen deposition (**CN**)
- Carbon–nitrogen, transient nitrogen deposition (**CN_{ndep}**)

For each model configuration, seven 32–year simulations individually examine the various forcings over 1973–2004:

- (1) **CTRL**, a control simulation without harvest/land cover change and with atmospheric CO_2, meteorology, and nitrogen deposition held constant
- (2) **CONC**, as in CTRL but with transient atmospheric CO_2 forcing
- (3) **CLIM**, as in CTRL but with climate change from the transient meteorology
- (4) **CONC×CLIM**, as in CTRL but with transient CO_2 *and* meteorological forcing
- (5)-(7) CONC, CLIM, and CONC×CLIM performed a second time with transient harvest/land cover change

Model analyses

ΔC_L = 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)

$\Delta\Delta C_L$ = the departure in ΔC_L between two experiments

The concentration-carbon (β_L) and climate-carbon (γ_L) parameters are diagnosed from the difference in ΔC_L between simulations

$$\beta_L = \frac{\Delta\Delta C_L^{CONC}}{\Delta C_A} = \frac{\Delta C_L^{CONC} - \Delta C_L^{CTRL}}{\Delta C_A}$$

$$\beta_L = \frac{\Delta\Delta C_L^{CONC}}{\Delta C_A} = \frac{\Delta C_L^{CONC\times CLIM} - \Delta C_L^{CLIM}}{\Delta C_A}$$

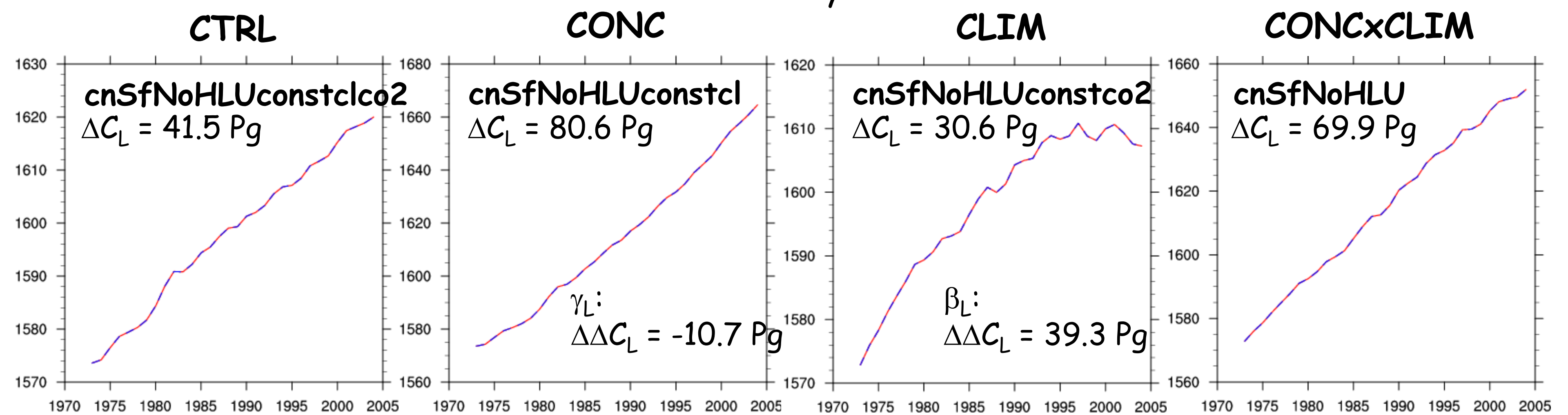
$$\gamma_L = \frac{\Delta\Delta C_L^{CLIM}}{\Delta T_L} = \frac{\Delta C_L^{CLIM} - \Delta C_L^{CTRL}}{\Delta T_L}$$

$$\gamma_L = \frac{\Delta\Delta C_L^{CLIM}}{\Delta T_L} = \frac{\Delta C_L^{CONC\times CLIM} - \Delta C_L^{CONC}}{\Delta T_L}$$

