CAMPBELL **BIOLOGY IN FOCUS**

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42

Ecosystems and Energy

Lecture Presentations by Kathleen Fitzpatrick and Nicole Tunbridge, Simon Fraser University

SECOND EDITION

Transformed to Tundra

- An **ecosystem** consists of all the organisms living in a community, as well as the abiotic factors with which they interact
- Entire ecosystems can be affected by changes in a single component
  - For example, the introduction of the arctic fox onto islands in Alaska and Russia resulted in a transformation from grassland to tundra ecosystem

- Ecosystems range from a microcosm, such as space under a fallen log or desert spring, to a large area, such as a lake or forest

- Ecosystem dynamics involve two main processes: energy flow and chemical cycling
- Energy flows through ecosystems, whereas matter cycles within them

Concept 42.1: Physical laws govern energy flow and chemical cycling in ecosystems

- Ecologists study the transformations of energy movement of chemical elements 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 transferred or transformed
- Energy enters an ecosystem as solar radiation, is transformed into chemical energy by photosynthetic organisms, and is dissipated 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
- Continuous input from the sun is required to maintain energy flow in Earth’s ecosystems

Conservation of Mass

- The **law of conservation of mass** states that matter cannot be created or destroyed

Conservation of Mass

- Chemical elements are continually recycled within ecosystems
    - Inorganic elements are taken up by autotrophs and transformed into biomass
    - Organic compounds are transferred to heterotrophs as food
    - Inorganic elements are released through metabolism and decomposition

- Elements can be gained or lost from a particular ecosystem
  - For example, 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

- Ecosystems can be sources or sinks for particular elements
- If a mineral nutrient's outputs exceed its inputs, it will limit production in that system

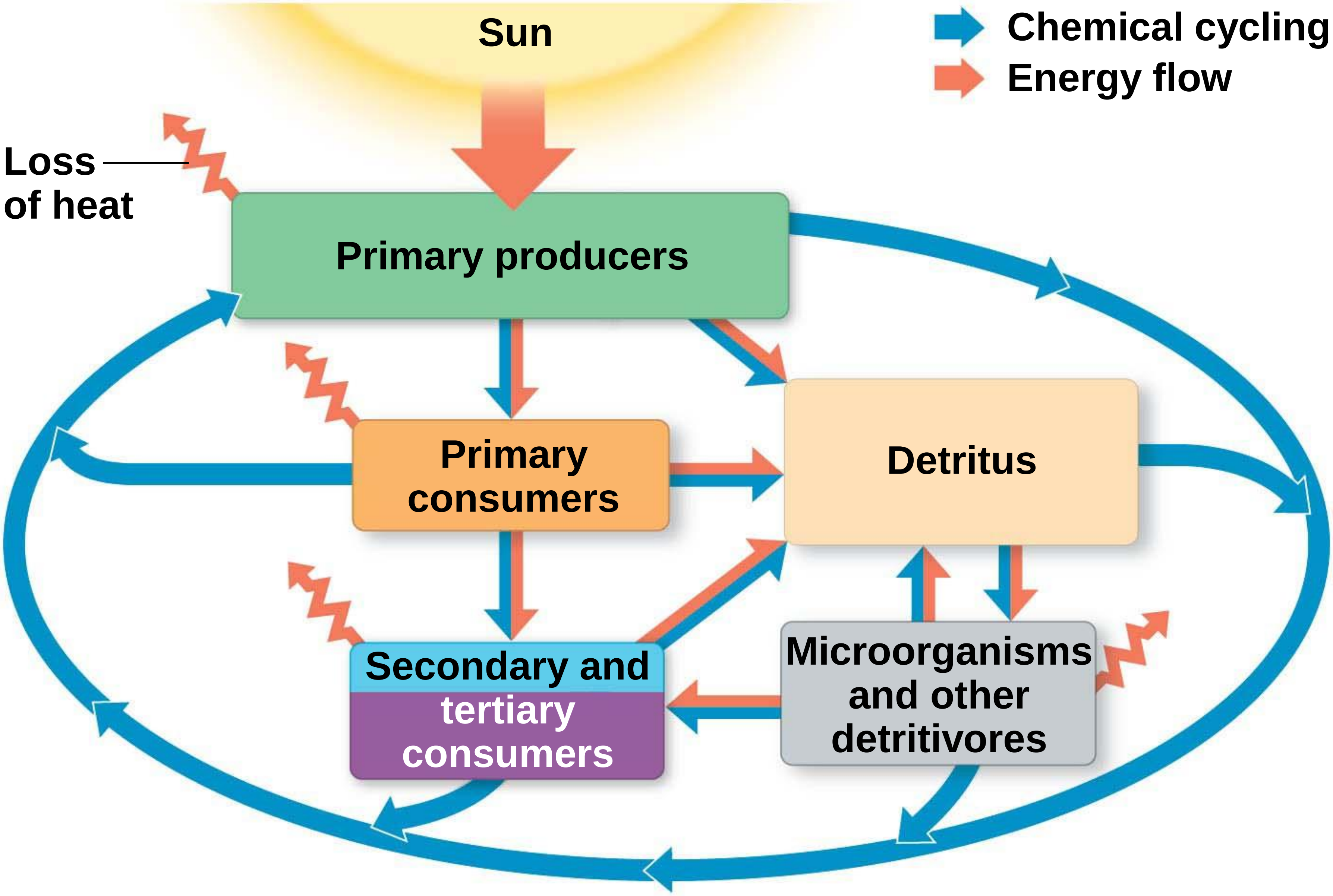
Energy, Mass, and Trophic Levels

- 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; detritivores are fed upon by secondary and tertiary consumers

Figure 42.4


Sun
Chemical cycling
Energy flow
Loss of heat
Primary producers
Primary consumers
Detritus
Secondary and tertiary consumers
Microorganisms and other detritivores

Concept 42.2: 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 "autotrophic respiration" (R_a)

$$\text{NPP} = \text{GPP} - R_a$$

- NPP is expressed as
  - Energy per unit area per unit time [$J/(m^2 \cdot yr)$], or
  - Biomass added per unit area per unit time [$g/(m^2 \cdot yr)$]

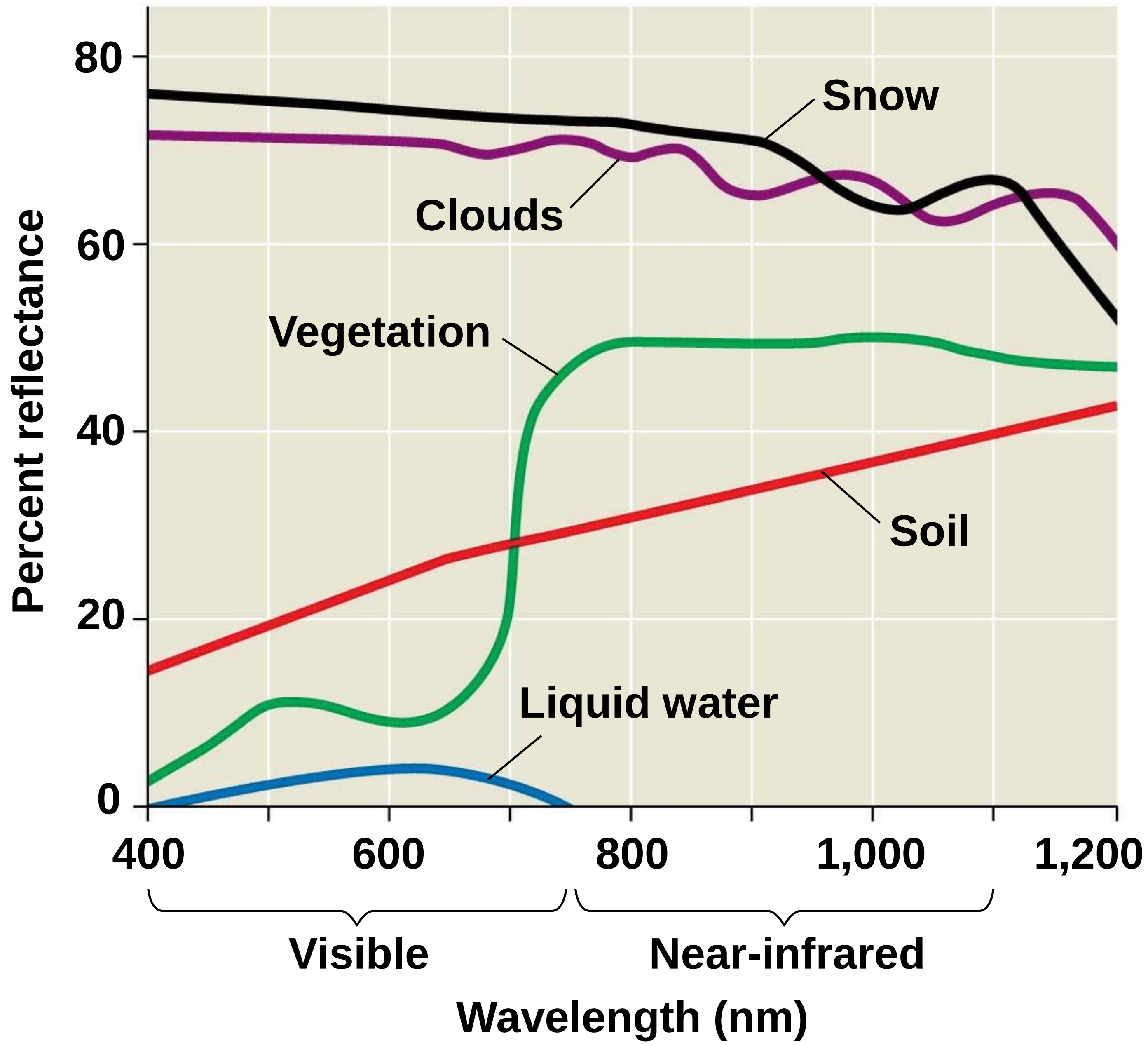
- NPP represents the energy that will be available to consumers in the ecosystem

- NPP is the amount of *new* biomass added in a given time period
- Standing crop is the total biomass of photosynthetic autotrophs at a given time
- Standing crop is not a reliable indicator of NPP

- Satellites can be used to estimate ecosystem productivity by detecting reflected light
- Vegetation reflects more near-infrared radiation than visible radiation

Figure 42.5

Technique



- 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 per unit area
- Open oceans are relatively unproductive per unit area, but contribute much to global NPP due to their size

- **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 (R_T)

$$NEP = GPP - R_T$$

- NEP is estimated by comparing the net flux of CO_2 and O_2 in an ecosystem
- These molecules are connected by photosynthesis
- The release of O_2 by a system is an indication that it is also storing CO_2

