Climate Forcing and Feedback from the Terrestrial Carbon Cycle and Land Cover Change

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Biogeochemistry and Environmental Biocomplexity
Cornell University
Ithaca, New York
Multi-model mean surface warming (relative to 1980-1999) for the scenarios A2, A1B and B1

Multi-model mean warming and uncertainty for 2090 to 2099 relative to 1980 to 1999:

A2:  +3.4°C (2.0°C to 5.4°C)
A1B: +2.8°C (1.7°C to 4.4°C)
B1:    +1.8°C (1.1°C to 2.9°C)


Previous simulations
- Natural forcings (solar variability, volcanoes)
- Anthropogenic forcings (GHG, ozone, aerosols)

Current simulations
- Land cover change and the carbon cycle
Multiple biogeophysical and biogeochemical influences of ecosystems
Ecosystems and climate policy

1. Introduction

Boreal forest – menace to society – no need to promote conservation

Temperate forest – reforestation and afforestation?

Tropical rainforest – planetary savior – promote avoided deforestation, reforestation, or afforestation

Biofuel plantations to lower albedo and reduce atmospheric CO₂
1. Introduction

2. Representing ecosystems in climate models

3. Carbon cycle and climate
   Concentration–carbon feedback (CO$_2$ fertilization)
   Climate–carbon feedback (temperature)
   Nitrogen cycle

4. Land use and land cover change
   4a. Biogeochemical
       Land use carbon flux
   4b. Biogeophysical
       Albedo and evapotranspiration

5. Climate change mitigation
Climate models use mathematical formulas to simulate the physical, chemical, and biological processes that drive Earth’s climate.

A typical climate model consists of coupled models of the atmosphere, ocean, sea ice, and land.

Land is represented by its ecosystems, watersheds, people, and socioeconomic drivers of environmental change.

The model provides a comprehensive understanding of the processes by which people and ecosystems affect, adapt to, and mitigate global change.
2. Models

The Community Land Model

Fluxes of energy, water, and carbon and the dynamical processes that alter these fluxes

Oleson et al. (2004) NCAR/TN-461+STR

Spatial scale
- 2.5° longitude × 1.875° latitude (144 × 96 grid)
- 1.25° longitude × 0.9375° latitude (288 × 192 grid)

Temporal scale
- 30-minute coupling with atmosphere
- Seasonal-to-interannual (phenology)
- Decadal-to-century climate (disturbance, land use, succession)
- Paleoclimate (biogeography)
### 2. Models

**Land surface heterogeneity**

CLM represents a model grid cell as a mosaic of up to 6 primary land cover types. Vegetated land is further represented as a mosaic of plant functional types.

<table>
<thead>
<tr>
<th>Land Cover Type</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glacier</td>
<td>16.7%</td>
</tr>
<tr>
<td>Lake</td>
<td>16.7%</td>
</tr>
<tr>
<td>Wetland</td>
<td>8.3%</td>
</tr>
<tr>
<td>Urban</td>
<td>8.3%</td>
</tr>
<tr>
<td>Crop</td>
<td>6.2%</td>
</tr>
<tr>
<td>Vegetated</td>
<td>43.8%</td>
</tr>
</tbody>
</table>

Subgrid land cover and plant functional types

- **Glacier** 16.7%
- **Lake** 16.7%
- **Wetland** 8.3%
- **Urban** 8.3%
- **Crop** 6.2%
- **Vegetated** 43.8%

- **Subgrid size**: 0.9375° in latitude (~100 km)
- **Subgrid size**: 1.25° in longitude (~100 km)

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Local land use is spatially heterogeneous

Global land use is abstracted to the fractional area of crops and pasture

Settlement and deforestation surrounding Rio Branco, Brazil (10°S, 68°W) in the Brazilian state of Acre, near the border with Bolivia. The large image covers an area of 333 km x 333 km (NASA/GSFC/LaRC/JPL)
Flux tower measurements – temperate deciduous forest

Morgan Monroe State Forest, Indiana

CLM3.0 - dry soil, low latent heat flux, high sensible heat flux
CLM3.5 - wetter soil and higher latent heat flux
Ecosystem Model-Data Intercomparison (EMDI) compilation of observations

- Class A (81 sites)
- Class B (933 sites)

NPP extracted for each model grid cell corresponding to a measurement location.
Integrate ecological studies with earth system models

Environmental Monitoring

Eddy covariance flux tower (courtesy Dennis Baldocchi)

Experimental Manipulation

Soil warming, Harvard Forest

CO₂ enrichment, Duke Forest

CO₂ × N enrichment, Cedar Creek

2. Models

Test model-generated hypotheses of earth system functioning with observations
2. Models

