The Global Ecosystem
Key Concepts

45.1 Climate and Nutrients Affect Ecosystem Function

45.2 Biological, Geological, and Chemical Processes Move Materials through Ecosystems

45.3 Certain Biogeochemical Cycles Are Especially Critical for Ecosystems
Key Concepts

45.4 Biogeochemical Cycles Affect Global Climate

45.5 Rapid Climate Change Affects Species and Communities

45.6 Ecological Challenges Can Be Addressed through Science and International Cooperation
How did Keeling’s research contribute to our understanding of the global ecosystem?
Ecosystem—an ecological community plus the abiotic environment with which it exchanges energy and materials.

Ecosystems are linked by exchanges of organisms and materials over large spatial scales.

It impossible to understand a local ecosystem completely without considering it in the context of the larger systems of which it is a part.
Ecosystem function: dynamic processes by which ecosystem components exchange and transform energy and materials.

Ultimately, movements of materials between the abiotic and biotic components are tied to carbon.

Net primary productivity (NPP) is a measure of the flow of materials and energy into the biotic component.
Other exchanges are fueled by the energy that enters the community via primary producers.

NPP can be estimated by instruments on satellites that measure wavelengths of light reflected from the Earth’s surface.

The resulting maps show that patterns of variation in NPP indicate factors that limit ecosystem function.
NPP varies among ecosystem types, mostly due to variation in climate and nutrient availability.

Tropical forests, swamps and marshes, and coral reefs are the most productive.

Cultivated land is less productive than many natural ecosystems.
Figure 45.1 NPP Varies among Ecosystem Types
NPP varies with latitude; the tropics are very productive; high latitudes are less productive.

This pattern parallels latitudinal gradients in solar energy input and temperature, showing that NPP increases with temperature.

Activity of photosynthetic enzymes increases with temperature (up to the point at which they denature).
Moisture also increases NPP.

Deserts and dry regions have low NPP.

At very high moisture levels, productivity may be inhibited by cloud cover or lack of oxygen in saturated soils.
Figure 45.3 Terrestrial NPP Varies with Temperature and Precipitation (Part 1)

(A) Temperature

- NPP (Mg/[ha x year])
- Mean annual temperature (°C)

The graph shows a positive correlation between NPP and mean annual temperature, with NPP increasing as temperature increases.
Figure 45.3 Terrestrial NPP Varies with Temperature and Precipitation (Part 2)

(B) Precipitation

![Graph showing the relationship between NPP (Mg/ha x year) and mean annual precipitation (mm)].

**NPP (Mg/ha x year)**

**Mean annual precipitation (mm)**

Elements such as nitrogen, phosphorus, and potassium can be in short enough supply to limit NPP in some areas.

In nutrient-poor soils in southwestern Australia, plants cannot afford to allocate scarce nitrogen to defensive compounds; it is used for proteins essential for metabolism and growth.
Aquatic NPP is strongly affected by nutrient availability and light.

Photosynthesis is restricted to surface waters with light penetration.

Hydrothermal vents are productive areas in the deep oceans, where chemolithotrophs use chemical energy rather than sunlight.
The open ocean is unproductive because dissolved nutrients are limited. Phytoplankton take them up quickly, then carry them to deep water when they die.

NPP is highest where nutrients are most abundant—in near-shore areas and upwellings.
Figure 45.4 Marine NPP Is Highest Near Coastlines
Earth is an open system with respect to energy, but a closed system with respect to matter.

There is a fixed amount of each element of matter, but biological, geological, and chemical processes can transform it and move it around the planet in biogeochemical cycles.

Energy from the sun and heat from Earth’s interior drive these transformations.
Different chemical forms and locations of elements determine whether they are accessible to living organisms.

The different forms and locations can be represented as compartments.

Atoms cycle repeatedly among compartments as they are chemically transformed or physically moved.
Figure 45.5  Chemical Elements and Compounds Cycle among Compartments of the Global Ecosystem
Processes that supply matter to organisms occur in the biosphere, where atmosphere, land, and water are in contact and where organisms live.
Pool—total amount of an element or molecule in a compartment; depends on rate of movement into and out of the compartment

Flux—rate of movement of an element or molecule between compartments
All the materials in the bodies of living organisms are ultimately derived from abiotic sources.