Primary Production in Aquatic Ecosystems

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

Light Limitation

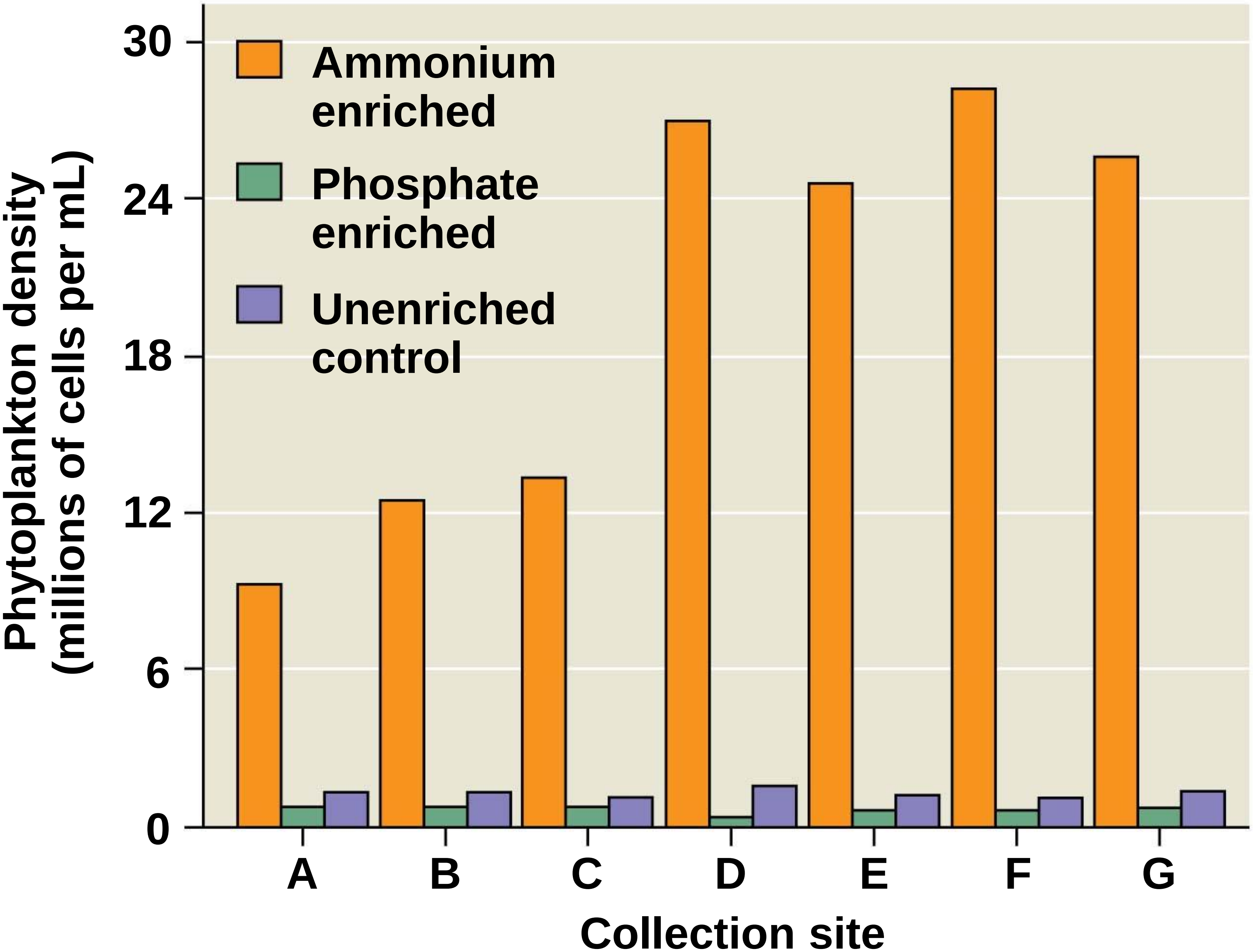
- Depth of light penetration affects primary production in the photic zone of an ocean or lake
- About half the solar radiation is absorbed in the first 15 m of water, and only 5–10% reaches a depth of 75 m

Nutrient Limitation

- More than light, nutrients limit primary production in oceans and lakes
- A **limiting nutrient** is the element that must be added for production to increase in an area
- Nitrogen and phosphorous most often limit marine production
  - For example, nitrogen limits phytoplankton growth off the south shore of Long Island, New York

Figure 42.7

Results



- Several large areas of the ocean have low productivity despite high nitrogen concentrations
- Nutrient enrichment experiments indicate that iron, a micronutrient, can be limiting in some marine ecosystems

Table 42.1

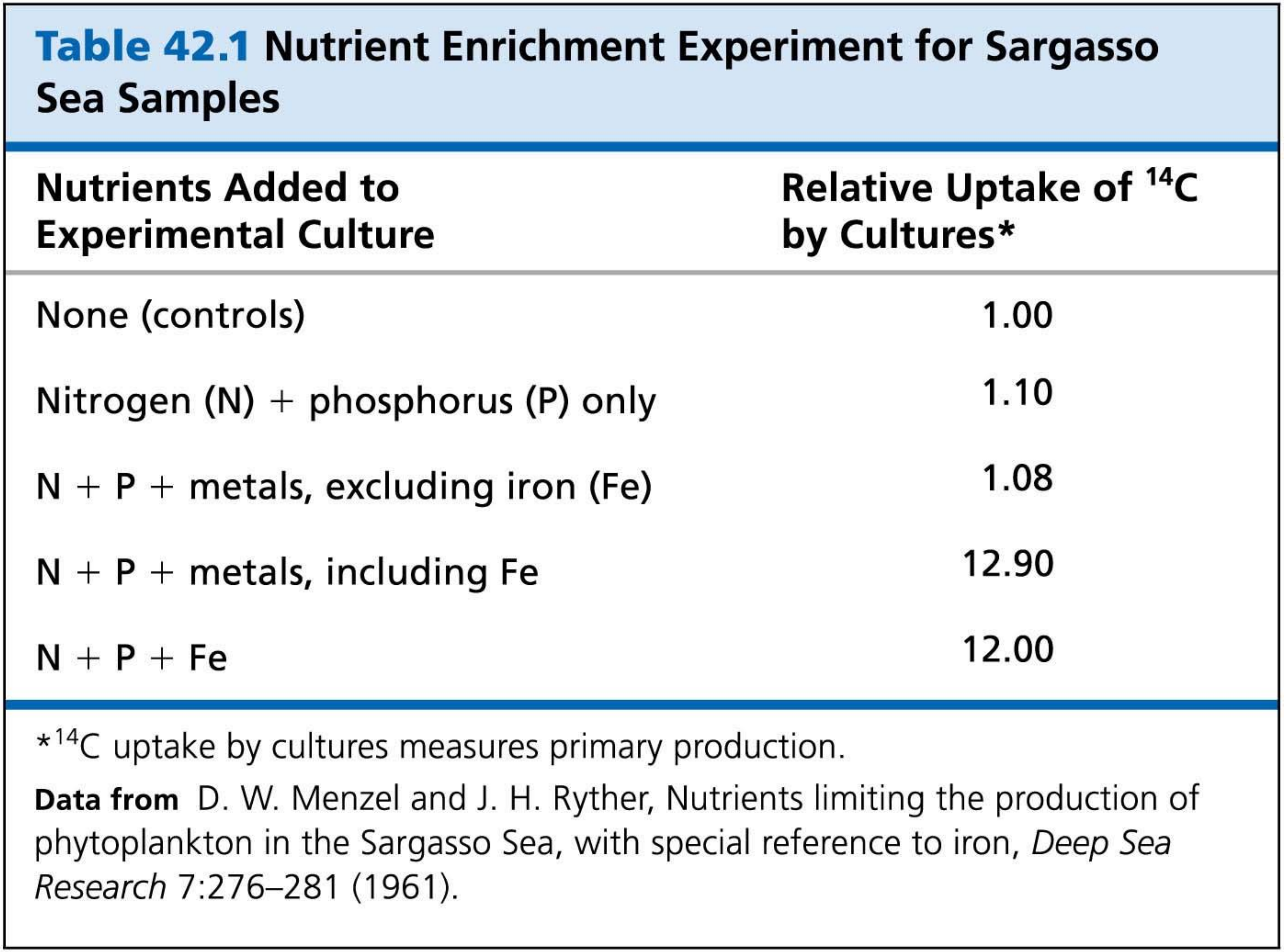


Table 42.1 Nutrient Enrichment Experiment for Sargasso Sea Samples

Nutrients Added to Experimental Culture	Relative Uptake of ^{14}C by Cultures*
None (controls)	1.00
Nitrogen (N) + phosphorus (P) only	1.10
N + P + metals, excluding iron (Fe)	1.08
N + P + metals, including Fe	12.90
N + P + Fe	12.00

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

Data from D. W. Menzel and J. H. Ryther, Nutrients limiting the production of phytoplankton in the Sargasso Sea, with special reference to iron, *Deep Sea Research* 7:276–281 (1961).

- Upwelling of nutrient-rich waters from the sea floor to the surface increases primary production in some areas

- The addition of large amounts of nutrients to lakes causes **eutrophication**
- Large populations of phytoplankton are supported in eutrophic lakes, but individual life spans are short
- Decomposition rates increase, causing oxygen depletion and the subsequent loss of fish species

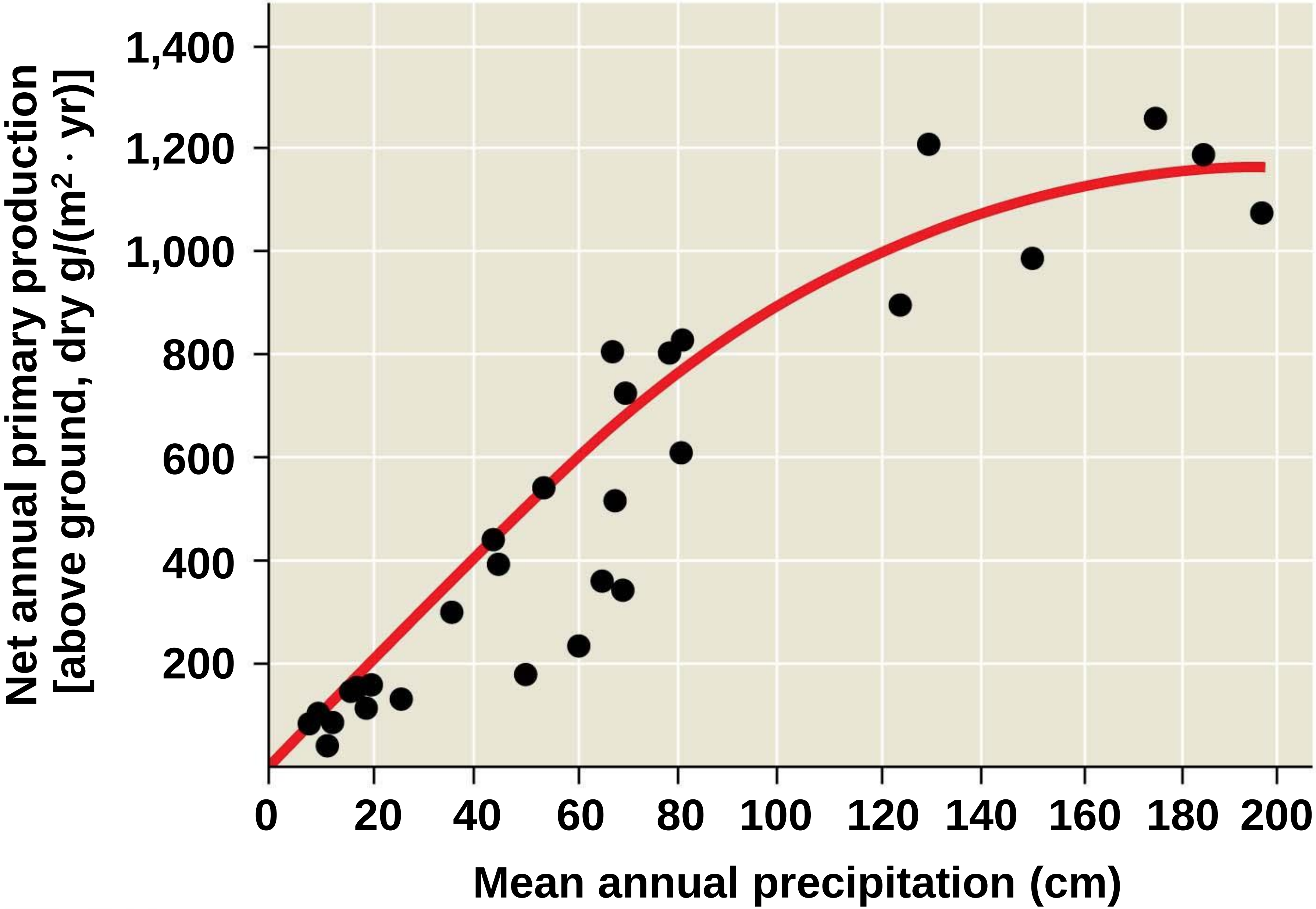
- In lakes, phosphorus limits cyanobacterial growth more often than nitrogen
- Phosphate-free detergents are now widely used to reduce nutrient pollution of lakes