**Comparison with FACE experiments**

Global response to a step change in atmospheric CO$_2$ from 362 ppm to 550 ppm

<table>
<thead>
<tr>
<th></th>
<th>Observed</th>
<th>CASA'</th>
<th>CN</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPP (%)</td>
<td>27 ± 2%</td>
<td>17 ± 2%</td>
<td>7 ± 3%</td>
</tr>
<tr>
<td>$\beta_{fert}$</td>
<td>0.67</td>
<td>0.43 ± 0.04</td>
<td>0.18 ± 0.09</td>
</tr>
</tbody>
</table>

Norby et al. (2005) PNAS 102:18052–18056

DukeFACE (NC)
AspenFACE (WI)
ORNL-FACE (TN)
POP-EuroFACE (Italy)

\[
NPP(t) = NPP(i) \cdot \left[ \beta \cdot \ln \left( \frac{CO_2(t)}{CO_2(i)} \right) + 1 \right]
\]

Randerson et al. (2009) GCB 15:2462-2484
Effect of climate change on carbon cycle

Climate-carbon cycle feedback

11 carbon cycle-climate models of varying complexity

All models have a positive climate-carbon cycle feedback (20 ppm to >200 ppm)

Atmospheric carbon increases compared with no climate-carbon cycle feedback, while land carbon storage decreases

Prevailing model paradigm

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

But what about the nitrogen cycle and land use?

Friedlingstein et al. (2006) J Climate 19:3337–3353
CO₂ fertilization enhances carbon uptake, diminished by decreased productivity and increased soil carbon loss with warming.

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

\( \beta_L > 0 \): concentration-carbon feedback (Pg C ppm⁻¹)
\( \gamma_L < 0 \): climate-carbon feedback (Pg C K⁻¹)
3. Carbon cycle

**Carbon-nitrogen interactions**

Reduces concentration-carbon feedback ($\beta_L$)
- Nitrogen limitation reduces the CO$_2$ fertilization gain in productivity

Changes sign of climate-carbon feedback ($\gamma_L$)
- 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

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**Land biosphere response to CO$_2$**

- Thick solid line is with preindustrial nitrogen deposition
- Thick dashed line is with anthropogenic nitrogen deposition
- Thin gray lines are C4MIP models
3. Carbon cycle

Carbon-nitrogen interactions

- Nitrogen reduces $\beta_L$ by 50%
- Nitrogen reduces carbon loss with climate change, but $\gamma_L$ remains negative

Effect of nitrogen on carbon storage, 1860-2100

The effect of nitrogen to reduce $CO_2$ fertilization is 7 times greater than the effect of nitrogen on the carbon-climate feedback

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

<table>
<thead>
<tr>
<th>Simulations</th>
<th>Atmos. $CO_2$ [ppm]</th>
<th>Temperature [K]</th>
<th>N deposition [Tg N yr$^{-1}$]</th>
<th>Cropland [$10^6$ km$^2$]</th>
<th>Wood harvest [$10^6$ km$^2$ yr$^{-1}$]</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.

Bonan & Levis (2010) GRL, in press
3. Carbon cycle

Quantifying carbon-nitrogen feedbacks in CLM4

Carbon fluxes 1973 - 2004

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>( \text{CN}_{\text{ndep}} )</th>
<th>GCP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land use (Pg C yr(^{-1}))</td>
<td>1.8</td>
<td>1.8</td>
<td>1.5</td>
</tr>
<tr>
<td>Land sink (Pg C yr(^{-1}))</td>
<td>2.5</td>
<td>1.8</td>
<td>2.0 - 2.4</td>
</tr>
</tbody>
</table>

Global Carbon Project (www.globalcarbonproject.org)
Le Quéré et al. (2009) Nature Geosci 2:831-836

Time series of annual land uptake

\( C: r = 0.86 \)
\( \text{CN}_{\text{ndep}}: r = 0.73 \)

Bonan & Levis (2010) GRL, in press
### Quantifying carbon-nitrogen feedbacks in CLM4

#### $\beta_L$ and $\gamma_L$ Calculated for Carbon-Only and Carbon-Nitrogen Simulations

<table>
<thead>
<tr>
<th></th>
<th>Without HLCC</th>
<th>With HLCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_L$ (Pg C ppm⁻¹)</td>
<td><strong>Constant Climate</strong></td>
<td><strong>Climate Change</strong></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>$CN_{ndep} (\Delta \Delta C_L^{NDEP})$</td>
<td>0.37</td>
<td>0.38</td>
</tr>
<tr>
<td>$\gamma_L$ (Pg C K⁻¹)</td>
<td><strong>Constant CO₂</strong></td>
<td><strong>Increasing CO₂</strong></td>
</tr>
<tr>
<td>C</td>
<td>-11.7</td>
<td>-11.7</td>
</tr>
<tr>
<td>CN</td>
<td>-0.7</td>
<td>-0.1</td>
</tr>
<tr>
<td>$CN_{ndep} (\Delta \Delta C_L^{NDEP})$</td>
<td>4.8</td>
<td>5.9</td>
</tr>
</tbody>
</table>

