Net Primary Production and Global Change

OCN 401 - Biogeochemical Systems

Reading: Schlesinger, Chapter 5

Outline

1. Fate of Net Primary Production
   • Ecosystem respiration
   • Net ecosystem production
      • Biomass
      • Detritus
      • Humus and soil organic carbon

2. Soil Organic Matter and Global Change
Net Ecosystem Production (NEP) = NPP - R_h - R_d

\[ R_h = \text{respiration rate of herbivores} \]
\[ R_d = \text{respiration rate of decomposers} \]

We have seen that NPP = GPP - R_{\text{plant}}

Thus, NEP = GPP - R_t, where R_t is total respiration (plant + herbivore + decomposer):

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As long-lived plants age, biomass reaches a maximum, but the increment decreases:

"Increment" - Increase in diameter, basal area*, height, or volume of individual trees or stands during a given period of time -- also known as "growth rate"

* Tree Basal Area is the cross-sectional area of trees at breast height (1.3 m above the ground); units = ft²/acre or m²/ha

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Calluna = heather
Thus, as long-lived plants age, NPP is not incorporated into biomass but is largely delivered to the soils

**Other losses of global NPP:**

- **Support of human activities** (food, fuel, etc.): ~6% of global NPP (3.3 x 10^{15} g C yr^{-1})
- **Herbivory**: ~5% of NPP (~ 3 x 10^{15} g C yr^{-1})
- **Fires**: ~5% of NPP (~2-5 x 10^{15} g C yr^{-1})
- **Reduced C compounds emitted from plants** to atm -- e.g., CO and isoprene from pine forests: up to ~2% of NPP (1.2 x 10^{15} g C yr^{-1})

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**Biomass**

Has decreased globally by 110 x 10^{15} g C (13%) since 1860

Doubling atm. CO_{2} will increase primary production 40% (in theory). However, growth is usually limited by other factors.

Elevated CO_{2} may increase WUE, as stomata are more closed or fewer. May lead to:

- Greater moisture in soil (unless plants increase leaf #s)
- Rise in stream flow rate
- Increased global riverflow

A complication: changes in distribution of vegetation as T and precipitation vary
Dead Plant Organic Matter ("Detritus")

Most NPP is delivered to soils as detritus

Detritus: Mostly dead leaves and root turnover. Also dead woody tissue, as forest ages.

Decomposition in upper layers of soil releases nutrients and produces humus (highly resistant organic compounds)

Humus accumulates in lower soil profile and is bulk of soil organic matter

Global patterns of deposition of litterfall are similar to NPP:
Declines with increasing latitude
An extreme case: In grasslands, litterfall ≈ NPP

Measurement of decay of detritus:

Approach #1 -- Use litterbags:
Fraction left after 1 yr = \( \frac{X_f}{X_o} = e^{-k} \)
\( k \) = fractional loss rate

Approach #2 -- Annual mass balance, assuming steady-state:
- Annual soil organic matter decomposition = annual input of detritus
- Thus, detrital-mass is constant
  \[ \text{litterfall} = k \cdot \text{(detrital-mass)} \quad \text{or} \]
  \[ k = \frac{\text{litterfall}}{\text{detrital-mass}} \]

At steady state, both approaches give same k, and mean residence time (MRT) = 1/k
Note: when using mass-balance, important to include fine roots!

When decomposition is fast (e.g., wet tropical regions):

\[ k > 1 \quad (i.e., \ MRT < 1 \ \text{yr}) \]

In contrast, in peatlands:

\[ k \approx 0.001 \]

Global average MRT for litter in surface soils \( \approx 3 \ \text{yr} \) (k= 0.33)

Decomposition rate is a function of moisture and temperature:

\[ Q_{10} \equiv \text{increase in biological rate for } 10^\circ\text{C increase in temp} \]

\[ \approx 2 \text{ for microbiological activity (i.e., doubles with every } 10^\circ\text{C increase)} \]

Evapotranspiration used to model k

In arid and semi-arid systems, soil moisture limits rates:

Results agree well with field observations
Humus and Soil Organic Carbon

*Humus* = non-cellular remnant of detritus resulting from microbial activity. Has large number of aromatic rings, C=C=C=C units, and -OOH and -OH groups

Characterized *operationally* by separation method:

Acid-soluble fraction $\equiv$ *fulvic acid* (transports Fe and Al in soils); acid-insoluble fraction $\equiv$ *humic acid*

Humic and fulvic acids associate with clays, and are resistant to microbial attack

MRT $\approx$ 30 years, but some fractions are much older (hundreds to thousands of years)

Soil org C (humus) is $>$ than overlying biomass in most forests

A comparison of global humus and surface litter:

<table>
<thead>
<tr>
<th>Ecosystem type</th>
<th>Mean soil organic matter (kg C m$^{-2}$)</th>
<th>World area (ha $\times 10^6$)</th>
<th>Total world soil organic carbon (mt C $\times 10^6$)</th>
<th>Amount in surface litter (mt C $\times 10^6$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical forest</td>
<td>10.4</td>
<td>24.5</td>
<td>255</td>
<td>3.6</td>
</tr>
<tr>
<td>Temperate forest</td>
<td>11.8</td>
<td>12</td>
<td>142</td>
<td>14.5</td>
</tr>
<tr>
<td>Boreal forest</td>
<td>14.9</td>
<td>12</td>
<td>179</td>
<td>24.0</td>
</tr>
<tr>
<td>Woodland and shrubland</td>
<td>6.9</td>
<td>8.5</td>
<td>59</td>
<td>2.4</td>
</tr>
<tr>
<td>Tropical savanna</td>
<td>3.7</td>
<td>15</td>
<td>56</td>
<td>1.5</td>
</tr>
<tr>
<td>Temperate grassland</td>
<td>19.2</td>
<td>9</td>
<td>173</td>
<td>1.8</td>
</tr>
<tr>
<td>Tundra and alpine</td>
<td>21.6</td>
<td>8</td>
<td>173</td>
<td>4.0</td>
</tr>
<tr>
<td>Desert scrub</td>
<td>5.6</td>
<td>18</td>
<td>101</td>
<td>0.2</td>
</tr>
<tr>
<td>Extreme desert, rock, and ice</td>
<td>0.1</td>
<td>24</td>
<td>3</td>
<td>0.02</td>
</tr>
<tr>
<td>Cultivated</td>
<td>12.7</td>
<td>14</td>
<td>178</td>
<td>0.7</td>
</tr>
<tr>
<td>Swamp and marsh</td>
<td>68.6</td>
<td>2</td>
<td>147</td>
<td>2.5</td>
</tr>
<tr>
<td>Totals</td>
<td></td>
<td>147</td>
<td><strong>1450</strong></td>
<td><strong>35.2</strong></td>
</tr>
</tbody>
</table>

*From Schlesinger (1977).*
Most turnover (respiration to CO₂) occurs in surface soil layers:

\[
\text{Soil Respiration}
\]

\[
\text{Turnover in 100's of yrs}
\]

\[
\text{Turnover in 1000's of yrs}
\]

\[
\text{Permanent Accumulations in the Lower Profile}
\]

\[
\text{Figure 5.17 Turnover of litter and soil organic fractions in a grassland soil. Note that mean residence time can be calculated for each fraction from measurements of the quantity in the soil and the annual production or loss (respiration) from that fraction. Flux estimates are in kg C m⁻² yr⁻¹. From Schlesinger (1977).}
\]

\[14\text{C dating: 16\% of organic matter in a pasture soil >5700 yrs old}\]

Can use of CO₂ flux to estimate soil organic matter turnover, but is complicated by root respiration

\[
\text{Figure 5.18 Latitudinal trends for carbon dynamics in forest and woodland soils of the world. The dashed line shows the mean annual input of organic carbon to the soil by litterfall. The solid line shows the loss of carbon, measured as the flux of CO₂ from the surface. The difference between these lines represents the loss of CO₂ from roots respiration and from the respiration of root detritus and mycorrhizae. From Schlesinger (1977).}
\]
Long-term accumulation of organic matter (NEP):
Greatest in wetlands, least in deserts

In forests:
Accumulation of organic matter increases from tropics to boreal climates (opposite to NPP trend)

Accumulation of soil organic matter:
• Primarily reflects differences in decomposition rates, not NPP
• Microbiological activity is controlled by temperature and moisture →

<table>
<thead>
<tr>
<th>Ecosystem type</th>
<th>Vegetation in terrestrial area</th>
<th>Accumulation rate of soil organic matter (g C m⁻² yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tundra</td>
<td></td>
<td>8.000, 9.000, 1.000, 9.000, 8.000</td>
</tr>
<tr>
<td>Boreal forest</td>
<td>Spruce</td>
<td>5.500</td>
</tr>
<tr>
<td></td>
<td>Spruce-fir</td>
<td>3.495</td>
</tr>
<tr>
<td></td>
<td>Spruce-fir</td>
<td>2.740</td>
</tr>
<tr>
<td>Temperate forest</td>
<td>Broadleaf evergreen</td>
<td>1.377</td>
</tr>
<tr>
<td></td>
<td>Coniferous</td>
<td>1.200</td>
</tr>
<tr>
<td></td>
<td>Deciduous</td>
<td>1.905</td>
</tr>
<tr>
<td></td>
<td>Coniferous</td>
<td>10.000</td>
</tr>
<tr>
<td></td>
<td>Angiosperms</td>
<td>4.200</td>
</tr>
<tr>
<td></td>
<td>Deciduous</td>
<td>6.500</td>
</tr>
<tr>
<td></td>
<td>Coniferous</td>
<td>5.000</td>
</tr>
<tr>
<td></td>
<td>Coniferous</td>
<td>9.000</td>
</tr>
<tr>
<td>Tropical forest</td>
<td>Metasequoia</td>
<td>3.500</td>
</tr>
<tr>
<td></td>
<td>Rain forest</td>
<td>8.020</td>
</tr>
<tr>
<td>Temperate grassland</td>
<td>Coniferous</td>
<td>9.000</td>
</tr>
<tr>
<td></td>
<td>Coniferous</td>
<td>3.940</td>
</tr>
</tbody>
</table>