Primary Production in Terrestrial Ecosystems

- At regional and global scales, temperature and moisture are the main factors controlling primary production in terrestrial ecosystems

- Mean annual precipitation and evapotranspiration, the total amount of water transpired by plants and evaporated from the landscape, are useful predictors of NPP
- Evapotranspiration increases with temperature and the amount of solar radiation

Figure 42.8



Net annual primary production [above ground, dry g/(m² · yr)]
1,400
1,200
1,000
800
600
400
200
0
20
40
60
80
100
120
140
160
180
200
Mean annual precipitation (cm)

Nutrient Limitations and Adaptations That Reduce Them

- Soil nutrients also limit primary production
- Globally, nitrogen is the most limiting nutrient in terrestrial ecosystems
- Phosphorus can also be a limiting nutrient, especially in older soils and soils with a basic pH

- Various adaptations help plants access limiting nutrients from soil
  - Some plants form mutualisms with nitrogen-fixing bacteria
  - Many plants form mutualisms with mycorrhizal fungi
  - Roots have root hairs that increase surface area
  - Many plants release enzymes that increase the availability of limiting nutrients

Concept 42.3: 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

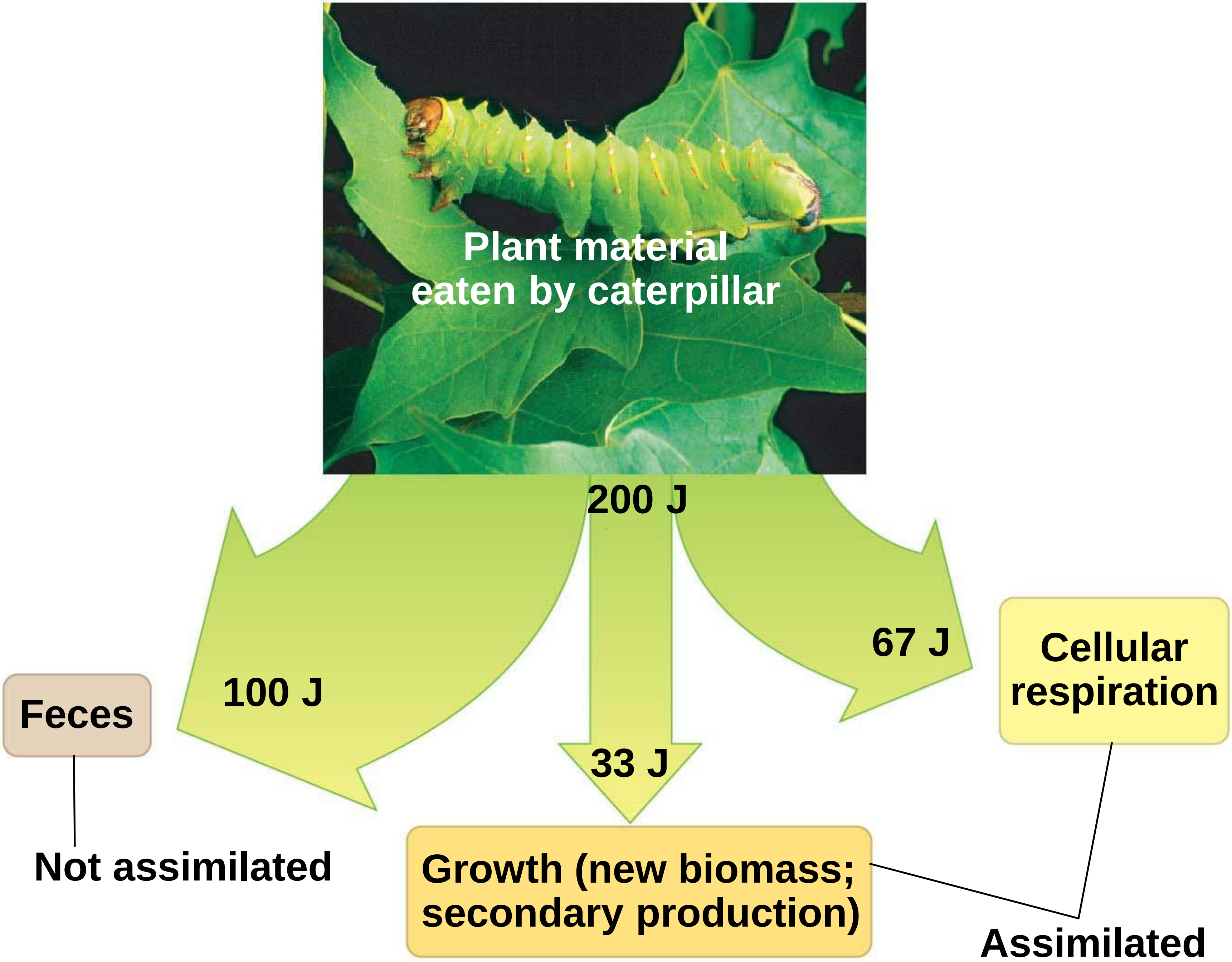
- Herbivores use only about one-sixth of the total energy stored in vegetation to produce new biomass

- An organism's **production efficiency** is the fraction of energy stored in food that is used for secondary production

$$\text{Production efficiency} = \frac{\text{Net secondary production} \times 100\%}{\text{Assimilation of primary production}}$$

- Net secondary production is the energy used for growth and reproduction
- Assimilation is the total energy consumed and used in growth, reproduction, and respiration

Figure 42.9



Plant material eaten by caterpillar

200 J

100 J

Feces

Not assimilated

33 J

Growth (new biomass; secondary production)

67 J

Cellular respiration

Assimilated

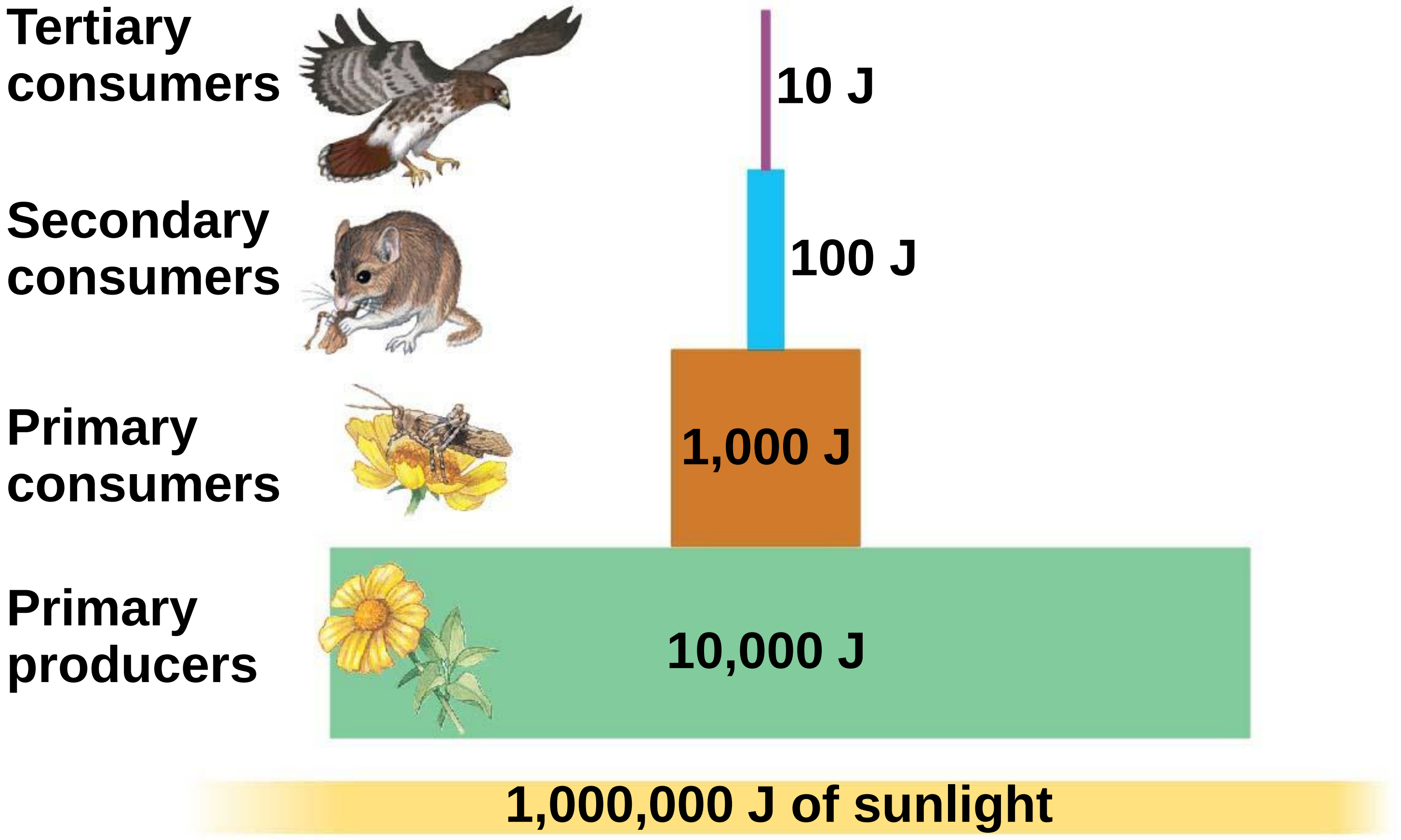
- Birds and mammals have production efficiencies in the range of 1–3% due to the high cost of endothermy
- Fish have production efficiencies around 10%
- Insects and microorganisms have efficiencies of 40% or more

Trophic Efficiency and Ecological Pyramids

- **Trophic efficiency** is the percentage of production transferred from one trophic level to the next, on average about 10%
- Trophic efficiencies take into account energy lost through respiration and feces, as well as energy stored in unconsumed portions of food