- $C$ mean $\beta_L$ is 3.7 times greater than $CN$ mean (i.e., 73% reduction in $\beta_L$)
- $19\%$ [Jain et al., 2010], $50\%$ [Zaehle et al., 2010], $58\%$ [Sokolov et al., 2008]

- Additional carbon from N deposition increases $\beta_L$ by 50%
- $CN$ reduces carbon loss with climate change, i.e., $\gamma_L$ increases

Bonan & Levis (2010) GRL, in press
Carbon budget analysis (Pg C yr\(^{-1}\))

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

<table>
<thead>
<tr>
<th>Simulation</th>
<th>(\Delta C_L)</th>
<th>(\Delta C_L')</th>
<th>(\Delta C_L^{\text{HIST}})</th>
<th>CONC</th>
<th>CLIM</th>
<th>NDEP</th>
<th>HLCC</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>
<td>-1.97</td>
</tr>
<tr>
<td>(CN_{\text{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>
<td>-1.92</td>
</tr>
<tr>
<td>(CN_{\text{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>
<td>0.05</td>
</tr>
</tbody>
</table>

C: CONC feedback is four times greater than CLIM feedback

- Similar to Gregory et al. [2009]

\(CN_{\text{ndep}}\): 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
1. For IPCC AR5 land use and land cover change are to be described consistently with Representative Concentration Pathways (RCP) scenarios.

2. All pathways share the same historical trajectory to 2005. After 2005 they diverge following own representative pathway.

3. For the historical period and for each RCP, land use that results in land cover change is described through annual changes in four basic land units:

   - Primary Vegetation (V)
   - Secondary Vegetation (S)
   - Cropping (C)
   - Pasture (P)

4. Harvesting of biomass is also prescribed for both primary and secondary vegetation land units.

5. George Hurtt and colleagues at University of New Hampshire are harmonizing the historical and RCP data (luh.unh.edu)
Historical land cover change, 1850 to 2005

4. Land use

Tree PFTs

Crop PFT

Shrub PFTs

Grass PFTs

(datasets by Lawrence & Feddema)
4. Land use

Future land cover change, 2005 to 20100

MINICAM (RCP 4.5 W m$^{-2}$)

MESSAGE (RCP 8.5 W m$^{-2}$)

IMAGE (RCP 2.6 W m$^{-2}$)

AIM (RCP 6.0 W m$^{-2}$)

(In development)

(datasets by Lawrence & Feddema)
4. Land use

Future land cover change, 2005 to 20100

**MESSAGE (RCP 8.5 W m$^{-2}$)**
- Map showing future land cover change from 2005 to 2100.
- Color scale indicates percentage change.

**MINICAM (RCP 4.5 W m$^{-2}$)**
- Map showing future land cover change from 2005 to 2100.
- Color scale indicates percentage change.

**IMAGE (RCP 2.6 W m$^{-2}$)**
- Map showing future land cover change from 2005 to 2100.
- Color scale indicates percentage change.

**AIM (RCP 6.0 W m$^{-2}$)**
- Map showing future land cover change from 2005 to 2100.
- Color scale indicates percentage change.

(In development)

(datasets by Lawrence & Feddema)
4. Land use

Land use - wood harvest

Primary Harvest 1971 - 2000

Secondary Young Forest Harvest 1971 - 2000

Secondary Mature Forest Harvest 1971 - 2000

(datasets by Lawrence & Feddema)
4. Land use

Land use carbon flux

- Land use carbon flux
- Wood harvesting
- Land cover change (e.g., deforestation)

(simulations by Sam Levis)
4. Land use

Land use carbon flux

Land Use Carbon Flux: CLM DWT_CLOSS+PRODUCT_CLOSS vs. GCP

- CLM
- CLM (new harvest coefficients)
- CLM (only vh1 & sh1 on)
- GCP

Three different harvest algorithms

Global Carbon Project
(www.globalcarbonproject.org)

(simulations by Sam Levis)
Models
Atmosphere - CAM3.5
Land - CLM3.5 + new datasets for present-day vegetation + grass optical properties
Ocean - Prescribed SSTs and sea ice

Experiments
30-year simulations ($CO_2 = 375$ ppm, SSTs = 1972-2001)
   PD - 1992 vegetation
   PDv - 1870 vegetation
30-year simulations ($CO_2 = 280$ ppm, SSTs = 1871-1900)
   PI - 1870 vegetation
   PIv - 1992 vegetation

5-member ensembles each
Total of 20 simulations and 600 model years

Multi-model ensemble of global land use climate forcing (1992-1870)