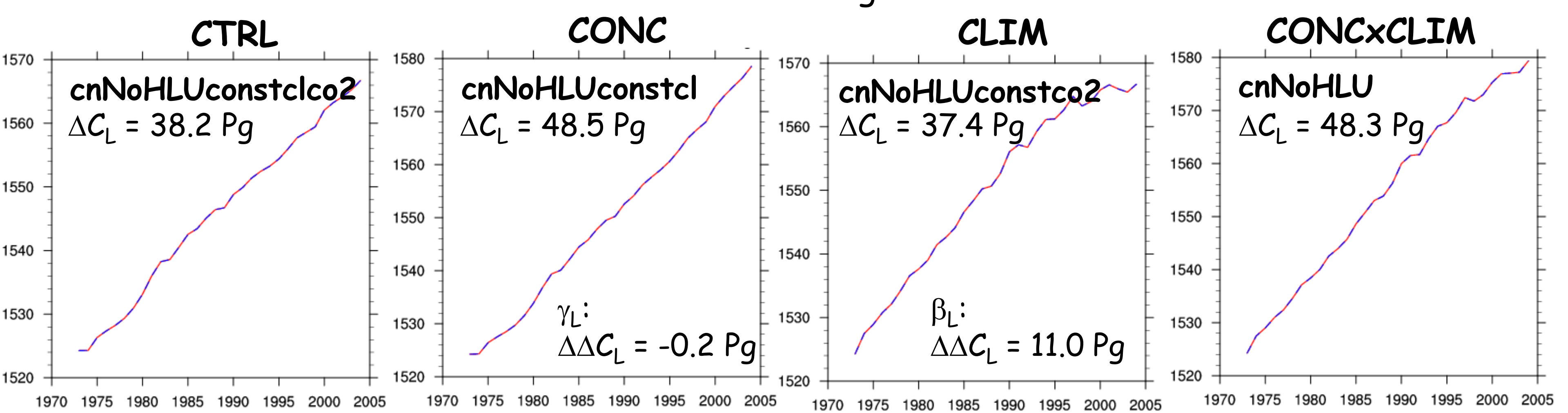
The difference between simulations removes background carbon trends associated with the non-equilibrium initial conditions. For comparison, we performed some additional simulations using equilibrium initial conditions for 1973. Estimates of β_L and γ_L from these simulations were nearly identical to the non-equilibrium estimates.

Example simulations

Carbon only



Carbon-Nitrogen



1973-2004 forcings

Annual Mean Forcings (Land Only) for Control and Experiment Simulations

				Land Use	
Simulations	Atmos. CO_2 [ppm]	Temperature [K]	N deposition [Tg N yr^{-1}]	Cropland [10^6 km^2]	Wood harvest [10^6 km^2 yr^{-1}]
Control	328.6	280.8	48.5	14.0	0
Experiments					
1973–77	331.0	280.9	51.2	14.1	0.14
2000–04	372.8	281.8	63.9	15.2	0.22
Change	41.8	0.9	12.7	1.1	0.08

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.

Comparison with GCP estimates

Carbon fluxes 1973 – 2004

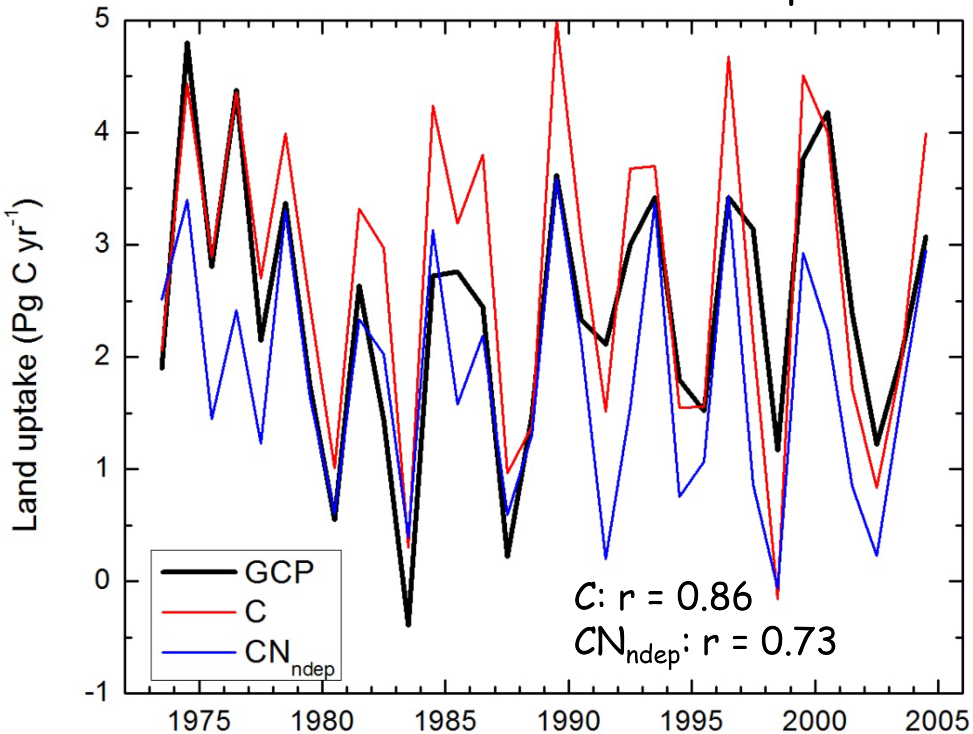
	C	CN_{ndep}	GCP
Land use ($Pg\ C\ yr^{-1}$)	1.8	1.8	1.5
Land sink ($Pg\ C\ yr^{-1}$)	2.5	1.8	2.0 – 2.4

