ESM 202

Terrestrial Carbon Cycle

The Carbon Cycle

- All life is composed of carbon compounds of one form or another.
- Most is found in storage pools
  - Carbonate sediments
- In its gaseous state,
  - Found mainly as carbon dioxide in the atmosphere and
  - Dissolved into fresh and salt water.
- In the sedimentary portion of the cycle
  - Found in carbohydrates, hydrocarbon compounds, and carbonate compounds.
- Enters the atmosphere through
  - Volcanic activity
  - Combustion of fossil fuels
  - Plant respiration
- Removed from the atmosphere by
  - Photosynthesis on land and in the ocean

Terrestrial carbon - net photosynthesis

- Both respiration and photosynthesis occur simultaneously in plants.
- Respiration occurs constantly, photosynthesis only occurs during periods of light.
- Net photosynthesis
  - The amount of carbohydrate remaining after respiration has broken down sufficient carbohydrate to power the plant.
  - Net photosynthesis = Gross photosynthesis - Respiration.

Photosynthesis and Respiration

- Photosynthesis
  - The production of carbohydrates through the chemical combination of water and carbon dioxide in plants.
  - \( \text{H}_2\text{O} + \text{CO}_2 + \text{light energy} \rightarrow -\text{CHOH-} + \text{O}_2 \)
  - In aqueous systems use \( \text{HCO}_3^- \)
  - Sunlight supplies the energy for the transformation.
  - Carbohydrates effectively store sunlight energy.
- Respiration
  - The opposite process.
  - \(-\text{CHOH-} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{chemical energy}\)
  - Carbohydrates are broken down and oxidized to yield carbon dioxide and water.
  - The chemical energy stored in photosynthesis is released to the cell.

Definitions

- GPP = Gross primary production (photosynthesis)
- NPP = Net Primary Production = GPP – Plant Respiration
- \( R_t \) = Total Ecosystem Respiration = Plant Respiration + Herbivore Respiration + Decomposition (microbial respiration)
- NEP = NPP – \( R_t \)
Temperature and Energy Flow

- Photosynthesis increases with temperature and then levels off.
- Respiration also increases with temperature, but does not level off.
- Thus, net photosynthesis initially increases with temperature and then decreases.

Net Photosynthesis

- Rates of net photosynthesis are strongly dependent on light and heat up to a limit.
- 10% to 30% of summer sunlight will allow maximum net photosynthesis.
- Net photosynthesis increases rapidly and then falls off as the additional heat causes respiration to increase.

Spatial-temporal variation in radiation

- Daylength and the duration of light varies with latitude and season - primary control on spatial patterns of photosynthesis.
- At high latitudes, winter brings short days and summer brings long days.
- In subarctic regions in summer, photosynthesis can take place for almost 24 hours, compensating (but not quite) for a short growing season.

Moisture Controls on NPP


Dryland response to rain

Source: Chris Williams, 2006

Drydown Diminished Diurnal Water and Carbon Fluxes

Source: Chris Williams, 2006
Net Primary Production

- Net primary production is measured in biomass - the dry weight of organic matter.
- Biomass is measured in:
  - Kilograms of biomass per square meter or
  - Metric tons of biomass per hectare (10,000 m²).
- High areas of net primary production
  - Land
    - Equatorial rainforest
    - Freshwater swamps and marshes
  - Oceans
    - Algal beds and reefs
    - Estuaries

Net Production and Climate

- Net primary production is determined by:
  - Light intensity and duration,
  - Temperature,
  - Water availability.
- Wet climates produce high productivity while dry climates (cold or hot) produce low productivity.

NEP through the life cycle

![Graph showing NEP through the life cycle](image)

Figure 5.14 Generalized trends in primary production and respiration during ecosystem development. Modified from Odum (1969).