Primary producers take up elements from inorganic pools and accumulate them as biomass.

Trophic interactions pass the elements on to heterotrophs.
Decomposers break down the dead organic matter into simpler compounds and elements that are available again for uptake by primary producers.

Much of this recycling of elements occurs locally, but some occurs on a larger scale when materials diffuse away in gaseous form or are carried away by wind or water.
Water is essential for life; it makes up 70% of living biomass.

It is the medium for metabolism and the solvent for biologically accessible forms of many elements.

Flowing water is an erosion agent and transports sediment, moving materials around the planet.

Water has a high heat capacity and distributes heat as it circulates through the oceans.
The global water cycle:

- Solar-powered evaporation moves water from ocean and land surfaces into the atmosphere.
- The energy is released again as heat when water vapor condenses.
- Some fluxes are gravity driven (precipitation and runoff).
Figure 45.6 The Global Water Cycle

Oceans: 1,338,000
Evaporation from sea: 434
Precipitation over sea: 398
Net transport over land: 36
Runoff: 36
Evaporation and transpiration from land: 71
Precipitation over land: 107
Ice, snow: 24,364
Living biomass: 1
Surface freshwater: 190
Soil moisture: 4
Groundwater: 23,416
Humans affect the water cycle:

- Removing vegetation (deforestation, crops, etc.) reduces precipitation retained in soil and increases amount that runs off.
- Pumping depletes groundwater, bringing it to the surface where it evaporates.
- Climate warming is melting ice caps and glaciers, increasing sea levels and evaporation. Water vapor is a greenhouse gas.
The global nitrogen cycle involves chemical transformations.

\( \text{N}_2 \) gas is 78% of the atmosphere, but most organisms cannot use this form.

Nitrogen fixation: some microbes can break the strong triple bond and reduce \( \text{N}_2 \) to ammonium (\( \text{NH}_4^+ \)).
INVESTIGATION

HYPOTHESIS

Nitrogen-fixing organisms in leaf-cutter ant nests supply nitrogen to the ants.

METHOD

1. Bring ant colonies into the laboratory and allow them to function in an environment with no other insects and no soil (i.e., where the only non-atmospheric source of N is fresh leaves supplied by the researchers).
2. Measure the nitrogen content of leaves, fungus, ants, and leaf refuse.
RESULTS

<table>
<thead>
<tr>
<th></th>
<th>Leaves</th>
<th>Fungus garden</th>
<th>Ant workers</th>
<th>Leaf refuse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen content (%)</td>
<td>1.5</td>
<td>3.0</td>
<td>12.0</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Error bars indicate 1 standard error from the mean; bars with different letters are statistically different from one another. (See Appendix B for discussion of statistical concepts.)

CONCLUSION

Nitrogen is being fixed within the ant nest.
The researchers measured activity of nitrogenase, an enzyme in the bacterial metabolic pathway that fixes atmospheric nitrogen. The results are shown in the figure to the left. Error bars indicate 1 standard error from the mean; different letters indicate significant differences in nitrogen content.

A. Where in the nest is nitrogen fixation occurring?

B. How can the ant workers have a higher nitrogen content than the fungus that they eat (see figure above)?

C. Can the researchers now conclude that the extra nitrogen comes from nitrogen-fixing bacteria living in the fungus gardens?
Other microbial species convert ammonium into nitrate (NO$_3^-$) and other oxides of nitrogen.

N-fixing reactions are reversed by yet another group of microbes in denitrification, which returns N$_2$ gas to the atmosphere.
Ammonium and nitrate are accessible to autotrophs because they dissolve in water and are easily taken up through cell membranes. Heterotrophs obtain nitrogen by consuming proteins. Much of the nitrogen in terrestrial ecosystems is recycled locally by decomposition of dead organic matter.
Human activities affect the nitrogen cycle:

- Burning fossil fuels, rice cultivation, and raising livestock releases oxides of nitrogen to the atmosphere.
  - These oxides contribute to smog and acid rain. \( \text{N}_2\text{O} \) is a greenhouse gas.