- Trophic efficiency is multiplied over the length of a food chain
- Approximately 0.1% of chemical energy fixed by photosynthesis reaches a tertiary consumer
- The loss of energy with each transfer in a food chain is represented by an energy pyramid

Figure 42.10



Tertiary consumers

10 J

Secondary consumers

100 J

Primary consumers

1,000 J

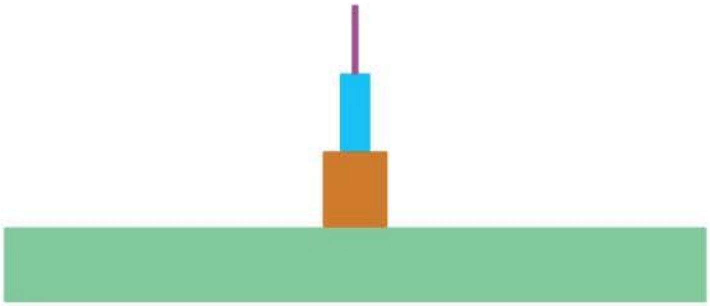
Primary producers

10,000 J

1,000,000 J of sunlight

- In a biomass pyramid, each tier represents the standing crop (total dry mass of all organisms) in one trophic level
- Most biomass pyramids show a sharp decrease at successively higher trophic levels

Figure 42.11



Trophic level	Dry mass (g/m^2)
Tertiary consumers	1.5
Secondary consumers	11
Primary consumers	37
Primary producers	809

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

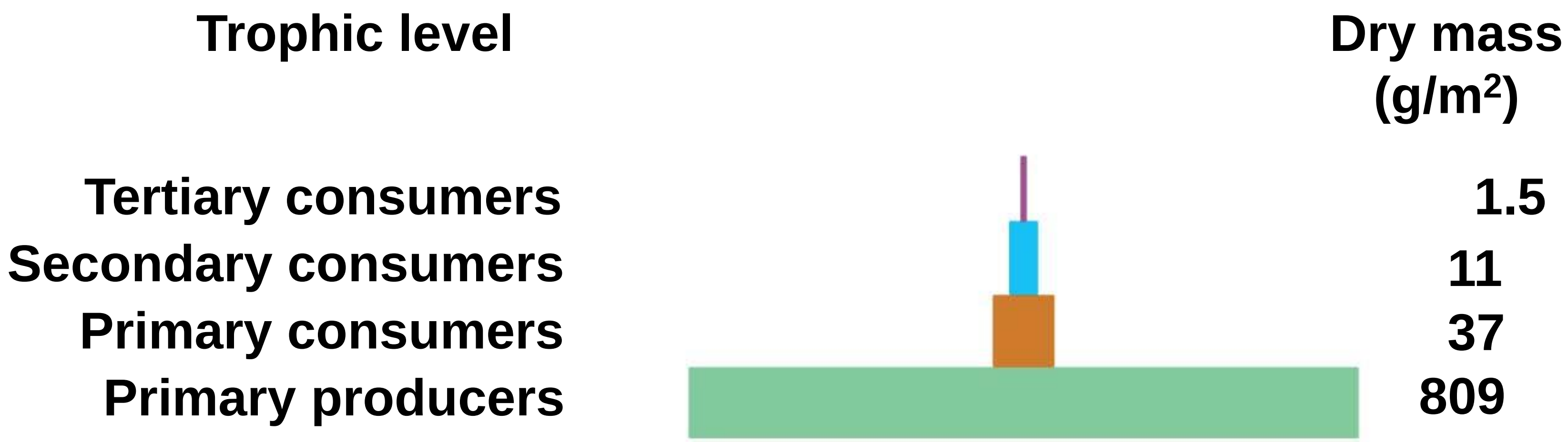
- Certain aquatic ecosystems have inverted biomass pyramids: primary consumers outweigh producers
- Phytoplankton (producers) are consumed quickly by zooplankton, but they reproduce faster and can support a larger biomass of zooplankton

Figure 42.11

Trophic level	Dry mass (g/m^2)
Primary consumers (zooplankton)	21
Primary producers (phytoplankton)	4

(b) Some aquatic ecosystems (data from the English Channel)

Figure 42.11



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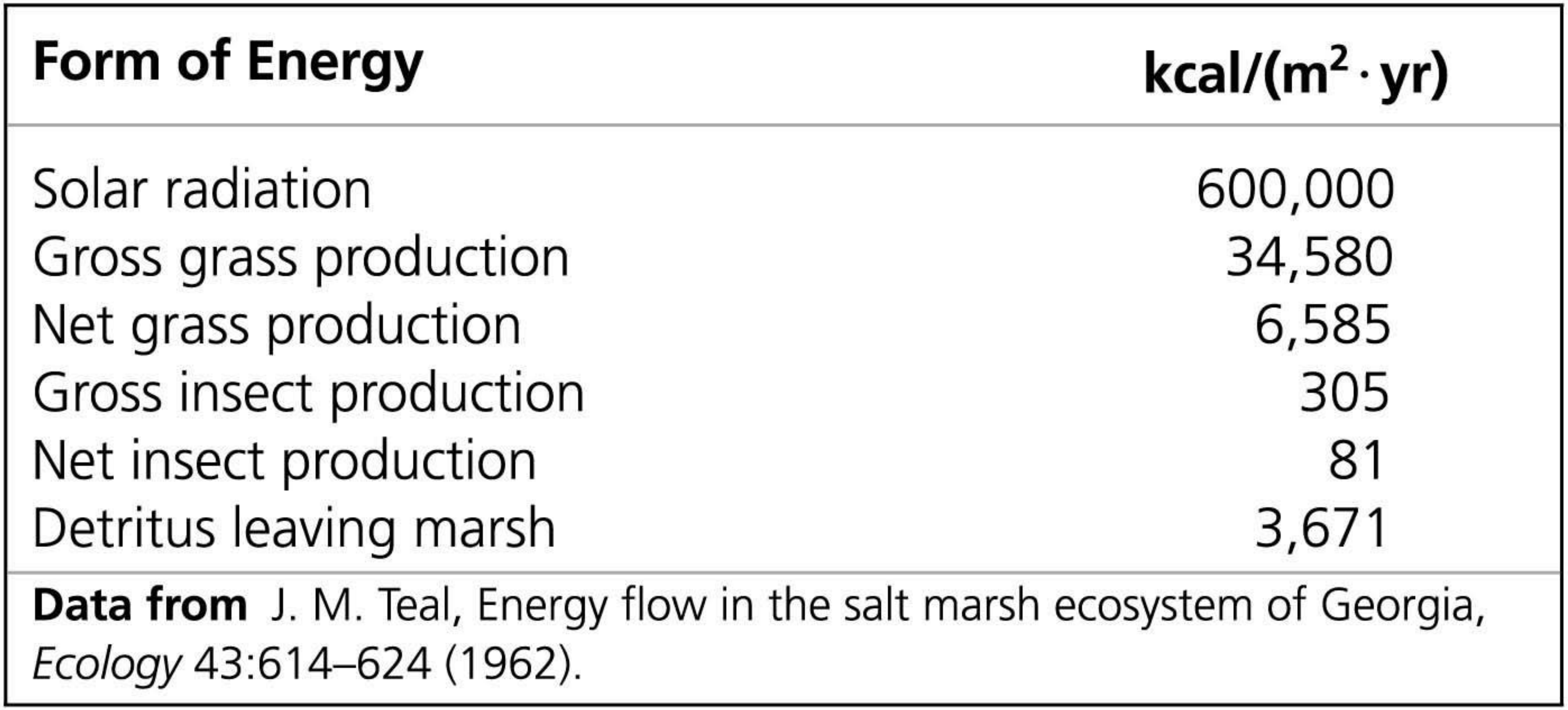
(b) Some aquatic ecosystems (data from the English Channel)

Figure 42.UN01-1



Form of Energy	**kcal/($m^2 \cdot yr$)**
Solar radiation	600,000
Gross grass production	34,580
Net grass production	6,585
Gross insect production	305
Net insect production	81
Detritus leaving marsh	3,671

Data from J. M. Teal, Energy flow in the salt marsh ecosystem of Georgia, *Ecology* 43:614–624 (1962).

- 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

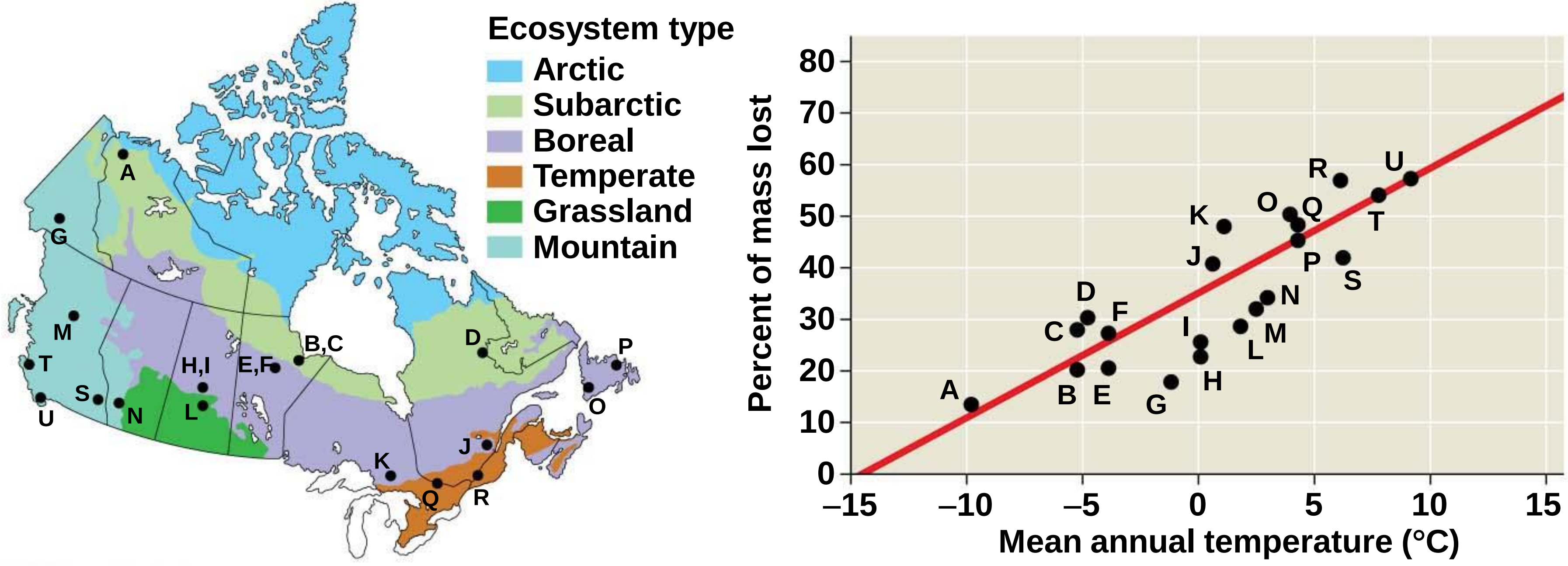
Concept 42.4: Biological and geochemical processes cycle nutrients and water in ecosystems

- Life depends on the recycling of essential chemical elements
- Decomposers play a key role in chemical cycling

