Nutrient limitation on global land carbon uptake

Ying-Ping Wang
CSIRO Marine and Atmospheric Research, Australia
Outline

• Why is nutrient limitation important?
• CABLE and global nutrient limitation
• An earth system model: COAL
  – Nutrient limitation on allowable CO2 emission
  – Nutrient limitation on CO2 emission/uptake from deforestation/reforestation
• Summary
What is carbon-climate feedback?

Increase in atmospheric [CO2] → Increase in surface T → Reduction in C uptake by land and ocean
Carbon-climate feedback:
C4MIP phase II simulations

• 11 models are used (see Friedlingstein et al. 2006);

• Key findings:
  – carbon-climate feedback is positive and highly uncertain;
  – an additional warming of 0.1K to 1.5K by 2100 (additional to a warming 2 to 4K without CC feedback).

• But none of those models include nutrient limitations
Coupled carbon-climate simulations differ by 292 ppm.
The question

• Carbon cycle is closely coupled to nitrogen cycle in terrestrial ecosystems;
• None of those 11 models include nutrient limitation on land carbon uptake;
• Is there enough N available to sustain the predicted C accumulation by all 11 models by 2100?
Nitrogen input to uncultivated land

• N deposition (Dentener 2006), only 7% to 17% available for storing C (schlesinger 2009)
  – 0.01 Gt N/year in 1860
  – 0.058 Gt N/year in 1993
  – 0.122 Gt N/year in 2050

• N fixation (Wang and Houlton 2009)
  – About 0.15 Gt N/year at present, may increase to 0.22 by 2100
Response of N fixation

![Graph showing response of N fixation to temperature increase and atmospheric [CO₂]. Results for (a) region 1 and (b) region 2 are shown for [CO₂] of 290 ppm (solid black line), 550 ppm (solid grey line) and 1000 ppm (dashed grey line).]

Source: Wang and Houlton 2009
The N required by 2100

• Depends on
  – How much C is stored (13 to 844 Gt C)
  – where C is stored
  – N:C ratio of different pools

• The amount of N required varies from 0 to 17.1 Gt N by 2100 for 11 models
N deficit and excess C

- **N deficit** = N available – N required

- **Excess C** = N deficit * $f(C:N$ ratio)

- Excess C is then partitioned to atmosphere and ocean, resulting in higher atmospheric CO$_2$ additional warming
The N deficit and excess C by 2100

N deficit (Gt N)

Excess C (Gt C)

C4MIP Model

high N fix
low N fix
N limitation causes more warming

![Graph showing warming from CC feedback]  
**Model**

<table>
<thead>
<tr>
<th>Year Range</th>
<th>C4MIP (°C)</th>
<th>High N Fixation (°C)</th>
<th>Low N Fixation (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2100-1900</td>
<td>0.66</td>
<td>0.69 to 1.19</td>
<td></td>
</tr>
</tbody>
</table>

*Source: Wang and Houlton, 2009, GRL*
Norby et al. 2005. NPP under elevated CO2 increased by 23±2%.

CABLE: its components

Biophysics + Biogeochemistry = CABLE

- Deposition
- Weathering
- Fixation
- Fertilizer

- Leaf
- Root
- Wood

- Metabolic
- Structural
- CWD

- Microbial
- Slow
- Passive

- Inorganic N
- Labile P
- Occluded P
- Sorbed P
- Strongly sorbed P

- N loss
- P loss
The coupled ocean atmosphere land model (COAL)

- The coarse resolution atmosphere model
- Ocean model (physics and ocean carbon)
- Land model, CABLE (biophysics and biogeochemistry)

- Projected climate as a function of RCP
Historical land use change (1850-2005)

Zhang et al. 2013 ESD
Different effects of nutrient limitation

1980's
1990's
2000's

Emission rate (Pg C/yr)

0.0
0.5
1.0
1.5
2.0
2.5

Total emission (Pg C)

0
50
100
150
200
250

1850-2005

Emission rate (Pg C/yr)

1.0
1.5
2.0
2.5

1980's
1990's
2000's

Other
COAL-C
COAL-CNP
ISAM-C
ISAM-CN
Global C budget (1850-2005)

<table>
<thead>
<tr>
<th></th>
<th>1850-2005</th>
<th>C only</th>
<th>CNP</th>
<th>GCP+others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil fuel</td>
<td>314</td>
<td>314</td>
<td>314±16</td>
<td></td>
</tr>
<tr>
<td>atmosphere</td>
<td>-200</td>
<td>-200</td>
<td>-200±11</td>
<td></td>
</tr>
<tr>
<td>Ocean uptake</td>
<td>-116</td>
<td>-118</td>
<td>-135±25</td>
<td></td>
</tr>
<tr>
<td>LUC emission</td>
<td>130</td>
<td>97</td>
<td>155±78</td>
<td></td>
</tr>
<tr>
<td>Residual land flux</td>
<td>-128</td>
<td>-93</td>
<td>-135±84</td>
<td></td>
</tr>
</tbody>
</table>

Fire emissions are not included in our model
What will happen in the future?

