Nutrient Cycling in Land Vegetation and Soils

OCN 401 - Biogeochemical Systems
17 September 2015

Reading: Schlesinger & Bernhardt, Chapter 6

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Outline

1. The annual Intrasystem Nutrient Cycle
3. Nutrient-use efficiency
4. Microbial cycling in soils
5. Organic matter in soils
**Annual Intrasystem Nutrient Cycle**

- Although **leaves** and **fine roots** (short-lived tissue) are a small fraction of total plant biomass, they receive the vast **majority of annual nutrient uptake**

- New foliage has high concs of **N**, **P** and **K** – these decrease with time due to the accumulation of carbohydrates and cellulose during the growing season

- **Nutrient concentrations** in mature foliage is related to the rate of **photosynthesis** and **plant growth**, and (consequently) the **soil fertility**

- However, **rainfall** can leach nutrients from leaf surfaces -- this is especially true for **K**, which is highly water soluble

- Leaching rates generally increase as foliage **senesces** before **abscission**. Losses due to leaching follow the order:

  \[ K >> P > N > Ca \]

- **Throughfall** - Rainfall that passes through a vegetation canopy

- **Stemflow** - Water that travels down the surface of stems and the trunk

  - Stemflow, although generally smaller than throughfall, is significant because it returns highly concentrated nutrient solutions to the soil at the **base of the plant**

- At the end of the growing season, nutrients are withdrawn (**reabsorbed**) from the leaves for reuse during the next year -- this is typically around 50% of the leaf **N** and **P** content

- **Litterfall** -- Dominant pathway for nutrient return to the soil, especially for **N** and **P**
C/N ratio of plant litterfall:
- Varies by a factor of ~4 across environments
- Inversely related to the nutrient availability of the site

Plants in low-nutrient environments:
- Tend to have low nutrient concs in mature leaves
- Generally reabsorb a smaller amount but a larger proportion of nutrients in senescent leaves

Nutrient-rich environments:
- Associated with high productivity and abundant nutrient circulation (next slide)
- Low nutrient-use efficiency
A plant's annual nutrient requirement is equal to the peak nutrient content in newly produced tissue during the growing season:

Without Steady-State Assumption (i.e., annual budgets):

- Nutrient uptake from soil cannot be measured directly, but must equal the increase in nutrients in perennial tissue (e.g., stem wood) plus the replacement of nutrient losses from plant due to litterfall and leaching:

  \[ \text{Uptake} = \text{Retained by plant} + \text{Returned to soil} \]

- A plant's annual nutrient requirement is equal to uptake plus the amount reabsorbed during the previous autumn:

  \[ \text{Requirement} = \text{Uptake} + \text{Reabsorption} \]

Example: California shrubland system

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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>Process</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>Intrasystem inputs</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>
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<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).
• Uptake = Retained + Returned

• Requirement = Uptake + Reabsorption

71% of annual N requirement is allocated to foliage, whereas much less is allocated to stem wood. Nevertheless, total nutrient storage in short-lived tissue is small compared to storage in wood (the latter reflects 22 years of accumulation).

For most nutrients, the storage in wood increases ~5% / year.

Despite substantial reabsorption of N and P, litterfall is the dominant pathway of reusing nutrients.

Note: Table does not accurately reflect belowground transfers!
• Nutrients tend to accumulate most rapidly during the early development of a forest (due to the greater percentage of leaf biomass), then slow to a steady state value.

• Thus C/N and C/P ratios for the whole-plant biomass increase with time as the vegetation becomes increasingly dominated by structural biomass.

And now for a short commercial announcement....

Plant Nutrition: Mineral Absorption

https://www.youtube.com/watch?v=6aC-WTAWgOg
Nutrient-Use Efficiency

- Mass balance allow us to calculate nutrient-use efficiency:
  - NUE = NPP / nutrient uptake
- Nutrient-use efficiency reflects factors such as:
  - Rate of photosyn per leaf nutrient supply rate
  - Uptake per root growth rate (Fig. 6.2)
  - Leaching rate
  - Reabsorption rate
- In temperate systems, nutrient-use efficiency in coniferous forest is greater than in deciduous forests -- due to conifers having:
  - Lower nutrient circulation (mostly due to lower leaf turnover)
  - Lower leaching losses
  - Greater photosynthesis per unit of leaf N
- May explain the dominance of conifers in low-nutrient environments and in boreal climates (where soil nutrient turnover is low)

However, the effects of temperature and rainfall are the primary determinants of NPP rates:

Figure 5.13 NPP in world forests vs. mean annual temperature
Microbial Cycling in Soils

Most of the land plant nutrients come from decomposition of dead material in the soil:

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• Included in decomposition is **remineralization**, the process that releases CO$_2$ and inorganic nutrients (e.g., N as NH$_4^+$ or NO$_3^-$)