- Humans fix nitrogen by an industrial process to manufacture fertilizer and explosives.
Topsoil and dissolved nitrates are lost from farm fields and deforested areas by wind and water runoff.

- The nitrates are deposited in aquatic ecosystems and result in eutrophication—rapid growth of phytoplankton and bacteria.

- Decomposition of the phytoplankton can deplete oxygen; other organisms cannot survive, and “dead zones” form offshore in summer.
Figure 45.9  High Nutrient Input Creates Dead Zones
Concept 45.3 Certain Biogeochemical Cycles Are Especially Critical for Ecosystems

• Excess nitrogen in terrestrial ecosystems can change plant species composition.
  ▪ Species adapted to low nutrient levels grow slowly, even when fertilized, and can be easily displaced by faster-growing species that take advantage of additional nutrients.
  ▪ In the Netherlands, this has contributed significantly to a recent loss of plant species diversity.
The global carbon cycle:

Movement of carbon is linked to energy flow through ecosystems; biomass is an important compartment of the cycle.

Most C in the atmosphere is CO$_2$ and CH$_4$.

Photosynthesis moves inorganic C from the atmosphere to the organic compartment; cellular respiration reverses this flux.
Figure 45.10 The Global Carbon Cycle

- Atmosphere (CO₂, CH₄): 760
- Outgassing: 91
- Dissolution: 92
- Biomass burning: 0.3
- Fossil fuel burning, cement manufacture: 9.5
- Altered land use: 1.7
- Photosynthesis: 123
- Respiration: 120
- Plant biomass: 650
- Soils: 1,500
- Ocean waters: 38,920
- Sediments: 150
- Marine biomass: 3
- Carbonate precipitation: 0.2
- Runoff: 0.8
- Detritus: 11
- Sand, detritus: 1,200
- Carbonate compounds: $18 \times 10^6$
- Fossil fuels: $25 \times 10^6$
The largest C pools are in fossil fuels and carbonate rocks. 

$\text{CO}_2$ dissolves in ocean water and some is converted by primary producers and enters the trophic system.

Organic detritus and carbonates continually drift down to the ocean floor.

Some organic detritus in ocean sediments is converted to fossil fuels. Carbonates can be transformed into limestone.
Human activities affect the global carbon cycle:

- Any activity that impacts primary productivity can alter fluxes.
- Any activity that affects runoff brings carbon to aquatic ecosystems.
- Deforestation, biomass and fossil fuel burning increase atmospheric CO$_2$.
- Heating CaCO$_3$ during cement manufacture also increases CO$_2$ in the atmosphere.
• Atmospheric CH$_4$ is increased through livestock production, rice cultivation, and water storage in reservoirs (microbes in water-logged soils produce CH$_4$).

Both CH$_4$ and CO$_2$ are greenhouse gases.
Biogeochemical cycles are interconnected:

- Fluxes of materials are linked if they share common physical or biological processes:
  - C, N, P, and S have water soluble forms that are transported together in runoff.
• Fluxes of materials through communities are linked because macromolecules in organisms have fixed proportions of elemental building blocks.
  - When biomass is produced, there is coordinated movement of these elements into living organic compartments; when biomass is decomposed or burned, they all move back into inorganic compartments.
Biogeochemical cycles can interact in hard-to-predict ways.

Increased atmospheric CO$_2$ can increase water-use efficiency by terrestrial plants:

- In a high CO$_2$ environment, the plants open their stomata less, which reduces loss of water vapor and slows the rate of water movement from soil to the atmosphere.
All objects that are warmer than absolute zero emit electromagnetic radiation. Wavelengths emitted depend on the temperature of the object.

Most of the incoming solar radiation is in the visible range of wavelengths.