Decomposition and Nutrient Cycling Rates

- The rate of nutrient cycling varies greatly among ecosystems, mostly as a result of decomposition rate
- Decomposer growth and decomposition rate are controlled by factors including temperature, moisture, and nutrient availability

Figure 42.12


Experiment

Results

Figure 42.12-1

Experiment

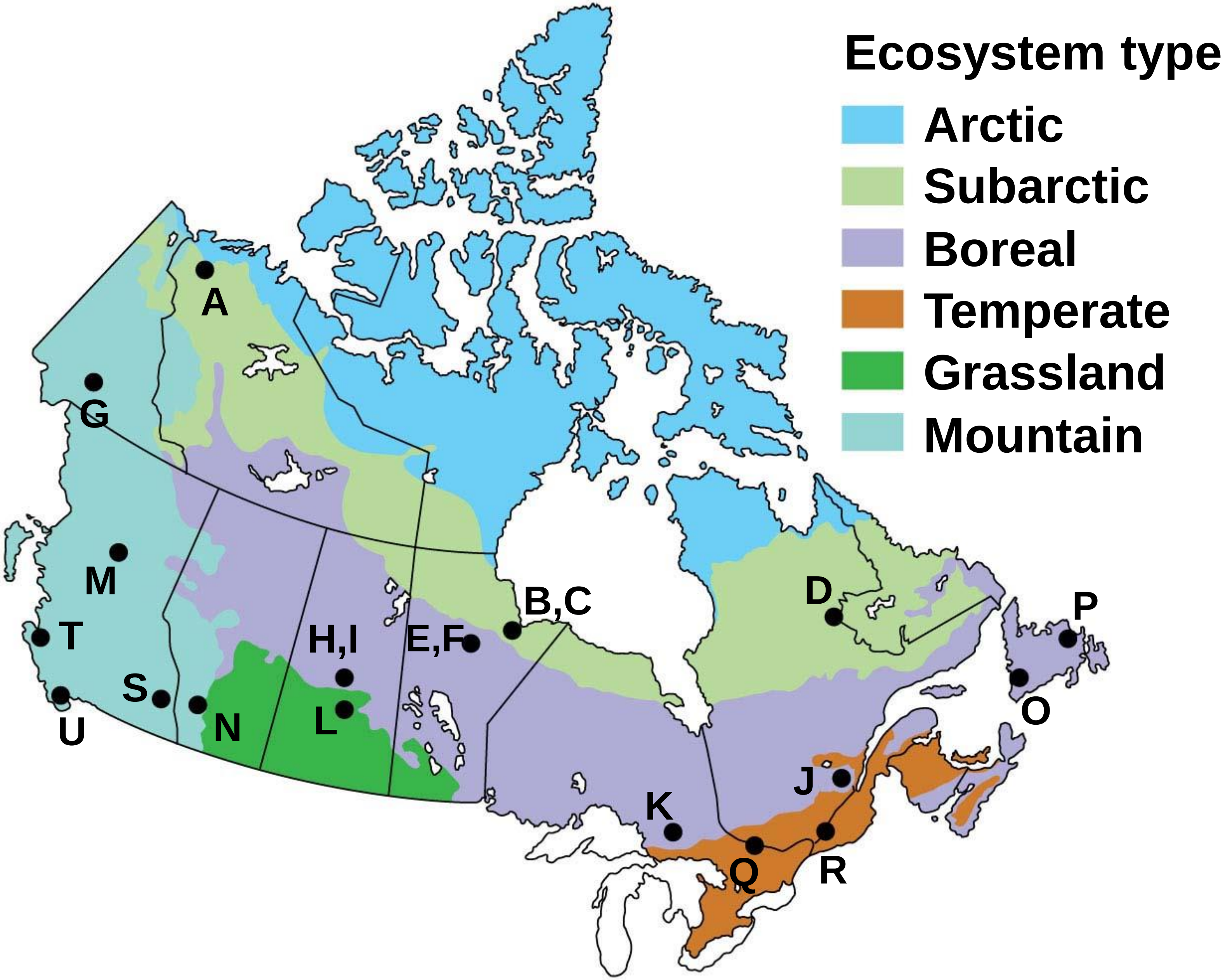
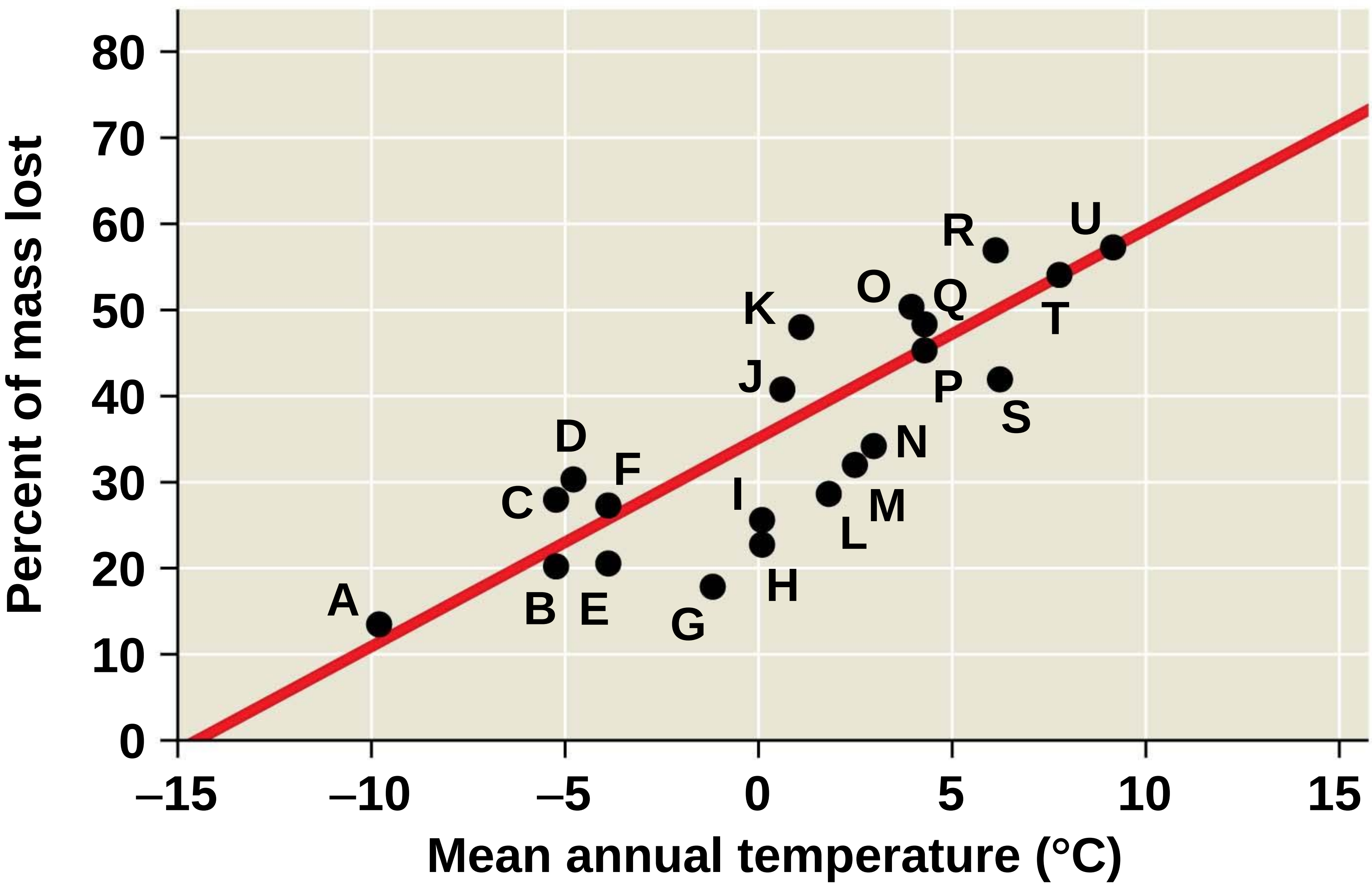


Figure 42.12-2

Results



- 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
- Decomposition is slow when soils are too dry or very wet and low in oxygen

- Decomposition is slow in the anaerobic muds of aquatic ecosystems
- Sediments constitute a nutrient sink; aquatic ecosystems require exchange between bottom layers and surface water to be highly productive

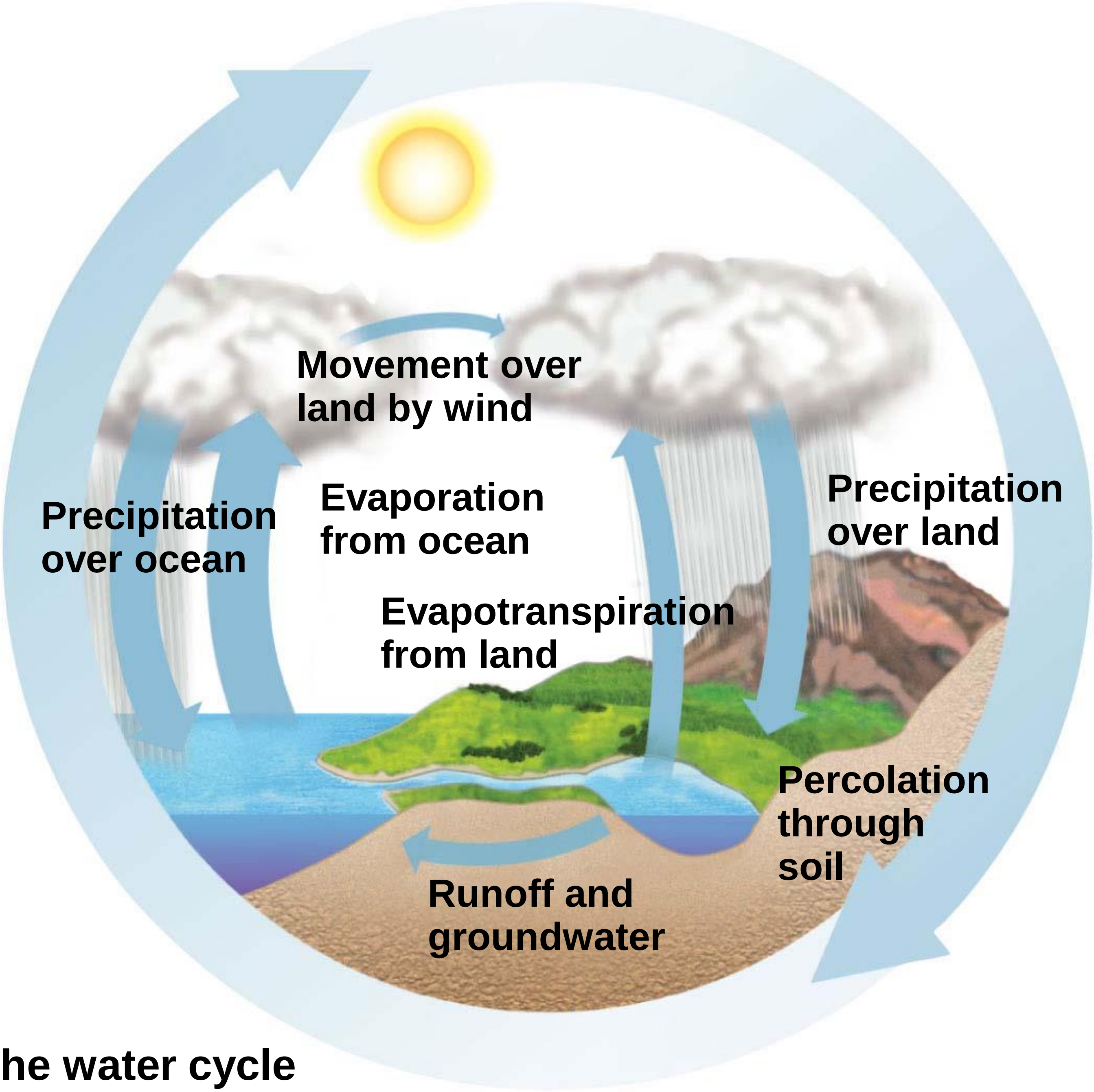
Biogeochemical Cycles

- Nutrient cycles are called **biogeochemical cycles** because they involve both biotic and abiotic components
- Biogeochemical cycles may be global or local

