Chapter 22: Energy in the Ecosystem

- What is ecology?
- Global human issues
- Physical limits
- Ecosystems
- Organisms
- Populations
- Species Interactions
- Communities
Energy flows and nutrients cycle

C, H₂O, P, N...
Elton’s concept: organisms that live in the same place

- linked into a single functional entity
- feeding relationships
- food web.
Who eats whom? A food chain...
Who eats whom and who competes for food?
A food web...
Tansley’s concept: Living interacting with non-living...

- in a given place
- forms a single functional unit
- the ecosystem

- concept:
  - “the biological and physical parts of nature together, unified by the dependence of animals and plants on their physical surroundings and by their contributions to maintaining the conditions and composition of the physical world.”
Lotka’s concept:
-- Laws of thermodynamics apply

conservation of matter
Lindemann’s synthesis and concepts: energy pyramid, flux, efficiency

- Flow of energy in food chain.
- Each link a trophic level.
- Inefficiencies in energy transformation lead to a pyramid of energy in the ecosystem.
Odum’s energy flux model

- Even though energy flows and nutrients cycle
- **Fluxes of energy and materials** closely linked
- Studies of nutrient cycling provide index to fluxes of energy
- The system = inputs and outputs of compartments
Energy: production and transfer

- Primary production
  - varies among biomes
  - gross
    - energy fixed by photosynthesis
  - net
    - accumulation of energy in biomass
    - \( = \) gross energy - respiration
Primary Production

- Light energy transformed into chemical bonds carbohydrate:
  - \(6\text{CO}_2 + 6\text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2\)

- The rate is primary productivity
  - For each g of C assimilated, 39 kJ energy stored
primary productivity

- How to measure it?
  - harvest, gas exchange, assimilation of labeled C
    - HARVEST energy accumulated in biomass
    - MEASURE
      - change in CO$_2$ in enclosed atmosphere
      - net in day + respiration at night
      - $\text{C}_{14}$ removed from atmosphere
      - $\text{O}_2$ consumption in aquatic systems
- What limits it?
  - light, transpiration, nitrogen, phosphorus
Measuring primary productivity...

- Energy per unit area per time
- kJ per square meter per year
- kJ per square centimeter per second
- grams of Carbon assimilated per area per time
  - each gram = 39 kJ approx.
Components of Primary Productivity

- **gross primary production** = total energy assimilated by primary producers
- **net primary production** = energy accumulated (in stored form) by primary producers
- gross - net = **respiration**
  energy consumed by producers for maintenance and biosynthesis
Measure CO₂ flux in chamber

GROSS = NET + RESPIRATION
Example:
• 5% $^{14}$C in chamber

• 10 mg in the plant after one hour

• $10/0.05 = 200$ mg C assimilated/hr

$p =$ proportion of $^{14}$C in chamber at the beginning of experiment

$g =$ grams of $^{14}$C in the plant after an hour

$g/p =$ carbon assimilation/hr
Limits to primary productivity

- **Light**
  - Photosynthetic efficiency is 1-2% only!

- **Water (Temperature)**
  - availability of soil moisture
  - plant’s ability to tolerate water loss
  - transpiration

- **Phosphorus**

- **Nitrogen**
Primary production varies among ecosystems.

- **Maximum**
  - intense sunlight
  - warm temperatures
  - abundant rainfall
  - ample nutrients

- **On land**, highest in humid tropics, lowest in tundra and desert.
...in Wetland and Aquatic Systems

- **Swamps and marshes**
  - especially **productive**
  - at interface of terrestrial and aquatic systems

- **aquatic systems** highly variable
  - open oceans **unproductive** (nutrient-limited)
  - upwelling areas and continental shelf more **productive**
  - estuaries, reefs, and coastal algal beds **highly productive**
Transfer of energy up the food chain

- Trophic levels
  - autotrophs
  - heterotrophs
    - primary consumers
    - secondary consumers
    - tertiary consumers
    - detritivores
  - typically the productivity of each level is only 5-20% of the level below it
Transfer of energy up the food chain: ecological efficiency