2.4 is C-only estimate with 0.4 residual
2.0 has zero residual

Global Carbon Project (www.globalcarbonproject.org)

Le Quéré et al. (2009) Nature Geosci 2:831-836

Time series of annual land uptake



β_L and γ_L

β_L and γ_L Calculated for Carbon-Only and Carbon-Nitrogen Simulations

	Without HLCC		With HLCC
β_L (Pg C ppm^{-1})	Constant Climate	Climate Change	Climate Change
C	0.94	0.94	0.92
CN_{ndep}	0.25	0.26	0.25
γ_L (Pg C K^{-1})	Constant CO_2	Increasing CO_2	Increasing CO_2
C	-11.7	-11.7	-11.0
CN_{ndep}	-0.9	-0.2	0.2

C mean β_L is 3.7 times greater than CN_{ndep} mean (i.e., 73% reduction in β_L)
➢ 19% reduction [*Jain et al.*, 2010], 58% reduction [*Sokolov et al.*, 2008]

CN_{ndep} reduces carbon loss with climate change, i.e., γ_L increases

Carbon budget analysis (Pg C yr^{-1})

$$\Delta C_L' = \Delta C_L^{HIST} + \Delta\Delta C_L^{CONC} + \Delta\Delta C_L^{CLIM} + \Delta\Delta C_L^{NDEP} + \Delta\Delta C_L^{HLCC}$$

					$\Delta\Delta C_L$			
Simulation	ΔC_L	$\Delta C_L'$	ΔC_L^{HIST}		CONC	CLIM	NDEP	HLCC
C	**0.62**	**0.62**	1.54		**1.43**	**-0.37**	0.00	-1.97
CN_{ndep}	**-0.13**	**-0.11**	1.22		0.38	0.01	0.19	**-1.92**
CN_{ndep} - C	-0.75	-0.73	-0.32		**-1.04**	**0.38**	**0.19**	0.05

C: CONC feedback is four times greater than CLIM feedback

- Similar to *Gregory et al.* [2009]

CN_{ndep}: decrease in CONC uptake is three times greater than reduction in CLIM loss

