Chapter 55
Ecosystems and Restoration Ecology
Overview: Cool Ecosystem

- An **ecosystem** consists of all the organisms living in a community, as well as the abiotic factors with which they interact.
- An example is the unusual community of organisms, including chemoautotrophic bacteria, living below a glacier in Antarctica.
Ecosystems range from a microcosm, such as an aquarium, to a large area, such as a lake or forest.
Regardless of an ecosystem’s size, its dynamics involve two main processes: energy flow and chemical cycling.

Energy flows through ecosystems, whereas matter cycles within them.
Concept 55.1: Physical laws govern energy flow and chemical cycling in ecosystems

- Ecologists study the transformations of energy and matter within ecosystems
Conservation of Energy

• Laws of physics and chemistry apply to ecosystems, particularly energy flow
• The first law of thermodynamics states that energy cannot be created or destroyed, only transformed
• Energy enters an ecosystem as solar radiation, is conserved, and is lost from organisms as heat
• The second law of thermodynamics states that every exchange of energy increases the entropy of the universe
• In an ecosystem, energy conversions are not completely efficient, and some energy is always lost as heat
Conservation of Mass

- The **law of conservation of mass** states that matter cannot be created or destroyed.
- Chemical elements are continually recycled within ecosystems.
- In a forest ecosystem, most nutrients enter as dust or solutes in rain and are carried away in water.
- Ecosystems are open systems, absorbing energy and mass and releasing heat and waste products.
Energy, Mass, and Trophic Levels

- Autotrophs build molecules themselves using photosynthesis or chemosynthesis as an energy source
- Heterotrophs depend on the biosynthetic output of other organisms
• Energy and nutrients pass from primary producers (autotrophs) to primary consumers (herbivores) to secondary consumers (carnivores) to tertiary consumers (carnivores that feed on other carnivores)
• Detritivores, or decomposers, are consumers that derive their energy from detritus, nonliving organic matter
• Prokaryotes and fungi are important detritivores
• Decomposition connects all trophic levels
Figure 55.4

Key

- Chemical cycling
- Energy flow

Sun

Primary producers

Primary consumers

Secondary and tertiary consumers

Detritus

Microorganisms and other detritivores

Heat

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Concept 55.2: Energy and other limiting factors control primary production in ecosystems

- In most ecosystems, primary production is the amount of light energy converted to chemical energy by autotrophs during a given time period.
- In a few ecosystems, chemoautotrophs are the primary producers.
Ecosystem Energy Budgets

• The extent of photosynthetic production sets the spending limit for an ecosystem’s energy budget
The Global Energy Budget

• The amount of solar radiation reaching Earth’s surface limits the photosynthetic output of ecosystems

• Only a small fraction of solar energy actually strikes photosynthetic organisms, and even less is of a usable wavelength
Gross and Net Production

- Total primary production is known as the ecosystem’s **gross primary production** (GPP).
- GPP is measured as the conversion of chemical energy from photosynthesis per unit time.
- **Net primary production** (NPP) is GPP minus energy used by primary producers for respiration.
- NPP is expressed as:
  - Energy per unit area per unit time (J/m$^2$·yr), or
  - Biomass added per unit area per unit time (g/m$^2$·yr)
NPP is the amount of new biomass added in a given time period. Only NPP is available to consumers. Standing crop is the total biomass of photosynthetic autotrophs at a given time. Ecosystems vary greatly in NPP and contribution to the total NPP on Earth.
• Tropical rain forests, estuaries, and coral reefs are among the most productive ecosystems per unit area
• Marine ecosystems are relatively unproductive per unit area but contribute much to global net primary production because of their volume
Figure 55.6

Net primary production (kg carbon/m²-yr)
• **Net ecosystem production (NEP)** is a measure of the total biomass accumulation during a given period

• NEP is gross primary production minus the total respiration of all organisms (producers and consumers) in an ecosystem

• NEP is estimated by comparing the net flux of CO$_2$ and O$_2$ in an ecosystem, two molecules connected by photosynthesis

• The release of O$_2$ by a system is an indication that it is also storing CO$_2$
Figure 55.7

Float surfaces for 6–12 hours to transmit data to satellite.

Float descends to 1,000 m and “parks.”

Drift time: 9 days

O₂ concentration is recorded as float ascends.