Some is absorbed in the atmosphere, some is reflected back to space, and some is absorbed at the Earth’s surface.
Figure 45.11 Earth’s Radiation Budget

- Incoming solar radiation: 100
- Radiation absorbed by atmosphere: 20
- Absorbed by surface: 49
- Reflected solar radiation: 31
  - Reflected by clouds, aerosols, and atmospheric gases: 23
  - Reflected by surface: 8
- Infrared radiation lost to space: 69
  - Emitted by atmosphere: 48
    - Atmospheric transmission: 12
  - Emitted by clouds: 9
  - Emitted by surface: 114
  - Absorbed by surface: 95

(PRINCIPLES OF LIFE 2e, Figure 45.11)
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Greenhouse effect:

Earth’s surface re-emits energy in longer, less energetic infrared wavelengths.

Some of this infrared radiation is absorbed by greenhouse gas molecules in the atmosphere.

Those molecules are warmed and radiate infrared photons back to Earth’s surface, keeping energy within the lower atmosphere.
Greenhouse gases include H\textsubscript{2}O, CO\textsubscript{2}, CH\textsubscript{4}, N\textsubscript{2}O.

Without the atmosphere, Earth’s average surface temperature would be about 34°C colder than at present.

Magnitude of the greenhouse effect depends on the amounts and types of greenhouse gases in the atmosphere.
Improved methods for measuring air samples show that the composition of the atmosphere is changing.

Keeling’s measurements from atop Mauna Loa in Hawaii show a steady increase in CO$_2$ since 1960.
Atmospheric Greenhouse Gas Concentrations Are Increasing (Part 1)

Figure 45.12

(A) CO₂ Concentrations Over Time

Year:
- 1960
- 1970
- 1980
- 1990
- 2000
- 2010
- 2013

CO₂ (ppm):
- 300
- 320
- 340
- 360
- 380
- 400

Seasons:
- Jan
- Apr
- Jul
- Oct
- Jan

Graph shows an increasing trend in CO₂ concentrations from 1960 to 2013, with seasonal variations indicated in the inset.
Analyses of air trapped in glacial ice demonstrate that CO$_2$ and other greenhouse gases began increasing after about 1880.

Average annual global temperature has also increased.

This global warming is affecting patterns of climate worldwide.
Figure 45.12  Atmospheric Greenhouse Gas Concentrations Are Increasing (Part 2)

(B)

<table>
<thead>
<tr>
<th>Year</th>
<th>CO₂ (ppm), N₂O (ppb)</th>
<th>CH₄ (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>Carbon dioxide (CO₂)</td>
<td>Nitrous oxide (N₂O)</td>
</tr>
<tr>
<td>300</td>
<td></td>
<td>Methane (CH₄)</td>
</tr>
<tr>
<td>350</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 45.13 Average Annual Global Temperatures Are Increasing
A warmer Earth means:

- Hotter air temperatures
- A more intense water cycle with greater overall evaporation and precipitation
- Hadley cells are expected to expand poleward; warmer tropical air will rise higher and expand farther toward the poles before sinking, changing precipitation patterns
Warming is spatially uneven, so precipitation changes will be season- and region-specific.

In general, wet regions are expected to get wetter and dry regions drier.

Precipitation trends in the 20th century support these expectations.
Figure 45.14  Global Precipitation Patterns Have Changed

Change in precipitation, 1901–2005 (%)
Warming may also increase storm intensity and weather variability.

Strong hurricanes (category 4 and 5) and “megastorms” such as Sandy in 2012 have become more frequent since the 1970s.
Human impacts on biogeochemical cycles also affect Earth’s radiation balance by adding greenhouse gases to the atmosphere:

- Fossil fuel burning, cement manufacture, forest clearing, expanded livestock production, water impoundment, wetland crop cultivation.
Expansion of livestock grazing, agriculture, and offroad vehicle traffic in arid regions increases airborne dust.

Deposition of dust and dark-colored soot particles (“black carbon”) from fossil fuel burning increases amount of solar energy absorbed by snow and ice and increases melting.
Other activities have the potential to counteract these effects:

- Adding aerosols to the atmosphere and land clearing increases the amount of solar energy that is reflected.