- Ingested energy
- Egested energy
- Assimilated energy
  - Respired energy used up in metabolism
  - Excreted energy
  - Growth and reproduction
  - Death
  - Available to consumers

CONSUMERS
Components of ecological efficiency:

- **Exploitation** efficiency = Ingestion of food / prey Production
- **Assimilation** efficiency = Assimilation / Ingestion
- **Net production** efficiency = Reproduction / Assimilation
- **Gross production** efficiency = Assimilation eff. x Net production eff. = Growth + Reproduction / Ingestion
Ecological (or Food Chain) Efficiency

- **Ecological efficiency** = Exploitation efficiency
  - Assimilation efficiency
  - Net production efficiency = Consumer production / Prey production
Assimilation efficiency

- **Consumers of plants**: amount of cellulose and lignin determine digestibility
  - seeds, young vegetation --- 60-80%
  - grazing on older, tougher leaves --- 30-40%
  - decaying wood feeders --- 15%

- **Consumers of animals**: amount of digestible to indigestible
  - insectivores --- 70-80 %
  - carnivores --- 90 %
Net Production Efficiencies

- Highly variable

- **Animals: maintenance, heat and movement**
  - Warm blooded animals --- 1 to 6%
  - Cold blooded animals --- as high as 75%

- **Plants: net production/gross production**
  - Temperate rapid growers - 75-85%
  - Tropical rapid growers - 40-60%
Gross production efficiencies

- depends upon
cost of metabolism and assimilation

- **warm blooded** animals --- < 5%
  - some birds and large mammals --- < 1%

- **cold blooded** animals --- higher
  - insects --- 5-15%
  - aquatic animals --- 30%
Grazing food chain vs. detritus food chain

- How much energy flows through grazing vs how much energy through detritus?
- Variable among systems
- Herbivores consume
  - 1.5 to 2.5 % of NPP in temperate deciduous forests
  - 12 % in temperate grassland
  - 60 - 99% of plankton
Energy moves through ecosystems at different rates.

- **residence time** measures the average time a packet of energy resides in storage:
  - residence time (yr) = energy stored in biomass/net productivity

- **biomass accumulation ratio** is a similar index based on biomass rather than energy:
  - biomass accumulation ratio (yr) = biomass/rate of biomass production
Biomass Accumulation Ratios

- humid tropical forests 23 yr
- forested terrestrial communities are typically >20 yr
- ratios for planktonic aquatic ecosystems are <20 days
Residence Time for Litter

Decomposition of litter is dependent on conditions of temperature and moisture. The index is:

\[
    \text{Residence Time} = \frac{\text{mass of litter}}{\text{accumulation/rate of litter fall}}
\]

- 3 months in humid tropics
- 1-2 yr in dry and montane tropics
- 4-16 yr in southeastern US
- >100 yr in boreal ecosystems
Energy transfer: general

- **Assimilation** efficiency increases at higher trophic levels.
- **Net and gross production** efficiencies decrease at higher trophic levels.
- **Ecological efficiency** averages about 10%.
- About 1% of net production of plants ends up as production on the third trophic level: the pyramid of energy narrows quickly.
- To increase human food supplies means eating lower on food chain!
### Ecological efficiency and number of trophic levels

<table>
<thead>
<tr>
<th>Ecosystem</th>
<th>$NPP$, kcal/m$^2$/yr</th>
<th>$E(n)$, kcal/m$^2$/yr (top predator)</th>
<th>$Eff$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open ocean</td>
<td>500</td>
<td>0.1</td>
<td>25%</td>
<td>7.1</td>
</tr>
<tr>
<td>Coastal marine</td>
<td>8000</td>
<td>10.0</td>
<td>20%</td>
<td>5.1</td>
</tr>
<tr>
<td>Temperate grassland</td>
<td>2000</td>
<td>1.0</td>
<td>10%</td>
<td>4.3</td>
</tr>
<tr>
<td>Tropical rainforest</td>
<td>8000</td>
<td>10.0</td>
<td>5%</td>
<td>3.2</td>
</tr>
</tbody>
</table>
Estimating the number of trophic levels