Total cycle time: 10 days
Primary Production in Aquatic Ecosystems

- In marine and freshwater ecosystems, both light and nutrients control primary production
Light Limitation

- Depth of light penetration affects primary production in the photic zone of an ocean or lake.
Nutrient Limitation

- More than light, nutrients limit primary production in geographic regions of the ocean and in lakes
- A **limiting nutrient** is the element that must be added for production to increase in an area
- Nitrogen and phosphorous are the nutrients that most often limit marine production
- Nutrient enrichment experiments confirmed that nitrogen was limiting phytoplankton growth off the shore of Long Island, New York
RESULTS

Phytoplankton density (millions of cells per mL)

- **Ammonium enriched**
- **Phosphate enriched**
- **Unenriched control**

Figure 55.8
Experiments in the Sargasso Sea in the subtropical Atlantic Ocean showed that iron limited primary production.
<table>
<thead>
<tr>
<th>Nutrients Added to Experimental Culture</th>
<th>Relative Uptake of $^{14}$C by Cultures*</th>
</tr>
</thead>
<tbody>
<tr>
<td>None (controls)</td>
<td>1.00</td>
</tr>
<tr>
<td>Nitrogen (N) + phosphorus (P) only</td>
<td>1.10</td>
</tr>
<tr>
<td>N + P + metals (excluding iron)</td>
<td>1.08</td>
</tr>
<tr>
<td>N + P + metals (including iron)</td>
<td>12.90</td>
</tr>
<tr>
<td>N + P + iron</td>
<td>12.00</td>
</tr>
</tbody>
</table>

*$^{14}$C uptake by cultures measures primary production.

• Upwelling of nutrient-rich waters in parts of the oceans contributes to regions of high primary production
• The addition of large amounts of nutrients to lakes has a wide range of ecological impacts
• In some areas, sewage runoff has caused **eutrophication** of lakes, which can lead to loss of most fish species
• In lakes, phosphorus limits cyanobacterial growth more often than nitrogen
• This has led to the use of phosphate-free detergents
Primary Production in Terrestrial Ecosystems

- In terrestrial ecosystems, temperature and moisture affect primary production on a large scale
- Primary production increases with moisture
Figure 55.9

Net annual primary production (above ground, dry g/m² yr) vs. Mean annual precipitation (cm)
• Actual evapotranspiration is the water transpired by plants and evaporated from a landscape
• It is affected by precipitation, temperature, and solar energy
• It is related to net primary production
Nutrient Limitations and Adaptations That Reduce Them

- On a more local scale, a soil nutrient is often the limiting factor in primary production.
- In terrestrial ecosystems, nitrogen is the most common limiting nutrient.
- Phosphorus can also be a limiting nutrient, especially in older soils.
Various adaptations help plants access limiting nutrients from soil
  – Some plants form mutualisms with nitrogen-fixing bacteria
  – Many plants form mutualisms with mycorrhizal fungi; these fungi supply plants with phosphorus and other limiting elements
  – Roots have root hairs that increase surface area
  – Many plants release enzymes that increase the availability of limiting nutrients

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Concept 55.3: Energy transfer between trophic levels is typically only 10% efficient

- **Secondary production** of an ecosystem is the amount of chemical energy in food converted to new biomass during a given period of time.
Production Efficiency

• When a caterpillar feeds on a leaf, only about one-sixth of the leaf’s energy is used for secondary production

• An organism’s production efficiency is the fraction of energy stored in food that is not used for respiration

\[
\text{Production efficiency} = \frac{\text{Net secondary production}}{\text{Assimilation of primary production}} \times 100\%
\]
Plant material eaten by caterpillar

Growth (new biomass; secondary production)

Cellular respiration

Assimilated

Not assimilated

Feces

200 J

100 J

33 J

67 J
• Birds and mammals have efficiencies in the range of 1–3% because of the high cost of endothermy
• Fishes have production efficiencies of around 10%
• Insects and microorganisms have efficiencies of 40% or more
Trophic Efficiency and Ecological Pyramids

- **Trophic efficiency** is the percentage of production transferred from one trophic level to the next.
- It is usually about 10%, with a range of 5% to 20%.
- Trophic efficiency is multiplied over the length of a food chain.
• Approximately 0.1% of chemical energy fixed by photosynthesis reaches a tertiary consumer
• A pyramid of net production represents the loss of energy with each transfer in a food chain
• In a biomass pyramid, each tier represents the dry mass of all organisms in one trophic level
• Most biomass pyramids show a sharp decrease at successively higher trophic levels
Trophic level | Dry mass (g/m²)
--- | ---
Tertiary consumers | 1.5
Secondary consumers | 11
Primary consumers | 37
Primary producers | 809

(a) Most ecosystems (data from a Florida bog)

Trophic level | Dry mass (g/m²)
--- | ---
Primary consumers (zooplankton) | 21
Primary producers (phytoplankton) | 4