• We studied the effect of nutrient limitation for three IPCC AR5 representative concentration pathways (RCP):
  – RCP2.6: a low emission scenario
  – RCP8.5: A high emission scenario with significant deforestation after 2005;
  – RCP4.5: A medium emission scenario with significant reforestation.
IPCC AR5 ESMs +COAL: sensitivities

CO2 sensitivity (Pg C/ppm)

Temp. sensitivity (Pg C/K)

ESM_C (n=7)
EMS_CN (n=2)
COAL_C
COAL_CN
COAL_CNP
Three RCPs and the compatible emissions from IAM

![Graph showing global warming and compatible fossil-fuel emissions for RCP2.6, RCP4.5, and RCP8.5.](image)
Nutrient limitation on land C uptake in the future

Nutrient limitation on allowable emissions
How much can we emit if we want to keep the global warming below 1K or 3K by 2100?

Nutrient limitation on emission/uptake from deforestation/afforestation
How effective is the forest management in CO₂ mitigation?
Two representative concentration path pathway (RCP)
How much can we emit?

• If we want to limit the global warming by 1K (RCP2.6) or 3 K (RCP8.5) by 2100.

• Simulations
  – Using prescribed atmospheric [CO2] (RCPs)
  – Run COAL from 1850 to 2100 with three different land BGC configurations (C, CN, CNP).
  – Allowable emission = atmospheric CO2 increase + ocean uptake + land uptake
Simulated ocean and land sinks

Source: Zhang et al. submitted
Land C accumulation from 2005 to 2100

Zhang et al. submitted
Nutrient limitation reduces land C accumulation

**Source:** Zhang et al. submitted
If we want to stay on the same concentration pathway (or 1K or 3K warming), then

Source: Zhang et al. submitted
Afforestation for mitigating climate change

Conversion of forest to crop/pasture

• Biophysical effects
  – Change surface albedo (increase)
  – Energy partitioning (decrease LE)

• Biogeochemical effects
  – Change carbon balance (decrease)
Four simulations (2006-2100)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Land use</th>
<th>C or CNP</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTL-C</td>
<td>Constant after 2005</td>
<td>C</td>
</tr>
<tr>
<td>CTL-CNP</td>
<td>Constant after 2005</td>
<td>CNP</td>
</tr>
<tr>
<td>LUC-C</td>
<td>Varied according to RCP</td>
<td>C</td>
</tr>
<tr>
<td>LUC-CNP</td>
<td>Varied according to RCP</td>
<td>CNP</td>
</tr>
</tbody>
</table>

“LUC-C” – “CTL-C”: effect of land use change without nutrient limitation;

“LUC-CNP” – “CTL-CNP”: effects of land use change with nutrient limitation
C pool change and CO2 emissions

C pool change with LUC

CO2 emission from LUC

Reforestation
deforestation

Zhang et al. submitted
CO2 emission from land use

C only

CNP

RCP4.5

RCP8.5

LUC-C"-"CTL-C"  "LUC-CNP"-"CTL-CNP"

Source: Zhang et al. submitted
Nutrient limitation on carbon flux from land use change (2006-2100)

Reforestation

Deforestation

CO₂ emission/uptake (Gt C)

C  CNP

-90  -60  -30  0  30  60

wood prod  soil  litter  vegetation
Conclusions

• Nutrient limitation reduces carbon uptake by global biosphere by up to 60%, with strong N limitation at high latitudes and P limitation at low latitudes;

• The allowable emission needs to be reduced by 8 to 10% for two RCPs, otherwise we will face additional warming;

• Nutrient limitation reduces the estimated CO2 emission from deforestation by about 20% (RCP8.5) or uptake from reforestation by 60% (RCP4.5)
Many thanks for the following people who have contributed to the work

• Qian Zhang (Beijing Normal University)
• Benjamin Houlton (UC Davis)
• Andy Pitman (UNSW)
• Richard Matear (CSIRO)
• Peter Lawrence, Gordon Bonan (NCAR)
Carbon climate feedback

Recent progress

Including carbon cycle into climate model => earth system model, therefore effects on climate change on carbon cycle, or so called carbon-climate feedback are now included.