- Study the comparisons among communities
- $E(n) = NPP \cdot Eff^{n-1}$
  - $E(n)$ is the energy available to a predator at trophic level $n$
  - $NPP$ is the net primary productivity
  - $Eff$ is the geometric mean of food chain efficiencies
    - geometric mean = the $n^{th}$ root of the product of $n$ factors multiplied together
Model for number of trophic levels

Trophic level, \( n \)  Energy available, \( E(n) \)

1 \hspace{10pt} NPP \hspace{10pt} \text{NPP}(Eff)^0
2 \hspace{10pt} \text{NPP}(Eff) \hspace{10pt} \text{NPP}(Eff)^1
3 \hspace{10pt} \text{NPP}(Eff)(Eff) \hspace{10pt} \text{NPP}(Eff)^2
4 \hspace{10pt} \text{NPP}(Eff)(Eff)(Eff) \hspace{10pt} \text{NPP}(Eff)^3
5 \hspace{10pt} \text{NPP}(Eff)(Eff)(Eff)(Eff) \hspace{10pt} \text{NPP}(Eff)^4

\[ E(n) = \text{NPP Eff}^{n-1} \]
\[ E(n) = NPP \text{ Eff}^{n-1} \]

*Use to calculate the length of a food chain*

- Take the log of both sides
- \[ \log(E(n)) = \log(NPP) + (n-1) \log(\text{Eff}) \]
- Subtract \( \log(NPP) \) from both sides and divide both sides by \( \log(\text{Eff}) \)
- \( \frac{\log(E(n)) - \log(NPP)}{\log(\text{Eff})} = n-1 \)
- Add 1 to both sides
- \( \frac{\log(E(n)) - \log(NPP)}{\log(\text{Eff})} + 1 = n \)
- Calculate \( n \) for different biomes: you need a calculator with a log key!
\[ \{ \log(E(n)) - \log(NPP) \} / \log(Eff) + 1 = n \]

Use to calculate the length of a food chain

- **Open ocean**
  - \( NPP = 500 \text{ kcal/sq.m/yr} \)
  - \( E(n) = 0.1 \text{ kcal/sq.m/yr} \)
  - \( Eff = 25\% = 0.25 \)
  - \( \log NPP = 2.69 \)
  - \( \log E(n) = -1 \)
  - \( \log Eff = -0.602 \)

\[ (-1 - 2.69) / -0.602 + 1 = 7.1 \]
\[
\frac{\log (E(n)) - \log NPP}{\log (Eff)} + 1 = n
\]

Use to calculate the length of a food chain

- Tropical rain forest
  - \(NPP = 8000 \text{ kcal/sq.m/yr}\)
  - \(E(n) = 10.0 \text{ kcal/sq.m/yr}\)
  - \(Eff = 5\% = 0.05\)
  - \(\log NPP = 3.903\)
  - \(\log E(n) = 1\)
  - \(\log Eff = -1.301\)

\[
(1 - 3.903)/-1.301 + 1 = 3.23
\]
\{ \log (E(n)) - \log NPP \}/ \log (Eff) + 1 = n

Use to calculate the length of a food chain

- Temperate grassland
  - \( NPP = 2000 \text{ kcal/sq.m/yr} \)
  - \( E(n) = 1 \text{ kcal/sq.m/yr} \)
  - \( \text{Eff} = 10\% = 0.10 \)
  - \( \log NPP = 3.301 \)
  - \( \log E(n) = 0 \)
  - \( \log \text{Eff} = -1 \)

\((0 - 3.301)/ -1 + 1 = 4.301\)
Summary

- **Ecosystem: giant energy-transforming machines**
  - energy enters through production by plants
  - transferred in food chain and detrital pathways.

- **Concepts** developed by Elton, Tansley, Lotka, Lindeman, and Odum

- **Primary production**
  - light, temperature, precipitation, nutrients

- **Secondary production**
  - food chain processing
  - various efficiencies
  - residence times of energy and materials.