Source: Biogeochemistry (Schlesinger, 1997)

Controls on NEP

- Environmental controls - light, water, heat, nutrients
- Disturbances (fire) and soil processes are also important
- Lateral fluxes (dissolved organic and inorganic carbon (DOC, DIC) as well as particulate organic carbon may be moved out of a system through erosion or animal migration
- Dominant controls vary with time and space scales

Global NPP and Biomass

<table>
<thead>
<tr>
<th>Ecosystem</th>
<th>Area (10⁶ m²)</th>
<th>Mean plant biomass (g C/m²)</th>
<th>Carbon in vegetation (184 g)</th>
<th>Mean net primary production (g C/m²/yr)</th>
<th>Net primary productivity (184 g C/m²/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical wet and moist forest</td>
<td>10.4</td>
<td>15</td>
<td>136.0</td>
<td>800</td>
<td>8.3</td>
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<tr>
<td>Tropical dry forest</td>
<td>7.7</td>
<td>6.5</td>
<td>45.7</td>
<td>620</td>
<td>4.8</td>
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<tr>
<td>Temperate forest</td>
<td>9.2</td>
<td>8</td>
<td>73.2</td>
<td>650</td>
<td>6.0</td>
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<tr>
<td>Boreal forest</td>
<td>15.0</td>
<td>9.8</td>
<td>145.0</td>
<td>450</td>
<td>6.4</td>
</tr>
<tr>
<td>Tropical woodland and savanna</td>
<td>15.6</td>
<td>12</td>
<td>45.8</td>
<td>320</td>
<td>4.9</td>
</tr>
<tr>
<td>Temperate steppe</td>
<td>15.1</td>
<td>5</td>
<td>45.8</td>
<td>320</td>
<td>4.9</td>
</tr>
<tr>
<td>Desert</td>
<td>18.2</td>
<td>0.5</td>
<td>5.9</td>
<td>80</td>
<td>1.4</td>
</tr>
<tr>
<td>Tundra</td>
<td>11.0</td>
<td>0.8</td>
<td>9.6</td>
<td>150</td>
<td>1.4</td>
</tr>
<tr>
<td>Wetland</td>
<td>2.9</td>
<td>2.7</td>
<td>7.8</td>
<td>1300</td>
<td>5.8</td>
</tr>
<tr>
<td>Subtropical forest</td>
<td>15.9</td>
<td>1.4</td>
<td>71.5</td>
<td>750</td>
<td>10.1</td>
</tr>
<tr>
<td>Rock and ice</td>
<td>15.2</td>
<td>0</td>
<td>6.6</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Global total</td>
<td>145.2</td>
<td>208</td>
<td>208</td>
<td>208</td>
<td>16.0</td>
</tr>
</tbody>
</table>

Table 5.2 Primary Production and Biomass Estimates for the World

*From Houghton and Skole (1990).*

Source: Biogeochemistry (Schlesinger, 1997)

Measuring NEP

- Eddy flux towers (small time-space scales; seconds; m to km)
- Field measurements of biomass and forest inventories (litter, soil, vegetation) (plot scale; integrated NPP/NEP over time)
- Tree rings (historic temporal patterns of productivity (NPP), individual trees)
- Remote sensing (change in above-ground biomass) (large spatial coverage; only for recent estimates; days, months, inter-annual)
Eddy flux towers

- Use change in concentration of moisture and carbon in turbulent eddies to estimate water and NEP
- FLUXNET - global network; Ameriflux - towers across US
- http://daac.ornl.gov/FLUXNET/
- http://public.ornl.gov/Ameriflux/

Remote Sensing

- Range of satellites with different spatial coverages, spatial, spectral (radiation) and temporal resolutions
- TM and ETM (Thematic Mapper), MODIS, AVHRR, SPOT

Models of Terrestrial Carbon Cycling

- Integrated models of physical controls on carbon cycling (and species specific characteristics)
- Examples
  - BIOME-BGC (carbon-nitrogen-water interactions)
  - RHESSys (similar to biome-bgc but includes distributed hydrology)
  - Century (focuses on soil organic matter)

Example (RHESSys)