Seven climate models of varying complexity with imposed land cover change (1992-1870)

Pitman, de Noblet-Ducoudré, et al. (2009)
GRL, 36, doi:10.1029/2009GL039076

No irrigation
Change in JJA near-surface air temperature (°C) resulting from land cover change (PD - PDv)

Change in JJA latent heat flux ($W\,m^{-2}$) resulting from land cover change (PD - PDv)

4. Land use

Albedo forcing, 1992-1870
4. Land use

Near-surface temperature, 1992-1870

Present Day - 1870 DJF Atmospheric Temperature (°C)

Present Day - 1870 MAM Atmospheric Temperature (°C)

Present Day - 1870 JJA Atmospheric Temperature (°C)

Present Day - 1870 SON Atmospheric Temperature (°C)
Increased rainfall enhances latent heat flux
Increased cloudiness reduces solar radiation
Reduced PBL height

Climate models simulate the large-scale response and include feedbacks with the atmosphere:
- Increased rainfall enhances latent heat flux
- Increased cloudiness reduces solar radiation
- Reduced PBL height

Flux towers measure local response
Land cover change offsets greenhouse gas warming

4. Land use

Land cover change with $CO_2 = 375$ ppm (1992)

Land cover change with $CO_2 = 280$ ppm (1870)

$CO_2$ forcing with 1870 land cover
Monthly shortwave surface albedo for dominant US land cover types in the Northeast (b) and Southeast (d)

Cropland has a high winter and summer albedo compared with forest

Higher summer albedo

Forest masking
4. Land use

Land cover change and evapotranspiration

Prevailing model paradigm

**Crops**
Low latent heat flux because of:
- Low roughness
- Shallow roots decrease soil water availability

**Trees**
High latent heat flux because of:
- High roughness
- Deep roots allow increased soil water availability

Tropical forest - cooling from higher surface albedo of cropland and pastureland is offset by warming associated with reduced evapotranspiration

Temperate forest - higher albedo leads to cooling, but changes in evapotranspiration can either enhance or mitigate this cooling

4. Land use

Reforestation cools climate

Albedo

<table>
<thead>
<tr>
<th></th>
<th>OF to PP</th>
<th>OF to HW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albedo</td>
<td>+0.9°C</td>
<td>+0.7°C</td>
</tr>
<tr>
<td>Ecophysiology and aerodynamics</td>
<td>-2.9°C</td>
<td>-2.1°C</td>
</tr>
</tbody>
</table>

Forest

Lower albedo (+)

Greater leaf area index, aerodynamic conductance, and latent heat flux (-)

Can Ameriflux provide insights?

3. Land use

NCEAS “Forest and Climate Policy”
working group

Crops
Mead irrigated sites have highest LH
LH varies with crop rotation
LH varies with crop type (winter wheat)
5. Mitigation

Climate change mitigation

Ecosystems

Management strategies
- Reforestation, afforestation, avoided deforestation
- Biofuels

Consequences
Biogeophysics and biogeochemistry (albedo, ET, carbon)

Urban planning and design
- White roofs
- Greenspaces

Average summer difference in the urban minus rural air temperature with roof albedos maximized

Future IPCC SRES land cover scenarios for NCAR LSM/PCM

Feddema et al. (2005) Science 310:1674-1678

5. Mitigation

Land use choices affect 21st century climate

Future IPCC SRES land cover scenarios for NCAR LSM/PCM

a) Present day land cover

b) B1 2050 land cover
d) A2 2050 land cover
c) B1 2100 land cover
e) A2 2100 and cover

A2 - Widespread agricultural expansion with most land suitable for agriculture used for farming by 2100 to support a large global population

B1 - Loss of farmland and net reforestation due to declining global population and farm abandonment in the latter part of the century

Feddema et al. (2005) Science 310:1674-1678
5. Mitigation

Land use choices affect 21st century climate

Change in temperature due to land cover

**B1**
- Weak temperate warming
- Weak tropical warming

**A2**
- Temperate cooling
- Tropical warming

Feddema et al. (2005) Science 310:1674-1678
Conclusions

The ecology of climate models

- Detailed representation of ecosystems
- Allows exploration of ecological feedbacks and mitigation options

Carbon cycle

- $CO_2$ fertilization enhances carbon gain, diminished by carbon loss with warming
- N cycle reduces the concentration-carbon gain and decreases climate-carbon loss
- The $CO_2$ fertilization effect is larger than the climate feedback effect

Land use and land cover change

Biogeochemistry
- Wood harvest flux is important
- Uncertainty in land use flux may be greater than the N-cycle feedback

Biogeophysics
- Higher albedo of croplands cools climate
- Less certainty about role of latent heat flux
- Implementation of land cover change (spatial extent, crop parameterization) matters