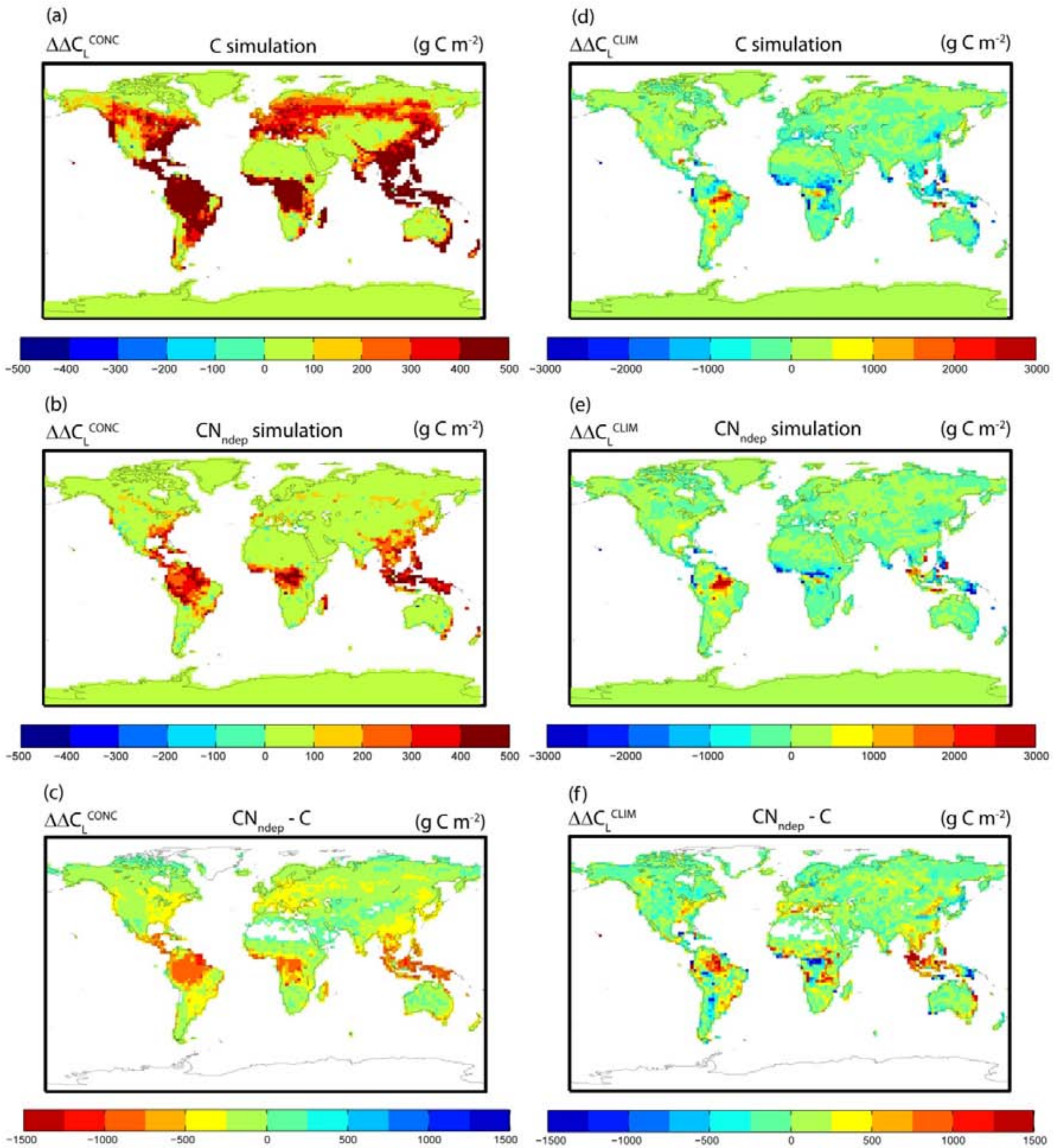
The influence of nitrogen on the concentration-carbon feedback is of greater importance for near-term climate change simulations than its effect on the climate-carbon feedback

The land use carbon flux greatly exceeds these carbon-nitrogen biogeochemical feedbacks

3. Results

Geographic patterns

The largest concentration–carbon feedback increase in ΔC_L occurs in tropical and temperate forests in both simulations. This carbon gain decreases in CN_{ndep}. The relative decline is less in tropical ecosystems (70%) than in mid-latitude (76%) and arctic (85%) ecosystems.



Some tropical regions show a climate-related increase in ΔC_L in the C simulation. The CN_{ndep} simulation has a similar geography, but some regions have enhanced climate-related carbon gain.

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

Carbon cycle

- Carbon–only simulations show that the carbon gain from increasing atmospheric CO_2 (the concentration–carbon feedback) is four times greater than the warming–induced carbon loss (the climate–carbon feedback).
- N cycle reduces the concentration–carbon gain and decreases climate–carbon loss. The decrease in the concentration–carbon feedback is three times greater than the effect on the climate–carbon feedback.
- 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.
- Uncertainty in land use flux may be greater than the N-cycle feedback.