- Nutrients that have a gaseous phase (carbon, oxygen, sulfur, and nitrogen) enter the atmosphere and cycle globally
- Heavier elements (phosphorus, potassium, and calcium) have no gaseous phase
- They cycle locally in terrestrial systems but more broadly when dissolved in aquatic systems

The Water Cycle

- **Biological importance**: Essential to all organisms
- **Forms available to life**: Primarily liquid, though some can harvest water vapor
- **Reservoirs**: 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
- **Key processes**: Evaporation, transpiration, condensation, precipitation, and movement through surface and groundwater



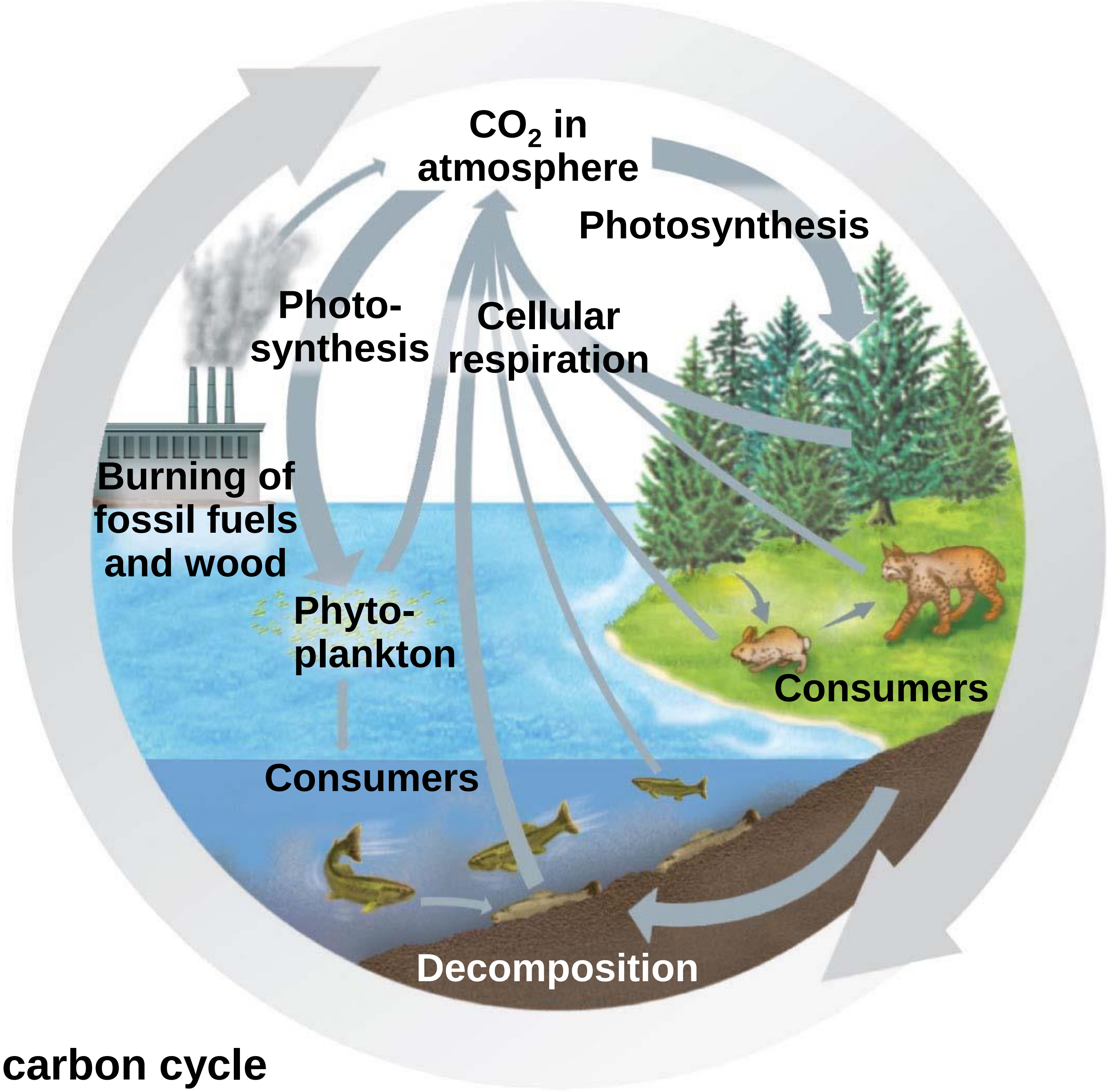
The water cycle

The Carbon Cycle

- **Biological importance**: Carbon-based organic molecules are essential to all organisms
- **Forms available to life**: Photosynthetic organisms convert CO_2 to organic molecules that are used by heterotrophs
- **Reservoirs**: Fossil fuels, soils and sediments, solutes in oceans, plant and animal biomass, the atmosphere, and sedimentary rocks

- **Key processes**: CO_2 is taken up by the process of photosynthesis and released into the atmosphere through cellular respiration
- Volcanic activity and the burning of fossil fuels also contribute CO_2 to the atmosphere

Figure 42.13-2



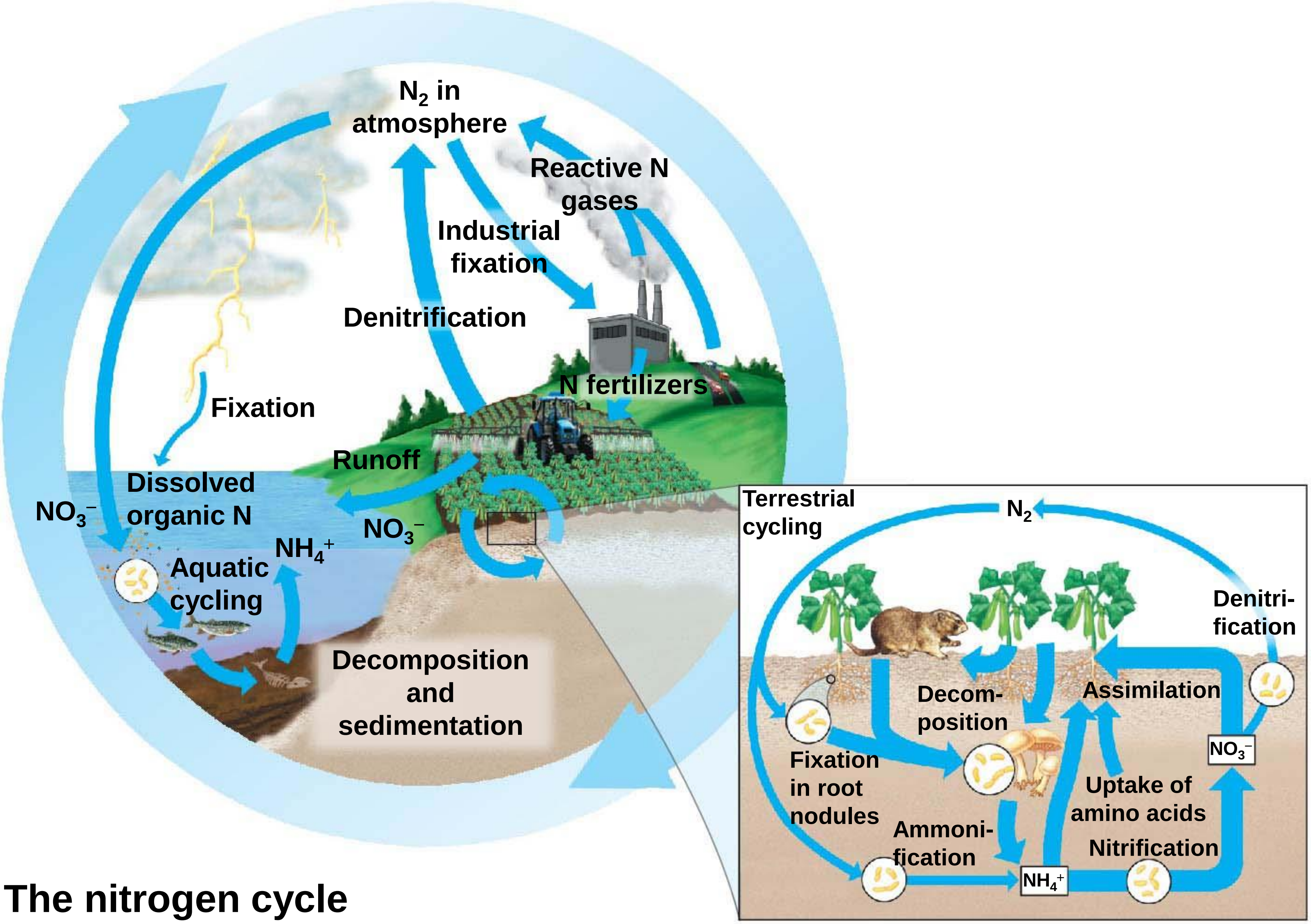
The carbon cycle

The Nitrogen Cycle

- **Biological importance**: Nitrogen is a part of amino acids, proteins, and nucleic acids and often limits primary productivity
- **Forms available to life**: Plants can use ammonium (NH_4^+), nitrate (NO_3^-), and amino acids; bacteria can also use nitrite (NO_2^-); animals can only use organic forms

