Nitrogen and phosphorous cycles in terrestrial ecosystems

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Outline

• Carbon-nutrient interaction and human influences on N and P cycles
• nitrogen cycle
• phosphorus cycles
• Effects of nutrient limitation of carbon production in land biosphere
• Global pattern of nutrient limitation
• Global models of terrestrial C, N and P cycles
• Summary
Interaction of carbon and nutrients

**Nutrients (N and P) affects**
- photosynthesis, respiration
- litter and SOM decomposition, therefore soil nutrient availability, carbon allocation, plant growth
Human influences of N and P cycles

Source: Reay et al. 2009

Cordell 2010
Global simulations of NxC interactions

1993. Melillo et al. published their estimate of NPP response to climate change and CO2;
1993. Schindler et al. showed N deposition could contribute to a carbon of 0.6 to 2 Gt C/yr; and that estimate was refined by Townsend et al. (1996) to 0.4 to 0.8 Gt C/yr in 1990’s.
Hungate et al. (2003), Wang & Houlton (2009) showed global models without N overestimated land C uptake and underestimated global warming
2008, Sokolov et al. conducted the first fully coupled CN simulation using a simple earth system model;
2013. AR5, only an ESM with N cycle, and its land C uptake sensitivity to CO₂ was about 25% of the mean of other models without N
Forms: Organic, inorganic \((\text{NH}_4, \text{NH}_3, \text{NO}_3, \text{NO}_2, \text{NO}, \text{N}_2\text{O}, \text{N}_2)\)

Inputs: Lightning
       Biological N fixation
       Anthropogenic N input

Outputs: Leaching, Gaseous loss

Source: Bouwman et al. 2009

Internal cycling:
assimilation (soil to plant)
resorption (plant)
litter fall (plant to litter)
ammonification: organic N to \(\text{NH}_4\)
nitrification: \(\text{NH}_4\rightarrow \text{NO}_3\)
denitrification: \(\text{NO}_3\rightarrow \text{N}_2\text{O}-\text{N}_2\)
Nitrogen input

Data source: Gruber and Galloway 2008
Natural N fixation

Cleveland et al. 1999

Plate 2. Mapped potential annual BNF by natural ecosystems based on the relationship between the central estimates of BNF (N fixation = 0.234(ET) - 0.172) and ecosystem ET. Values are kg N ha\(^{-1}\) yr\(^{-1}\). White areas represent regions where modeled ET values are unavailable.

Wang and Houlton 2009
Internal N process: Resorption

Leaf litter

Resorption coefficient

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>P</th>
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<tbody>
<tr>
<td>Evergree</td>
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<tr>
<td>Deciduous</td>
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<tr>
<td>Forbs</td>
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<tr>
<td>Grass</td>
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<tr>
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</table>

Source: Aerts 1995

Fine roots

Nitrogen (g/kg)

Source: Gordon and Jackson 2000
Internal processes: plant uptake

Plant N uptake: Plant can take up both NH4 and NO3 and dissolved organic N. Plant N uptake rate depends on the rate of soil supply, root length and root activities.

However, nutrient diffusion is not explicitly represented in global models. Nutrient uptake is usually modeled as the smaller value of available nutrient and plant demand.

Source: Yanai 1994
**Internal N process: Mineralization/immobilization**

**Gross mineralization** (G): the rate of total amount of N released via mineralization

**Immobilization** (I): uptake of N by soil microbes and used for their growth

**Net mineralization** (N) = gross mineralization - immobilization

**Microbial carbon use efficiency** (e): the fraction of carbon uptake that is used for growth. Theoretical max: 0.6 for soil microbes (see Sinsbaugh et al. 2013).

**The critical C:N ratio of substrate**

Assuming C:N of soil microbes of 10:1 with e= 0.4;

BY decomposing 100 g litter C, soil microbes increase their body mass by 40 g C and requires 4 g N (immobilization).

Gross mineralization rate =100/(C:N ratio of litter)

If litter C:N ratio is higher than 25:1, N <0

If litter C:N ratio lower than 25:1, N>0,

*25:1 is the critical C:N ratio of decomposing substrate.*
N mineralization and carbon use efficiency

Parton et al. 2008

Sinsbaugh et al. 2013
Internal processes: nitrification and denitrification

Nitrification (aerobic): conversion of $\text{NH}_4^+$ to $\text{NO}_3^-$.  
Denitrification (anaerobic, or low oxygen): $\text{NO}_3^->\text{NO}_2->\text{NO}->\text{N}_2\text{O}->\text{N}_2$

Source: Davidson et al. 2000
Denitrification: interactive effects of temperature and moisture

Fig. 8. Influence of the temperature on the anaerobic fraction of the aggregates for a soil having a bulk density of 1.1 and a mean aggregate radius of 0.0025 m and for a real $Q_{10}$ of O$_2$ consumption of 2.