But when all human effects are added to climate models, climate scientists conclude human activities are contributing significantly to global warming.
Recent climate change has been far more rapid than anything organisms have experienced in their evolutionary histories.

Life cycles have evolved so that critical events occur at favorable times of year, but climate change is altering the timing of environmental cues.

Rates of evolution may be too slow to keep up with an environment that is changing rapidly.
In the short term, many species seem to be adapting (e.g., trees leaf out earlier in the spring).

But some species may not respond to climate change or may not be able to continue adaptive tracking.
Some environmental cues do not change, such as day length, so temporal relationships among cues are shifting.

There may be timing mismatches among species in a community, which will disrupt interactions (e.g., hatch of pollinators and opening of flowers).
One documented mismatch:

- In the Netherlands, winter moth eggs hatch too early—before the oak leaves they feed upon have emerged, and the caterpillars starve.

- Great tits feed on winter moth caterpillars, but they are not nesting earlier because their cue is day length; their fecundity is decreasing.
If populations cannot respond to changing environments, they may go extinct, resulting in changing species compositions and loss of diversity.

Shifts in geographic distributions can lead to assembly of novel communities; for instance, some species have moved up mountains and towards higher latitudes.

Species shift at different rates or not at all, resulting in different species combinations.
Warmer temperatures in western North America are speeding up the life history of mountain bark beetles and decreasing winter mortality rate.

Beetle populations have increased, causing widespread pine and spruce mortality from New Mexico to Alaska.

Loss of conifers has cascading effects on consumers that depend on them, water runoff, wildfire frequency, and NPP.
Increased frequency of extreme climate events will also alter species distributions.

A rapid shift in plant community boundaries occurred after a drought in northern New Mexico: a ponderosa pine forest shrank abruptly and drought-adapted piñon–juniper woodland expanded by more than 2 km in less than 5 years.

The new community persisted after the drought ended.
Climate has changed throughout Earth’s history.

Wobble in the planet’s orbit around the sun, continental drift, volcanic activity, sunspots, and asteroid impacts have caused Earth’s climates to change, precipitating five major mass extinctions.
There is precedent for atmospheric changes induced by organisms: the first photosynthetic microbes increased O$_2$ concentrations to a level that was toxic to the anaerobic prokaryotes.

The first land plants caused another rise in oxygen concentrations 250 million years ago.
Present climate change is due to activities of a single species: *Homo sapiens*.

But, science equips us to understand the natural world and devise solutions to problems.

*Homo sapiens* also has a remarkable capacity for cooperative action.
Governments of separate nations have been cooperating in global-scale initiatives to tackle complex environmental issues:

- The International Geophysical Year supported the first years of Dave Keeling’s work
- The United Nations’ Intergovernmental Panel on Climate Change
- World Meteorological Organization
International agreements include:

- Montreal Protocol to prevent depletion of the UV-absorbing ozone layer
- Kyoto Protocol to reduce emissions of greenhouse gases
- Convention on International Trade in Endangered Species (CITES) to conserve species by eliminating international trade.
A major challenge is that economic policies of every nation aim for continual economic growth—ever-increasing production and consumption of goods and services—despite the fact that Earth has finite resources.

A related challenge is the continued multiplicative growth of the human population. On a crowded planet with limited resources, cooperation becomes more difficult.
Dave Keeling’s measurements quickly led to better understanding of the pools and fluxes of the global carbon cycle, including the influence of fossil fuel burning and cement production.

Better understanding of the carbon cycle has contributed to greatly improved global climate models.
Keeling’s results were noticed immediately, and warnings began amid growing scientific consensus that climate change poses a critical environmental challenge.

The number of scientists studying climate change and the sophistication of experiments and models grew rapidly.

Average temperature increased by 0.7°C during the 20th century, an increase very close to predictions of global climate models.
The IPCC was formed in 1988 by a scientific collaboration of governments to summarize and report the latest scientific information on climate change.

The 2009 IPCC report predicted further human-caused increase in global average temperature between 1.8°C and 4.0°C by the year 2100.