- Regional hydro-ecologic simulation system
- http://fiesta.bren.ucsb.edu/~rhessys/

Global NEP - Models

Simulation for one day, hour by hour

NPP Anomalies

- 18 years (1982-1999) of both climatic data and satellite observations of vegetation activity
- Net primary production (NPP) increased 6% (3.4 Pg C/18 yr) globally
- Largest increase in tropical ecosystems.
Spatial pattern of US-NPP trends

Estimated from model of photosynthesis (BIOME-BGC)

Decadal changes may be related to spatial temporal patterns of precipitation

Terrestrial Biosphere

Where is the carbon stored?

More is stored in ocean than on land but terrestrial exchanges are larger

More carbon is stored in soil/litter than vegetation

Relevance

- Terrestrial Carbon Sinks have significant differences in
  - Total C stored
  - Rate at which C is stored
  - Stability/Vulnerability of C storage
  - Other limitations to C storage
  - Conditions that may release C to atmosphere

Key CO₂ processes

- Decomposition
  - Processing of dead organic matter to break it down and remove nutrients
  - Obtain energy
  - Releases CO₂ back to atmosphere, uses O₂
  - Done mostly by microbes, fungi
  - Common assumption is that a natural ecosystem is at steady state with regards to these processes

Decomposition Rates

Source: Biogeochemistry (Schlesinger, 1997)

Soil Formation

TIME ➔ WEATHERING ➔ HUMUS FORMATION ➔ PROFILE DEVELOPMENT
Soil Formation

- Most active soil forming processes occur through biotic interaction
- Plants and microbes are important in the storage, use and release of C, N, P and other nutrients in soils

Soil Profile: characterization of the various layers (horizons) forming a particular soil (vertical cut)

- Horizons:
  - A: top soil, mineral mixed with humus, usually dark colored
  - E: horizon where minerals are washed away through the input of precipitation (with the accompanying acids from the atmosphere); concentrates in quartz

- Horizons
  - B: zone of accumulation of minerals (Fe, Al, CaCO₃, CaSO₄, salts and clays) from other layers
  - C: unconsolidated material under A, E and B horizons
  - R: consolidated material (rock)

- Not all soils have all horizons, and some horizons may be represented in several layers, as materials accumulate with time

Major input to soils is from atmosphere

- H₂O, CO₂, O₂, nitrogenous compounds, acids, pollutants, salts and dust
- Composition of input can vary significantly as it passes through the canopy
  - throughfall
- Canopy can
  - neutralize some of acidity
  - contribute to acidity
  - modify input (transform compounds)
Soil Organic Matter

- SOM is the result of plant, animal and microbial remains
- Composed of sugars, proteins, cellulose, lignin, waxes and phenols, organic acids, aminoacids, etc.
- Microbial decomposition is not complete due to the complexity of some of the organic molecules
  - releases significant amounts of stored energy and nutrients

Soil Organic Matter

- In humid areas, SOM up to 5% on a dry-weight basis
- In arid areas, with low inputs of plant residues, SOM typically < 1%
- Rate of litter decomposition is most rapid in well-aerated, moist, mesic, near neutral soils
- Decomposition rate is also affected by the nature of the SOM as well as its nitrogen content