Source: Renault and Sierra 1994
Nitrogen loss

Nitrogen leaching represent a loss of inorganic N (nitrate) and organic N from terrestrial ecosystems. Globally it can be larger than gaseous loss (Bai et al. 2012), accounting for about 65% of N loss from natural ecosystems. For managed the systems, fraction of gaseous loss can be significantly larger than leaching, but loss of N$_2$ is difficult to measure, therefore closing a N budget is difficult for many ecosystems.
Nitrogen gaseous loss (hole in the pipe)

Source: Bouwman 1998
Two approaches for N loss

1: A hole in the pipe approach
Total N loss $\propto$ gross N min.
$\text{NO:N}_2\text{O:N}_2 = \text{function (WFPS)}$

2: explicit representation of
• Anaerobic fraction
• nitrification
• denitrification
• diffusion of $O_2$, $N_2O$

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Fig. 3. Model of N gas production as a function of WFPS (water-filled pore space, %). The solid line represents NO; short dashed line represents $N_2O$ fraction; and long dashed line represents $N_2$.

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Davidson 1991, Potter et al. 1996
Forms: organic, inorganic ($\text{H}_2\text{PO}_4$, $\text{HPO}_4$, $\text{PO}_4$)
Inputs: weathering
dust deposition
Anthropogenic P input
Outputs: Leaching, runoff, erosion, adsorption

Internal cycling:
assimilation (soil to plant)
resorption (plant)
litter fall (plant to litter)
Biological mineralization
Biochemical mineralization

Sources: Bouwman et al. 2009
Soil P availability

- Soil pH determines the most abundant form of inorganic P in soil

\[ H_2PO_4^- \leftrightarrow H^+ + H_2PO_4^{2-} \leftrightarrow 2H^+ + PO_4^{3-} \]

\( \text{pH range} [4, 10, 14] \)

Figure 3. The availability of phosphorus is affected by soil pH.
P weathering rate of different soils (g P m^{-2} year^{-1})

- Entisol: 0.05
- Aridisol: 0.01
- Ultisol: 0.005
- Oxisol: 0.003
Biochemical mineralization

Biochemical mineralization is the processes of converting organic P to inorganic P by enzymatic reaction (phosphatase). Both plant roots and soil microbes can produce phosphatase (acid and alkaline phosphatase). Following Hui et al. (2013), the activity of phosphatase, $V$, can be modeled as

$$V = V_0 f_1(T)f_2(pH)$$

$$f_1(T) = \exp \left( -\frac{E_a}{R} \left( \frac{1}{T} - \frac{1}{T_{ref}} \right) \right)$$

$$f_2(pH) = \exp \left( -\left( \frac{pH - pH_{opt}}{pH_{sen}} \right)^2 \right)$$
P sorption in soil can be modelled using the Langmuir equation:

$$\frac{P_{\text{solution}}}{P_{\text{sorbed}}} = \frac{1}{bS_{\text{max}}} + \frac{P_{\text{solution}}}{S_{\text{max}}}$$

Parameter $b$ is a constant related to bonding energy, $S_{\text{max}}$ is the Langmuir sorption maximum, both $S_{\text{max}}$ and $b$ vary with soil pH, content of Al, Fe, Clay and organic C content etc.
Fractionation of soil P

Source: Yang and Post 2011
Soil P dynamics at geological time scale (Walker and Syers’ theory)

Key points:
all P land biosphere is derived from Rock weathering. For young soil, most P is in mineral form, and P available for plant uptake is high, as soil ages, mineral P becomes adsorbed, and unavailable to plant. Therefore productivity of plant ecosystem is P limited.

Total amount of soil P also decreases as soil ages, as soil P is lost via leaching or soil erosion.

Source: Filippelli 2002
## Global N and P fluxes (Tg N or P/yr)

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<td>N fixation</td>
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<td>N gas flux</td>
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<td>N mineralization</td>
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<td>P leaching</td>
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<td>P fixation</td>
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<td>P uptake</td>
<td>60</td>
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<tr>
<td>P mineralization</td>
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</tr>
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</table>
Effect of N and P on photosynthesis

Source: Reich et al. 2009 for 314 species
Effect of nitrogen on carbon fluxes

Reich et al. 2008
Effect of phosphorous on carbon cycle

\[ G = Y_g \left( A - R_m \right) \]

\[ Y_g \propto \frac{N_b}{P_b} \]

