Ecology [part 2]

IF3211 Domain Specific Computation

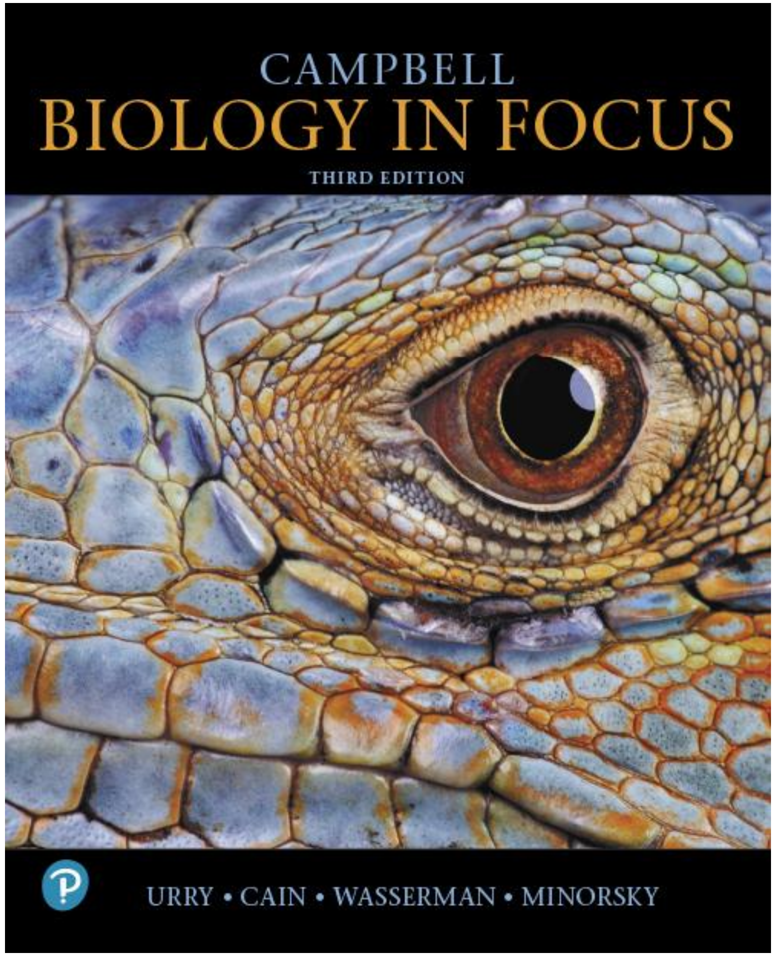
School of Electrical Engineering and Informatics ITB

Content

- Ecosystems and Energy
- Conservation Biology and Global Change

Campbell Biology in Focus

Third Edition



Chapter 42

Ecosystems and Energy

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

Pearson

Overview

- An **ecosystem** consists of all the organisms living in a community and 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

- Ecologists study the transformations of energy in an ecosystem and map the movements of chemical elements

Figure 42.1

How Can Foxes Transform a Grassland into Tundra?

Conservation of Energy

- Laws of physics and chemistry apply to ecosystems
- **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; some energy is always lost as heat

Conservation of Mass

- The **law of conservation of mass** states that matter cannot be created or destroyed
- Unlike energy, chemical elements can be 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
- Ecosystems are open systems, absorbing energy and mass and releasing heat and waste products