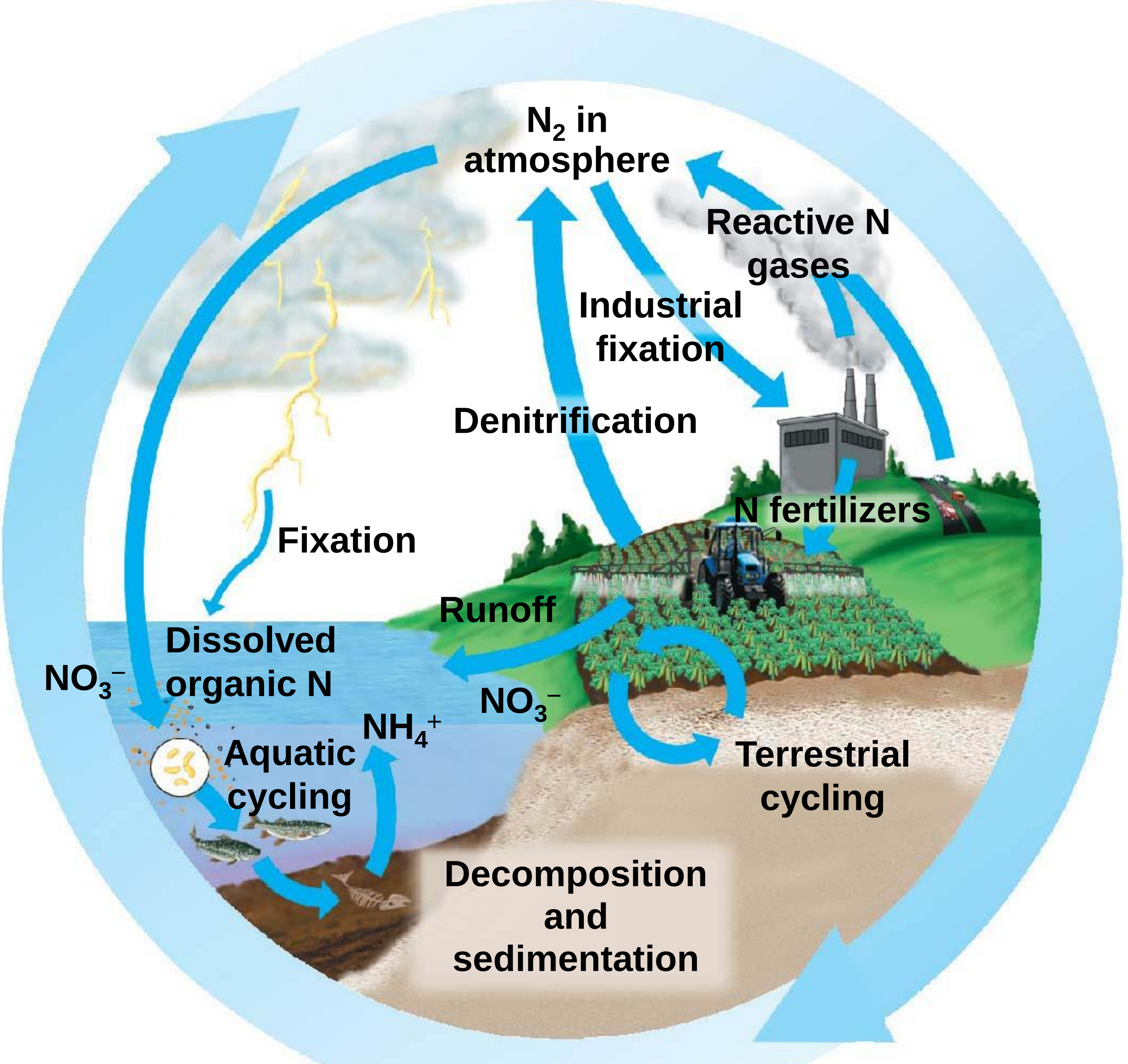
- **Reservoirs**: The atmosphere is the main reservoir (N_2); other reservoirs include soils, aquatic sediments, surface and groundwater, and biomass
- **Key processes**: Biotic and abiotic fixation of N_2, nitrification of NH_4^+ to NO_3^-, denitrification of NO_3^- to N_2, and human inputs including agricultural fertilization, legume crops, and nitrogen gas emissions

Figure 42.13-3



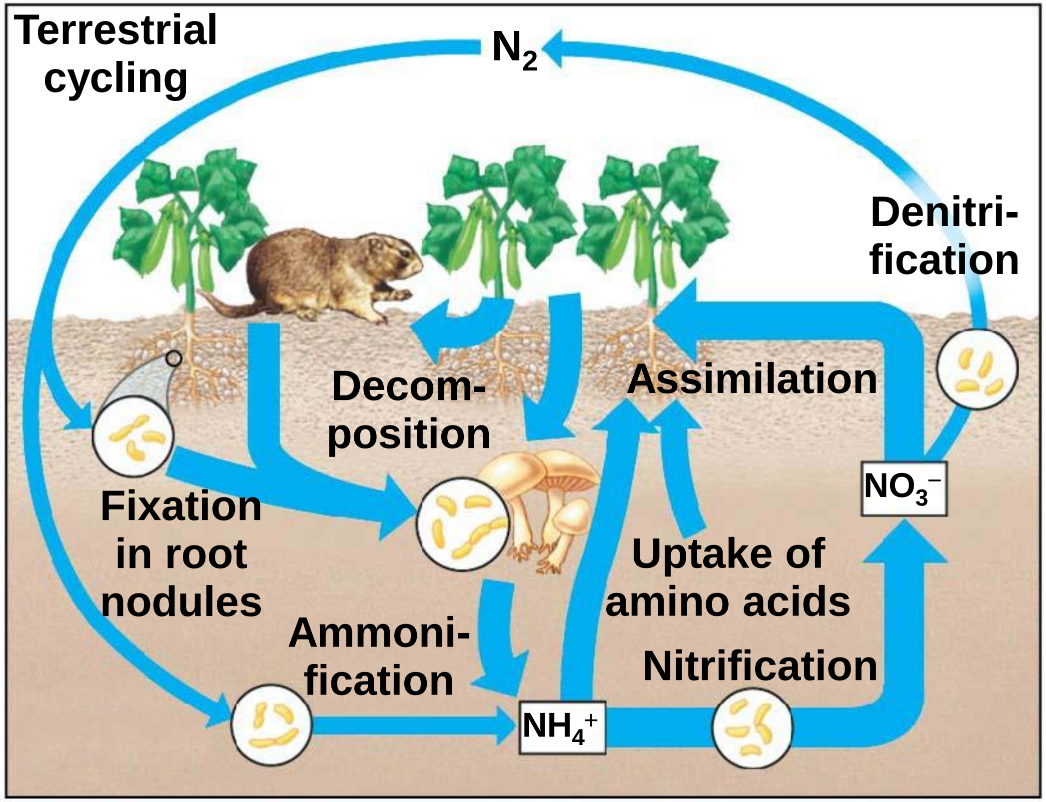
The nitrogen cycle

Figure 42.13-3a



The nitrogen cycle

Figure 42.13-3b

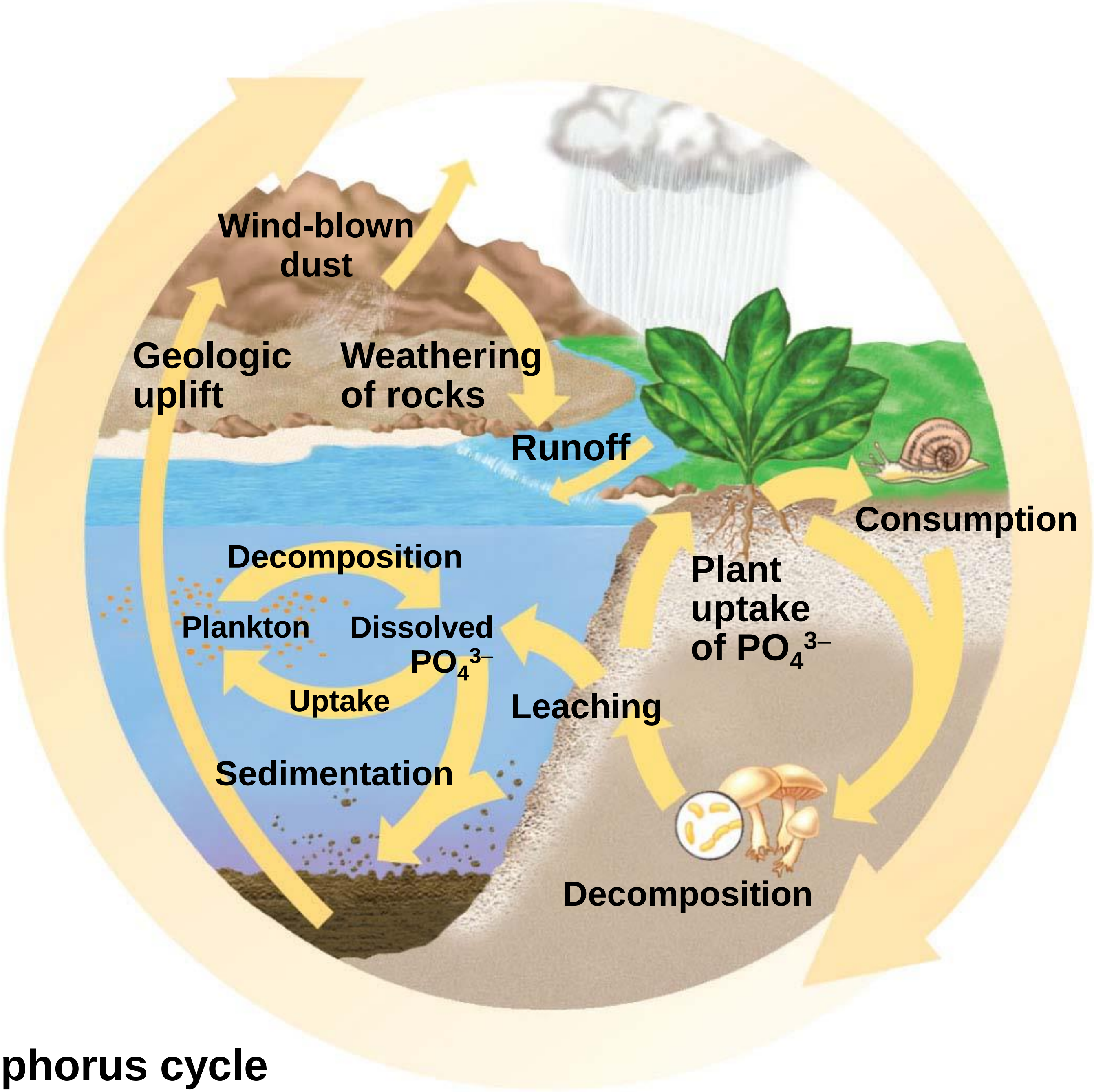


The nitrogen cycle

The Phosphorus Cycle

- **Biological importance**: Phosphorus is a major constituent of nucleic acids, phospholipids, and ATP
- **Forms available to life**: Phosphate (PO_4^{3-}) is the most important inorganic form of phosphorus
- **Reservoirs**: Sedimentary rocks of marine origin, the soil, oceans (dissolved form), and organisms
- **Key processes**: Weathering of rock, leaching into ground and surface water, incorporation into organic molecules, excretion by animals, and decomposition