Table 5.3 Distribution of Soil Organic Matter by Ecosystem Type*

<table>
<thead>
<tr>
<th>Ecosystem type</th>
<th>Mean soil organic carbon (kg C m⁻²)</th>
<th>Mean soil organic content (kg C m⁻²)</th>
<th>Amount in surface litter (kg C m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical forest</td>
<td>10.4</td>
<td>26.5</td>
<td>225</td>
</tr>
<tr>
<td>Temperate forest</td>
<td>11.6</td>
<td>27</td>
<td>142</td>
</tr>
<tr>
<td>Coniferous</td>
<td>9.1</td>
<td>21</td>
<td>102</td>
</tr>
<tr>
<td>Deciduous</td>
<td>11.1</td>
<td>27</td>
<td>142</td>
</tr>
<tr>
<td>Mediterranean</td>
<td>10.2</td>
<td>26</td>
<td>142</td>
</tr>
<tr>
<td>Tropical grassland</td>
<td>10.2</td>
<td>26</td>
<td>142</td>
</tr>
<tr>
<td>Tropical wetland</td>
<td>10.1</td>
<td>25</td>
<td>130</td>
</tr>
<tr>
<td>Tropical desert</td>
<td>7.5</td>
<td>20</td>
<td>110</td>
</tr>
<tr>
<td>Tropical savanna</td>
<td>8.7</td>
<td>20</td>
<td>110</td>
</tr>
<tr>
<td>Temperate forest</td>
<td>10.2</td>
<td>26</td>
<td>142</td>
</tr>
<tr>
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<td>26</td>
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</tr>
<tr>
<td>Temperate desert</td>
<td>7.5</td>
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<td>110</td>
</tr>
<tr>
<td>Temperate savanna</td>
<td>8.7</td>
<td>20</td>
<td>110</td>
</tr>
</tbody>
</table>

*From Schlesinger (1977).

Soil Organic Matter

- Cold, humid environments with high water tables and acidic throughfall favor accumulation of SOM (lower decomposition rate)
- In areas of high rainfall, basic cations (Mg²⁺, Al³⁺, Ca²⁺) are leached out and with higher SOM, soils tend to be acidic
- In arid areas, low leaching rates and low SOM, plus higher water evaporation rates which leaves behind salts => soil is more alkaline

Turnover Rates (by region)

<table>
<thead>
<tr>
<th>Region</th>
<th>Mean Residence Time (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boreal forest</td>
<td>2.5</td>
</tr>
<tr>
<td>Temperate forest</td>
<td>1.5</td>
</tr>
<tr>
<td>Coniferous</td>
<td>1.2</td>
</tr>
<tr>
<td>Deciduous</td>
<td>1.3</td>
</tr>
<tr>
<td>Mediterranean</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Table 6.8 Mean Residence Time (yr) for Organic Matter and Nutrients in the Surface Litter of Forest and Woodland Ecosystems*

<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>3.5</td>
<td>230</td>
<td>324</td>
<td>94</td>
<td>149</td>
<td>455</td>
</tr>
<tr>
<td>Temperate forest</td>
<td>1.2</td>
<td>17.0</td>
<td>15.3</td>
<td>2.2</td>
<td>3.9</td>
<td>12.9</td>
</tr>
<tr>
<td>Coniferous</td>
<td>1.2</td>
<td>17.0</td>
<td>15.3</td>
<td>2.2</td>
<td>3.9</td>
<td>12.9</td>
</tr>
<tr>
<td>Deciduous</td>
<td>1.3</td>
<td>5.5</td>
<td>5.8</td>
<td>1.3</td>
<td>3.0</td>
<td>3.4</td>
</tr>
<tr>
<td>Mediterranean</td>
<td>1.1</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</td>
<td>1.2</td>
<td>0.4</td>
<td>2.0</td>
<td>1.6</td>
<td>0.7</td>
<td>1.5</td>
</tr>
</tbody>
</table>

* 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 Gribb (1982) and Edwards (1977, 1982), and Mediterranean values are from Gray and Schlesinger (1981).

Overall turnover

- Highest per area organic matter in swamps
- Boreal forest (both high soil and litter)
- Tropical forest (moderate amount per area * large area) yields greatest SOM stores

Decomposition strong function of T
Summary: Terrestrial carbon cycle

- Terrestrial carbon stores and fluxes reflect a balance between photosynthesis and respiration.
- Environmental factors (light, water, heat, nutrients) control rates of NPP and carbon accumulation and result in spatial-temporal patterns.
- Monitoring and understanding terrestrial carbon flux involves a combination of field, satellite and modeling approaches.
- Soil decomposition is an important part of the terrestrial carbon cycle due to long time scales relative to vegetation processes.