(b) Some aquatic ecosystems (data from the English Channel)
• Certain aquatic ecosystems have inverted biomass pyramids: producers (phytoplankton) are consumed so quickly that they are outweighed by primary consumers

• **Turnover time** is the ratio of the standing crop biomass to production
• Dynamics of energy flow in ecosystems have important implications for the human population
• Eating meat is a relatively inefficient way of tapping photosynthetic production
• Worldwide agriculture could feed many more people if humans ate only plant material
Concept 55.4: Biological and geochemical processes cycle nutrients and water in ecosystems

• Life depends on recycling chemical elements
• Nutrient cycles in ecosystems involve biotic and abiotic components and are often called biogeochemical cycles
Biogeochemical Cycles

- Gaseous carbon, oxygen, sulfur, and nitrogen occur in the atmosphere and cycle globally.
- Less mobile elements include phosphorus, potassium, and calcium.
- These elements cycle locally in terrestrial systems but more broadly when dissolved in aquatic systems.
• A model of nutrient cycling includes main reservoirs of elements and processes that transfer elements between reservoirs
• All elements cycle between organic and inorganic reservoirs
Reservoir A
Organic materials available as nutrients
Living organisms, detritus

Fossilization
Peat
Coal
Oil

Reservoir C
Inorganic materials available as nutrients
Minerals in rocks

Weathering, erosion
Formation of sedimentary rock

Reservoir D
Inorganic materials unavailable as nutrients
Minerals in rocks

Respiration, decomposition, excretion

Assimilation, photosynthesis

Burning of fossil fuels
In studying cycling of water, carbon, nitrogen, and phosphorus, ecologists focus on four factors:

- Each chemical’s biological importance
- Forms in which each chemical is available or used by organisms
- Major reservoirs for each chemical
- Key processes driving movement of each chemical through its cycle
The Water Cycle

- Water is essential to all organisms.
- Liquid water is the primary physical phase in which water is used.
- The oceans contain 97% of the biosphere’s water; 2% is in glaciers and polar ice caps, and 1% is in lakes, rivers, and groundwater.
- Water moves by the processes of evaporation, transpiration, condensation, precipitation, and movement through surface and groundwater.
The Carbon Cycle

- Carbon-based organic molecules are essential to all organisms
- Photosynthetic organisms convert $\text{CO}_2$ to organic molecules that are used by heterotrophs
- Carbon reservoirs include fossil fuels, soils and sediments, solutes in oceans, plant and animal biomass, the atmosphere, and sedimentary rocks
• CO₂ is taken up and released through photosynthesis and respiration; additionally, volcanoes and the burning of fossil fuels contribute CO₂ to the atmosphere
Figure 55.14b

CO₂ in atmosphere

Photosynthesis

Cellular respiration

Burning of fossil fuels and wood

Phytoplankton

Consumers

Consumers

Decomposition
The Nitrogen Cycle

- Nitrogen is a component of amino acids, proteins, and nucleic acids
- The main reservoir of nitrogen is the atmosphere ($\text{N}_2$), though this nitrogen must be converted to $\text{NH}_4^+$ or $\text{NO}_3^-$ for uptake by plants, via nitrogen fixation by bacteria
• Organic nitrogen is decomposed to $\text{NH}_4^+$ by ammonification, and $\text{NH}_4^+$ is decomposed to $\text{NO}_3^-$ by nitrification
• Denitrification converts $\text{NO}_3^-$ back to $\text{N}_2$
Figure 55.14c

- Fixation
- Denitrification
- Reactive N gases
- Industrial fixation
- N in atmosphere
- Reactive N gases
- Fixation in root nodules
- Decomposition
- Sedimentation
- Dissolved organic N
- Runoff
- N fertilizers
- Ammonification
- Nitrification
- Nitrogen fixation
- Uptake of amino acids
- Assimilation
- NO$_3^-$
- NO$_2^-$
- NH$_4^+$
- NH$_3$

Terrestrial cycling

Aquatic cycling

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Fixation

Denitrification

$\text{N}_2$ in atmosphere

Reactive N gases

Industrial fixation

Dissolved organic N

Aquatic cycling

Runoff

$\text{NO}_3^-$

$\text{NH}_4^+$

N fertilizers

$\text{NO}_3^-$

Decomposition and sedimentation

Terrestrial cycling
Figure 55.14cb

Terrestrial cycling: N₂

Decomposition

Fixation in root nodules

Ammonification: NH₃ → NH₄⁺

Nitrification: NH₄⁺ → NO₂⁻ → NO₃⁻

Uptake of amino acids

Assimilation

Denitrification
The Phosphorus Cycle

- Phosphorus is a major constituent of nucleic acids, phospholipids, and ATP
- Phosphate ($\text{PO}_4^{3-}$) is the most important inorganic form of phosphorus
- The largest reservoirs are sedimentary rocks of marine origin, the oceans, and organisms
- Phosphate binds with soil particles, and movement is often localized
Geologic uplift