• These processes are mainly performed by bacteria and fungi via **extracellular enzymes**, although larger organisms (e.g., earthworms) fragment and mix fresh litterfall

• **Microbial biomass** typically compose <3% of the soil organic matter (OM) -- higher levels are found in forest soils, and lower levels in deserts

• Accumulation of nutrients into the solid-phase of soil is known as **immobilization** -- most important for N and P

• Immobilization is due to:
  - Accumulation of nutrients into soil microbes (see Fig. 6.9)
  - Chemical adsorption onto mineral surfaces (esp. important for P)
  - Chemical precipitation of solid minerals

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The effect of immobilization is displayed in **litterbag** experiments:

<table>
<thead>
<tr>
<th>Table 6.7 Ratios of Nutrient Elements to Carbon in the Litter of Scots Pine (<em>Pinus sylvestris</em>) at Sequential Stages of Decomposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/N</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Needle litter</td>
</tr>
<tr>
<td>Initial</td>
</tr>
<tr>
<td>After incubation of:</td>
</tr>
<tr>
<td>1 yr</td>
</tr>
<tr>
<td>2 yr</td>
</tr>
<tr>
<td>3 yr</td>
</tr>
<tr>
<td>4 yr</td>
</tr>
<tr>
<td>5 yr</td>
</tr>
<tr>
<td>Fungal biomass</td>
</tr>
<tr>
<td>Scots pine forest</td>
</tr>
</tbody>
</table>

Note that C/N and C/P ratios decline, which indicates retention of these nutrients as C is lost, whereas C/Ca and C/K ratios increase, which indicates that these nutrients are lost more rapidly than carbon. From Staaf and Berg (1982).

Decomposition also leads to formation of **fulvic** and **humic** compounds with high N content and high stability -- known as **geopolymers** because they are random compounds formed abiotically.
Release rates from soil OM differ for different nutrients (some faster, others slower):

<table>
<thead>
<tr>
<th>Region</th>
<th>Organic matter</th>
<th>N</th>
<th>P</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boreal forest</td>
<td>355</td>
<td>230</td>
<td>324</td>
<td>94</td>
<td>149</td>
<td>455</td>
</tr>
<tr>
<td>Temperate forest</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coniferous</td>
<td>17</td>
<td>17.9</td>
<td>15.3</td>
<td>2.2</td>
<td>5.9</td>
<td>12.9</td>
</tr>
<tr>
<td>Deciduous</td>
<td>4</td>
<td>5.5</td>
<td>5.8</td>
<td>1.5</td>
<td>3.0</td>
<td>3.4</td>
</tr>
<tr>
<td>Mediterranean</td>
<td>3.8</td>
<td>4.2</td>
<td>3.6</td>
<td>1.4</td>
<td>5.0</td>
<td>2.8</td>
</tr>
<tr>
<td>Tropical rainforest</td>
<td>0.4</td>
<td>2.0</td>
<td>1.6</td>
<td>0.7</td>
<td>1.5</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Notes: Values are calculated by dividing the forest floor mass by the mean annual litterfall. Boreal and temperate values are from Cole and Rapp (1981), tropical values are from Edwards and Grubb (1982) and Edwards (1977, 1982), and Mediterranean values are from Gray and Schlesinger (1981).
In most ecosystems, the pool of soil organic matter greatly exceeds the mass of live biomass.

Typically, less than 5% of soils is composed of organic matter -- the organic matter content of some agricultural soil is <1%.

Humus: Soil organic matter which has reached a point of stability.

Because of its high nutrient content, the humus fraction dominates the storage of biogeochemically elements in most systems.

Soil organic matter provides numerous ecosystem services:

- Provides carbon, nitrogen, and energy for soil bacteria and fungi.
- Supplies nutrients for plants.
- Acts as a “glue” to bind soil particles together to stabilize soils.
- Serves as a reservoir for plant nutrients.
- Serves as a sink for CO₂, thus reducing greenhouse gases.
- Contributes to high soil biodiversity.
- Binds pesticides and heavy metals, thus reducing water pollution.
- Enhances water- and nutrient-holding capacity of soils, thus improving plant productivity.

pnwsteep.wsu.edu/edsteep/
Several factors affect the amount of soil organic matter, including:

- **Climate** – the rate of decomposition doubles for every 8-9°C increase in mean annual temperature
- **Soil type** – clay soils retain more organic matter than sandy soils
- **Vegetation** – the more vegetation and litter produced, the more organic matter in the soil; also, high C:N ratios of vegetation slow down decomposition
- **Topography** – organic matter can accumulate in soils with poor drainage
- **Tillage** – tilling soil causes a decrease in organic matter by facilitating its decomposition

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