Source: Kerkhoff et al. 2005
Global pattern of N vis P limitation

Source: Hedin 2004

N:P <14, N limiting;
N:P >16, P limiting
(Koerselman and Meuleman (1996))
Global nutrient limitation

Wang, Law and Pak et al. 2010, Biogeosciences
Progressive nitrogen limitation

Luo et al. 2004,
Response of C flux to $2\times\text{CO}_2$

Source: Cumins and McMurtrie 1993
Modelling N and P cycles on land

Compartmental modeling approach:

Compartmental modeling: divide the pools by function (Plant, litter, soil) and residence time (fast, slow);

Plant: leaf, wood, root (coarse root, fine root)

Litter: metabolic, structure litter, coarse woody debris

Soil: organic and inorganic

Pool dynamics is modeled using first-order, or Michaelis-Menten kinetics
How nutrient-carbon interactions are represented in global land models?

Source: Sokolov et al. 2008

Source: http://www.ntsg.umt.edu/project/biome-bgc
Comparing the two models

<table>
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<tr>
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<th>IGSM (TEM)</th>
<th>CCSM (CN)</th>
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<tbody>
<tr>
<td>Biophysics</td>
<td>CLM2.0</td>
<td>CLM4.0</td>
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<tr>
<td>Time step</td>
<td>daily</td>
<td>hourly</td>
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</table>
| Nitrogen feedback on GPP and Rm | Empirical model       | $V_{\text{cmax}} = f(\text{leaf } n)$  
|                              |                        | $R_m = f_2(\text{tissue } N)$   |
| Stomatal conductance         | Not modelled           | Ball-Berry model       |
| Plant uptake                 | Michaelis-menton       | A function of demand   |
| C and N pools                | 2 C pools
|                              | 3 N pools              | >30 C pools
|                              |                        | >30 N pools            |
| N fixation and N pools       | prescribed             | modelled               |
Effects of nitrogen limitation (IGSM)

Source: Sokolov et al. 2008
Effect of nitrogen limitation (CCSM3)

Source: Thornton et al. 2009
CABLE: its components

Biophysics + Biogeochemistry = CABLE

- CABLE: components
  - Deposition
  - Weathering
  - Fixation
  - Fertilizer
  - Root
  - Wood
  - Leaf
  - Metabolic
  - Structural
  - CWD
  - Microbial
  - Slow
  - Passive
  - Occluded P
  - Sorbed P
  - Strongly sorbed P
  - N loss
  - P loss
C accumulation from 1850 to 2100

Zhang et al. submitted
Effects of both N and P

Source: Zhang et al. submitted
Sensitivities of land carbon

Change in total carbon pool, \( \Delta C_L \) in response to increasing atmospheric \( \text{CO}_2 \) \( \Delta \text{CO}_2 \) and climate change \( \Delta T \) can be approximated as

\[
\Delta C_L = \beta_L \Delta \text{CO}_2 + \gamma_L \Delta T
\]

\( \beta_L \) is the \( \text{CO}_2 \) sensitivities of land carbon in Gt C/ppm \((>0)\)
\( \gamma_L \) is the climate sensitivity of land carbon in Gt C/K \((<0)\).

Values of \( \beta_L \) and \( \gamma_L \) are estimated from the differences of simulated carbon pool size between control, uncoupled (only changing \( \text{CO}_2 \) is seen by land biosphere) and coupled (both climate and \( \text{CO}_2 \) are seen by land biosphere) simulations.
The $T$ and $\text{CO}_2$ sensitivities of global land carbon uptake

\[ \Delta C_l = \alpha \Delta T + \beta \Delta c \]

$\alpha < 0.0$

$\beta > 0.0$
IPCC AR5 models + COAL

CO₂ sensitivity (g GT C/ppm)

MPI
IPSL
BCC
HadGEM
UVic
CanESM
No-ESM
CESM
MIROC
COAL-C
COAL-CN
COAL-CNP

Temp. sensitivity (Gt C/K)

CN model

-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160

-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160

MPI
IPSL
BCC
HadGEM
UVic
CanESM
No-ESM
CESM
MIROC
COAL-C
COAL-CN
COAL-CNP
Human activities have significantly altered the nutrient cycles globally;
Nutrient limitation can significantly affect all carbon fluxes in terrestrial ecosystem;
N limitation dominates at mid- and high latitudes while P limitation dominates at low latitudes and southern hemisphere;
Globally, sensitivity of photosynthetic carbon uptake to increasing CO$_2$, so-called CO$_2$ fertilization effect, by 2100 can be reduced by 50% by nitrogen limitation, and another 40% by phosphorous limitation. These estimates have very large uncertainties.
Acknowledgment

Many thanks for the people whose work is used in this talk, particularly

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