Nutrient Cycling in Land Plants

OCN 401 - Biogeochemical Systems
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Reading: Chapter 6

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Outline

1. Plant nutrient requirements and sources
2. Nutrient uptake by plants
   - Nutrient balances
3. Biogeochemical nitrogen cycle
   - Nitrogen speciation
   - Nitrogen biogeochemical cycle
   - Nitrogen assimilation
   - Nitrogen fixation
   - Mycorrhizal fungi
Nutrient Requirements & Sources – The Big Picture

• Plant organic matter is mainly \( \text{C}, \text{H}, \text{and O} \) (i.e., \( \text{CH}_2\text{O} \)), with traces of 20 other elements needed for growth (e.g., \( \text{N}, \text{P}, \text{Ca}, \text{Mo}, \text{S}, \text{Fe}, \text{Mg} \))

• \( \text{C:N} = 20 - 50 \) in leaf tissue \( \text{N:P} = 10 - 20 \) in vegetation

• Availability of \( \text{N} \) or \( \text{P} \) may control rate of NPP (since other elements are rarely limiting): \( \text{P} \) is a major limiting nutrient in older tropical soils, \( \text{N} \) is the major limiting nutrient in younger temperate and high-latitude soils

• Biological processes affect geochemical cycling of biologically important elements -- less effect on elements with small biological role in global cycles (e.g., Na, Cl)

• Atmosphere is dominant source of \( \text{C}, \text{N} \) and \( \text{S} \) to terrestrial systems; rock weathering is dominant source for Mg, Ca, K, Fe, P

Limiting ”Nutrients”
Why do [excess] nutrients stimulate [excess] production?

Organisms have specific elemental needs to carry out cellular functions.

Activities have specific elemental needs to carry out cellular functions.

Concentrations below symbols in log₁₀ fmol kg⁻¹

Concentrations below symbols in log₁₀ fmol kg⁻¹

"P-limited" and "N-limited"

Liebig’s Law of the Minimum

Growth is NOT controlled by the total amount of resources available! Instead, growth is controlled (limited) by the scarcest resource.

Remember: “Scarcest” is in the eye of the beholder… adaptation can alter demand when supply is insufficient, but only within the bounds of biology.
Elements in the ocean vs. cells:

Which are limiting?

Which could be limiting?

Where is the 1:1 line?

Table 6.1 Percentage of the Annual Requirement of Nutrients for Growth in the Northern Hardwoods Forest at Hubbard Brook, New Hampshire, That Could Be Supplied by Various Sources of Available Nutrients*

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>P</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Growth requirement (Kg ha⁻¹ yr⁻¹)</td>
<td>115.4</td>
<td>12.3</td>
<td>66.9</td>
<td>62.2</td>
<td>9.5</td>
</tr>
<tr>
<td>Percentage of the requirement that could be supplied by:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intersystem transfers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atmospheric</td>
<td>18</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Rock weathering</td>
<td>0</td>
<td>13</td>
<td>11</td>
<td>34</td>
<td>37</td>
</tr>
<tr>
<td>Intrasystem transfers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reabsorptions</td>
<td>31</td>
<td>28</td>
<td>4</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Detritus turnover (includes return in throughfall and stemflow)</td>
<td>69</td>
<td>67</td>
<td>87</td>
<td>85</td>
<td>87</td>
</tr>
</tbody>
</table>

* Calculated using Eqs. 6.2 and 6.3. Reabsorption data are from Ryan and Bormann (1982). Data for N, K, Ca, and Mg are from Likens and Bormann (1995) and for P from Yanai (1992).

Retention and internal recycling of essential nutrients is largest source of chemicals supporting growth Inputs from external sources support “new growth” (“new production” in the ocean)
Nutrient Uptake – A Wide Range of Strategies!

- Ion exchange and solubility in soil control basic availability of nutrients.

- However, plants can increase uptake rates by:
  - Passive uptake: plant uptake alters soil:root equilibrium -- thus, more dissolution from host rock
    - Used when concentrations are relatively high
  - Deliberate uptake: release of enzymes to promote solubility or transport
    - E.g., low-concentration, biogeochemically important ions (e.g., N, P, K) are actively transported by enzymes in root membranes

Enzyme systems can adapt to availability of elements

*E.g.*, there are low P levels in cold soils (due to slow weathering rates), so arctic plants have fast uptake at low temperatures:

- Presumably due to lower temperature optima for arctic plant enzymes
- In both populations, enzymes allow rapid uptake at low concentrations

\[ \text{Carex = grassy sedge} \]
• Uptake of P and N is typically rapid, and soil concs are low – so diffusion within the adjacent soil is commonly the limiting factor

• Moreover, root growth rate correlates with N assimilation rate (i.e., N is “controlling”):

![Graph showing the correlation between root growth rate and N assimilation rate](image)

Figure 6.2 The rate of N uptake in tobacco as a function of the relative growth rate of roots. From Raper et al. (1978).

• P is commonly immobilized in soils, but plants can increase “root/shoot ratio” to get more P if needed
  (shoot = plant material above soil line)

• Phosphatases released by higher plants and microbes remove P from organic matter -- enzyme activity varies inversely with P availability

  In low-P environments, phosphatase activity can provide majority of P (e.g., up to 69% in tundra)

  In contrast to low-conc ions….

• High concentration ions may be actively excluded at the root zone -- e.g., Ca excluded as CaCO₃ in desert regions with calcareous soils
**Nutrient Balances**

- **Element Balance:** Plants need all nutrients simultaneously -- imbalance leads to slow growth (but deficiency symptoms only appear when a nutrient abundance is very low)

- **Charge Balance:** Most nutrients are positively charged ions (*cations*), but charge balance must be maintained across the cell membrane
  - Excess cation uptake is balanced by release of $H^+$ from roots -- leading to acidification of soil around root regions, which releases other cations (*e.g.*, $K^+$) (see Fig. 6.3 in text)
  - Excess anion uptake is balanced by release of $HCO_3^-$ and organic anions to balance charge

**Nitrogen Speciation**

<table>
<thead>
<tr>
<th>Name</th>
<th>Chemical formula</th>
<th>Oxidation state of N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrate</td>
<td>$NO_3^-$</td>
<td>+5</td>
</tr>
<tr>
<td>Nitrite</td>
<td>$NO_2^-$</td>
<td>+3</td>
</tr>
<tr>
<td>Dinitrogen</td>
<td>$N_2$</td>
<td>0</td>
</tr>
<tr>
<td>Ammonium</td>
<td>$NH_4^+$</td>
<td>-3</td>
</tr>
<tr>
<td>Organic N</td>
<td>$R-NH_2$</td>
<td>-3</td>
</tr>
</tbody>
</table>

Note: $NH_3$ is *ammonia* (non-ionic, volatile compound)
Nitrogen Biogeochemical Cycle

AMMONIUM (REDUCED)

NITRATE (OXIDIZED)

N-Fix

Assimilation

Org.N

Amm.

Anammox

Nitrification

Denitrification

DNRA

ANOXIC

OXIC

NH₄⁺

NO₃⁻

NO₂⁻

N₂O

NO

N₂