Wind-blown dust

Weathering of rocks

Runoff

Decomposition

Plankton uptake of $\text{PO}_4^{3-}$

Dissolved $\text{PO}_4^{3-}$ uptake

Sedimentation

Plant uptake of $\text{PO}_4^{3-}$

Leaching

Decomposition

Consumption

Figure 55.14d

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Decomposition and Nutrient Cycling Rates

- Decomposers (detritivores) play a key role in the general pattern of chemical cycling.
- Rates at which nutrients cycle in different ecosystems vary greatly, mostly as a result of differing rates of decomposition.
- The rate of decomposition is controlled by temperature, moisture, and nutrient availability.
Figure 55.15

**EXPERIMENT**

Ecosystem type
- Arctic
- Subarctic
- Boreal
- Temperate
- Grassland
- Mountain

**RESULTS**

Mean annual temperature (°C)

Percent of mass lost

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• Rapid decomposition results in relatively low levels of nutrients in the soil
  – For example, in a tropical rain forest, material decomposes rapidly, and most nutrients are tied up in trees and other living organisms
• Cold and wet ecosystems store large amounts of undecomposed organic matter as decomposition rates are low
• Decomposition is slow in anaerobic muds
Case Study: Nutrient Cycling in the Hubbard Brook Experimental Forest

- The Hubbard Brook Experimental Forest has been used to study nutrient cycling in a forest ecosystem since 1963
- The research team constructed a dam on the site to monitor loss of water and minerals
- They found that 60% of the precipitation exits through streams and 40% is lost by evapotranspiration
Figure 55.16

(a) Concrete dam and weir

(b) Clear-cut watershed

(c) Nitrate in runoff from watersheds

<table>
<thead>
<tr>
<th>Year</th>
<th>Nitrate concentration in runoff (mg/L)</th>
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<tbody>
<tr>
<td>1965</td>
<td>0</td>
</tr>
<tr>
<td>1966</td>
<td>4</td>
</tr>
<tr>
<td>1967</td>
<td>8</td>
</tr>
<tr>
<td>1968</td>
<td>2</td>
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</table>

Completion of tree cutting

Deforested

Control
• In one experiment, the trees in one valley were cut down, and the valley was sprayed with herbicides
• Net losses of water were 30–40% greater in the deforested site than the undisturbed (control) site
• Nutrient loss was also much greater in the deforested site compared with the undisturbed site
  – For example, nitrate levels increased 60 times in the outflow of the deforested site
• These results showed how human activity can affect ecosystems
Figure 55.16c

(c) Nitrate in runoff from watersheds

Nitrate concentration in runoff (mg/L)

- Completion of tree cutting
- Deforested
- Control

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Concept 55.5: Restoration ecologists help return degraded ecosystems to a more natural state

- Given enough time, biological communities can recover from many types of disturbances
- Restoration ecology seeks to initiate or speed up the recovery of degraded ecosystems
- Two key strategies are bioremediation and augmentation of ecosystem processes
Figure 55.17

(a) In 1991, before restoration

(b) In 2000, near the completion of restoration
(a) In 1991, before restoration
(b) In 2000, near the completion of restoration
Bioremediation

- **Bioremediation** is the use of organisms to detoxify ecosystems
- The organisms most often used are prokaryotes, fungi, or plants
- These organisms can take up, and sometimes metabolize, toxic molecules
  - For example, the bacterium *Shewanella oneidensis* can metabolize uranium and other elements to insoluble forms that are less likely to leach into streams and groundwater
Figure 55.18

Days after adding ethanol

Concentration of soluble uranium (μM)

Days after adding ethanol
Biological Augmentation

- **Biological augmentation** uses organisms to add essential materials to a degraded ecosystem
  - For example, nitrogen-fixing plants can increase the available nitrogen in soil
  - For example, adding mycorrhizal fungi can help plants to access nutrients from soil
Restoration Projects Worldwide

- The newness and complexity of restoration ecology require that ecologists consider alternative solutions and adjust approaches based on experience.
Figure 55.19b

Kissimmee River, Florida
Figure 55.19c

Truckee River, Nevada

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Tropical dry forest, Costa Rica
Figure 55.19e

Rhine River, Europe

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Succulent Karoo, South Africa
Coastal Japan
Maungatautari, New Zealand