From Schlesinger (1990); citations to original literature are given therein.
* Converted from values given in original publication.
Importance of humus to global NPP

Global humus prod < $0.4 \times 10^{15} \text{ g C yr}^{-1}$

*** Transport rate of organic carbon (OC) in rivers is upper limit for terrestrial NEP ***

Global transport of OC in rivers $\approx 0.4 \times 10^{15} \text{ g C yr}^{-1}$ (good agreement with global humus prod)

On a global basis:
NEP / NPP = fraction of NPP going to humus

$\approx \frac{0.4 \times 10^{15} \text{ g C yr}^{-1}}{53 \times 10^{15} \text{ g C yr}^{-1}} = 0.7\%$

From last lecture

Current OC storage rate on land ($0.4 \times 10^{15} \text{ g C yr}^{-1}$) is too small to act as a sink for anthropogenic CO$_2$

Moreover, total OC in soils ($1460 \times 10^{15} \text{ g C}$) accounts for only 0.03% of atm O$_2$

$(\text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{CH}_2\text{O} + \text{O}_2)$

Thus, atm O$_2$ can’t be due to OC storage on land

Long-term marine OC storage accounts for most of the O$_2$
Changes in isotopic composition of atmospheric CO\(_2\) recorded in ice cores, tree rings etc. can be used to estimate:

- Fossil fuel usage (no \(^{14}\)C, negative \(\delta^{13}\)C)
- Biomass burning (modern \(^{14}\)C, negative \(\delta^{13}\)C)

Atmospheric CO\(_2\) increasing due mainly to:

- Fossil fuel \((5 \times 10^{15} \text{ g C yr}^{-1})\)
- Forest clearing \((\sim 1.6 \times 10^{15} \text{ g C yr}^{-1})\)

Soil Organic Matter and Global Change

Cultivation reduces OC in soil (20-30%) in first few decades:

Due to lower prod of detritus and greater rate of decomposition

\(~0.8 \times 10^{15} \text{ g C yr}^{-1}\) added to atmosphere from land-use changes

Note: Charcoal from fires during forest clearing is resistant OC, but is not likely an important part of global C flux

Figure 5.19: Decline in soil organic matter following conversion of native soil to agriculture in two grassland soils. From Schimel (1993).
Conversely, abandonment of agricultural land leads to rapid increase in soil organic C:

### Climate Change Effects

Warming of soils will increase decomposition rates (and OC loss)

Example: CO₂ fluxes from tundra increase with increasing temp. Greatest fluxes when warmed and water table lowered due to melting of permafrost.

However, if atmosphere CO₂ levels also increase, tundra may begin net OC storage:

Nutrients released from increased rates of decomposition may increase photosynthesis (tundra are typically nutrient-limited) --- complex interactions!

Conclusion: OC storage in the future is closely linked to changes in distribution and productivity of ecosystems.

**Table 5.5** Accumulation of Soil Organic Matter in Abandoned Agricultural Soils and in Other Disturbed Sites, Which are Allowed to Return to Native Vegetation

<table>
<thead>
<tr>
<th>Ecosystem type</th>
<th>Previous land use</th>
<th>Period of abandonment (yr)</th>
<th>Rate of accumulation (g C m⁻³ yr⁻¹)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subtropical forest</td>
<td>Cultivation</td>
<td>40</td>
<td>30–50</td>
<td>Lugo et al. (1986)</td>
</tr>
<tr>
<td>Temperate deciduous forest</td>
<td>Cultivation</td>
<td>100</td>
<td>45</td>
<td>Jenkinson (1990)</td>
</tr>
<tr>
<td>Temperate coniferous forest</td>
<td>Cultivation</td>
<td>50</td>
<td>21–26</td>
<td>Schiffman and Johnson (1989)</td>
</tr>
<tr>
<td></td>
<td>Diked soils</td>
<td>100</td>
<td>26</td>
<td>Beke (1990)</td>
</tr>
<tr>
<td>Temperate deciduous forest</td>
<td>Mine spoils</td>
<td>50</td>
<td>55</td>
<td>Leisman (1957)</td>
</tr>
<tr>
<td>Temperate grassland</td>
<td>Mine spoils</td>
<td>28–40</td>
<td>28</td>
<td>Anderson (1977)</td>
</tr>
<tr>
<td>Temperate grassland</td>
<td>Cultivation</td>
<td>53</td>
<td>1.55</td>
<td>Burke et al. (1995)</td>
</tr>
<tr>
<td>Temperate grassland</td>
<td>Cultivation</td>
<td>5</td>
<td>110.0</td>
<td>Gebhart et al. (1994)</td>
</tr>
</tbody>
</table>
Northward migration of productive forests may increase C storage by $180 \times 10^{15}$ g C when fully adjusted for an atm CO$_2$ doubling.

Alternatively, land may become a net source of CO$_2$ as quicker warming of land than ocean leads to desertification.

In any case, change in vegetation boundaries may be first indicators of climate change.