Figure 42.13-4



The phosphorus cycle

Case Study: Nutrient Cycling in the Hubbard Brook Experimental Forest

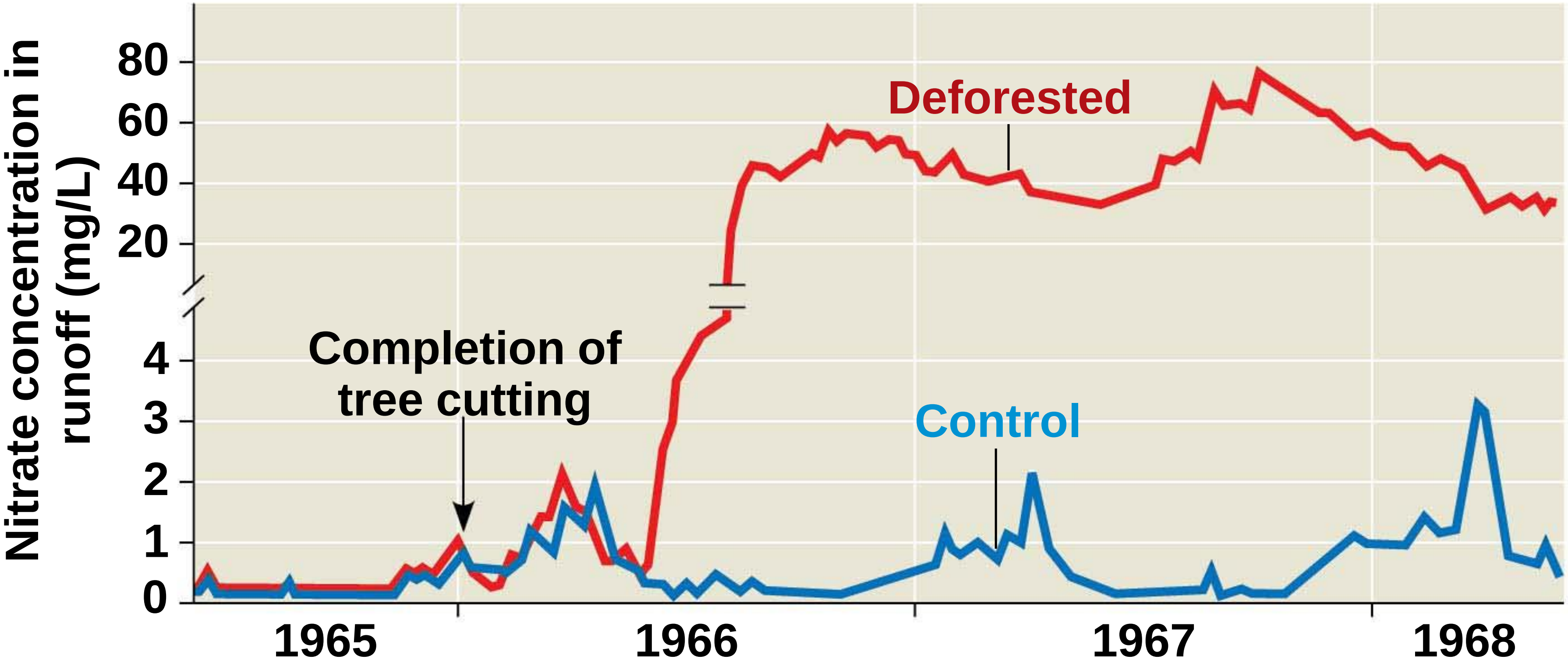
- The mineral budget for six valleys in the Hubbard Brook Experimental Forest was determined by measuring input and output of key nutrients
- Rainfall was collected to measure water and dissolved mineral inputs
- A dam was constructed to monitor water and mineral outputs

- About 60% of precipitation exited through the stream and 40% was lost by evapotranspiration
- Internal cycling conserved most of the mineral nutrients in the system
- Small gains in nutrients were measured in most years

- In another 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 in 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
- The amount of nutrients leaving a forest ecosystem is controlled mainly by plants

Figure 42.14-3



(c) Nitrate in runoff from watersheds

Concept 42.5: Restoration ecologists 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

(a) In 1991, before restoration

(b) In 2000, near the completion of restoration

(a) In 1991, before restoration

Figure 42.15-2

(b) In 2000, near the completion of restoration

- The long-term objective of restoration projects worldwide is to return an ecosystem as much as possible to its predisturbance state

Kissimmee River, Florida

- Conversion of the Kissimmee River to a 90-km canal threatened many fish and wetland bird populations
- Filling 12 km of the canal has restored natural flow patterns to 24 km of the river, helping to foster a healthy wetland ecosystem

Succulent Karoo, South Africa

- Overgrazing by livestock has damaged vast areas of land in this region
- Restoration efforts have included revegetating the land and employing sustainable resource management

Maungatautari, New Zealand

- Introduction of exotic mammals including weasels, rats, and pigs has threatened many native plant and animal species
- Restoration efforts include building fences around reserves to exclude introduced species

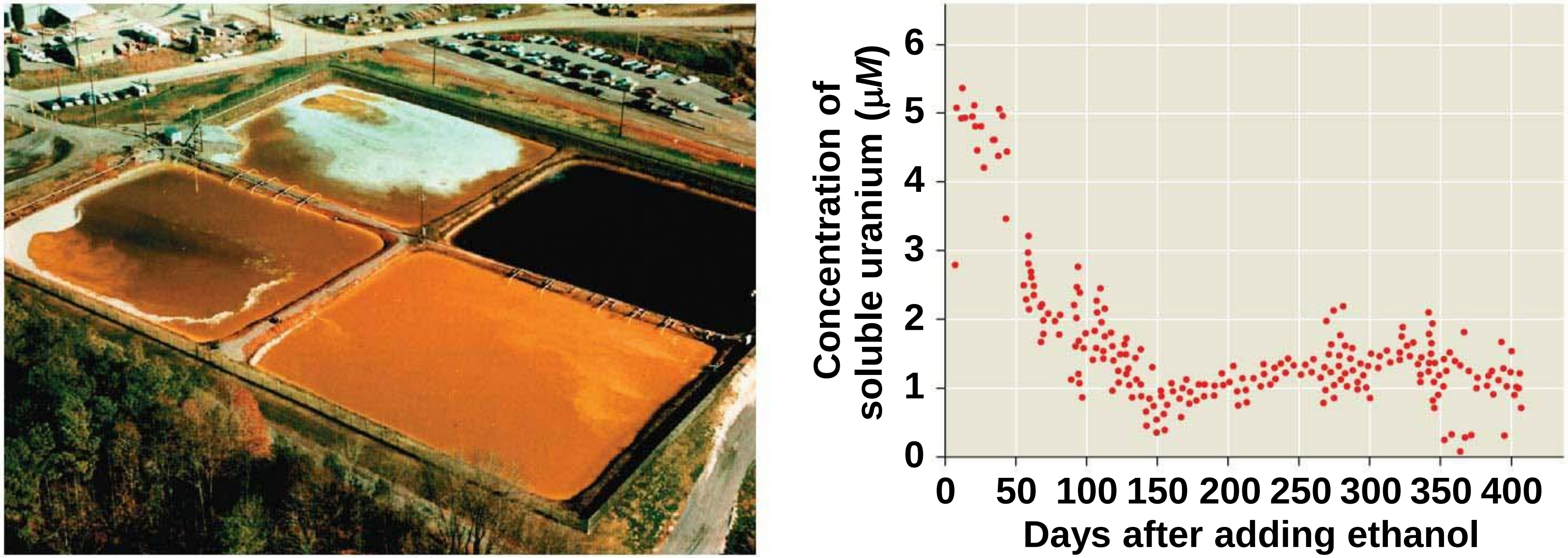
Coastal Japan

- Destruction of coastal seaweed and seagrass beds has threatened a variety of fishes and shellfish
- Restoration efforts include constructing suitable habitat, transplantation, and hand seeding

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

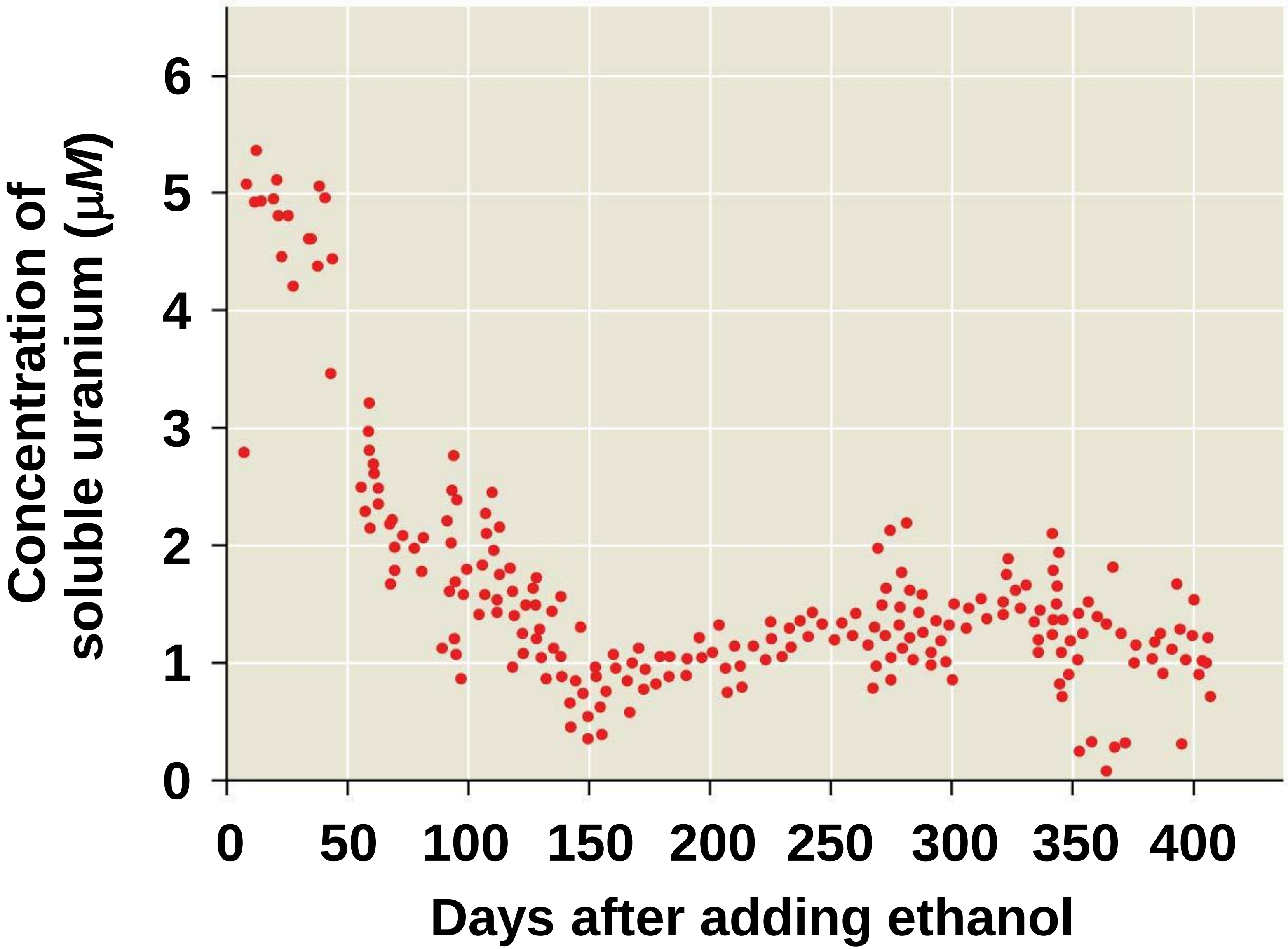
Figure 42.17



(a) Wastes containing uranium, Oak Ridge National Laboratory

(b) Decrease in concentration of soluble uranium in groundwater

Figure 42.17-2



(b) Decrease in concentration of soluble uranium in groundwater

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

Ecosystems: *A Review*

- Ecosystems represent dynamic interactions among living organisms and between biotic and abiotic components of the environment
- Energy transfer and nutrient cycling are key ecosystem processes