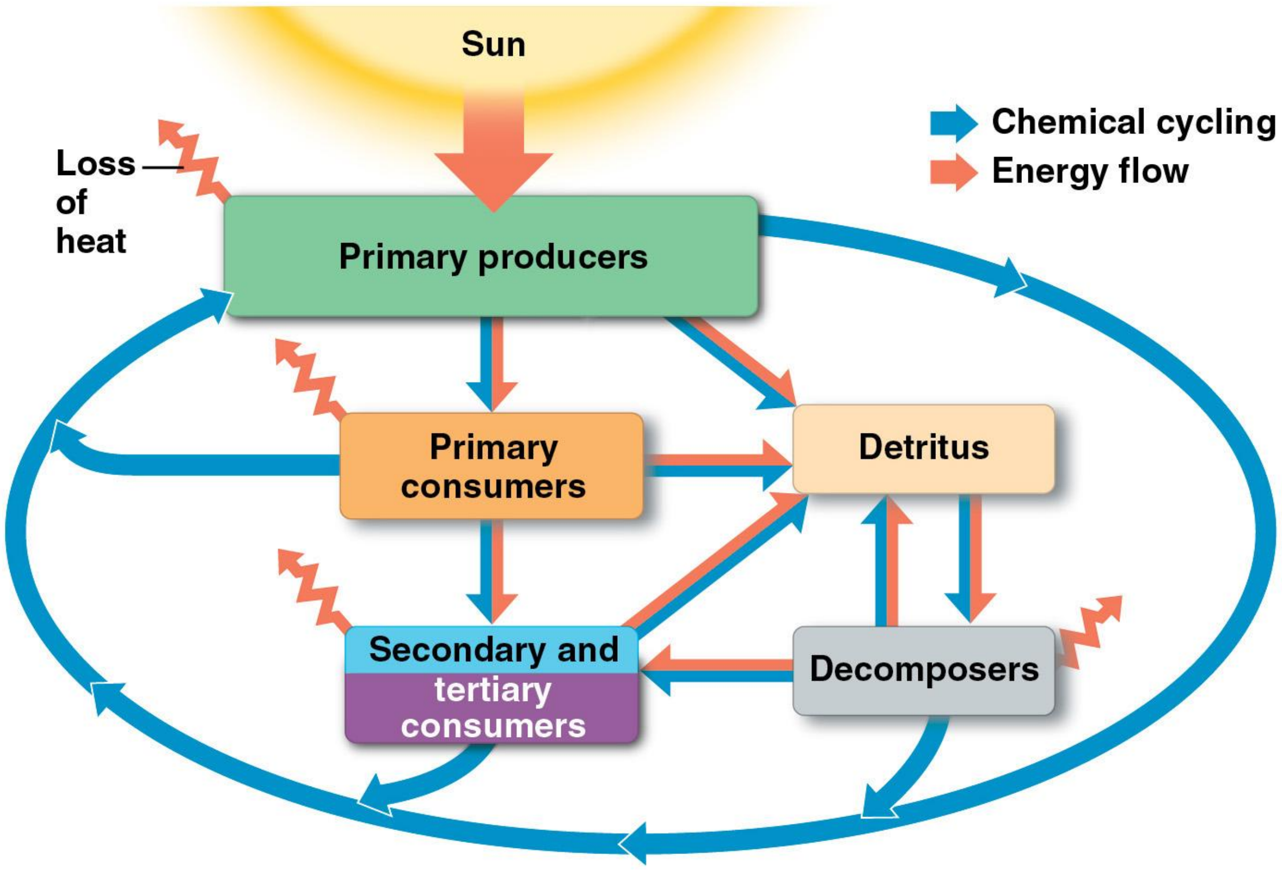
Energy, Mass, and Trophic Levels

- Ecologists group species into trophic levels based on feeding relationships
- Energy and nutrients pass from primary producers (autotrophs) to **primary consumers** (herbivores)
- **Secondary consumers** are carnivores that eat herbivores
- **Tertiary consumers** are carnivores that feed on other carnivores

- **Detritivores,** or **decomposers**, are consumers that derive their energy from **detritus**, nonliving organic material

Figure 42.4

An Overview of Energy and Nutrient Dynamics in an Ecosystem



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
- **Secondary production** of an ecosystem is the amount of chemical energy in food converted to new biomass during a given period of time
- Ecosystems Energy Budgets: The total amount of photosynthetic production sets the “spending limit” for an ecosystem’s energy budget
- Only a fraction of the solar radiation strikes photosynthetic organisms, and only certain wavelengths are absorbed by them
- About 1% of visible light striking photosynthetic organisms is converted into chemical energy

Gross and Net Production

- Total primary production is known as the ecosystem's **gross primary production** (**GPP**)
- GPP is measured as the amount of energy from light (or chemicals, in chemoautotrophic systems) converted to chemical energy per unit time
- **Net primary production** (**NPP**) is GPP minus energy used by primary producers for "autotrophic respiration" (R_a)

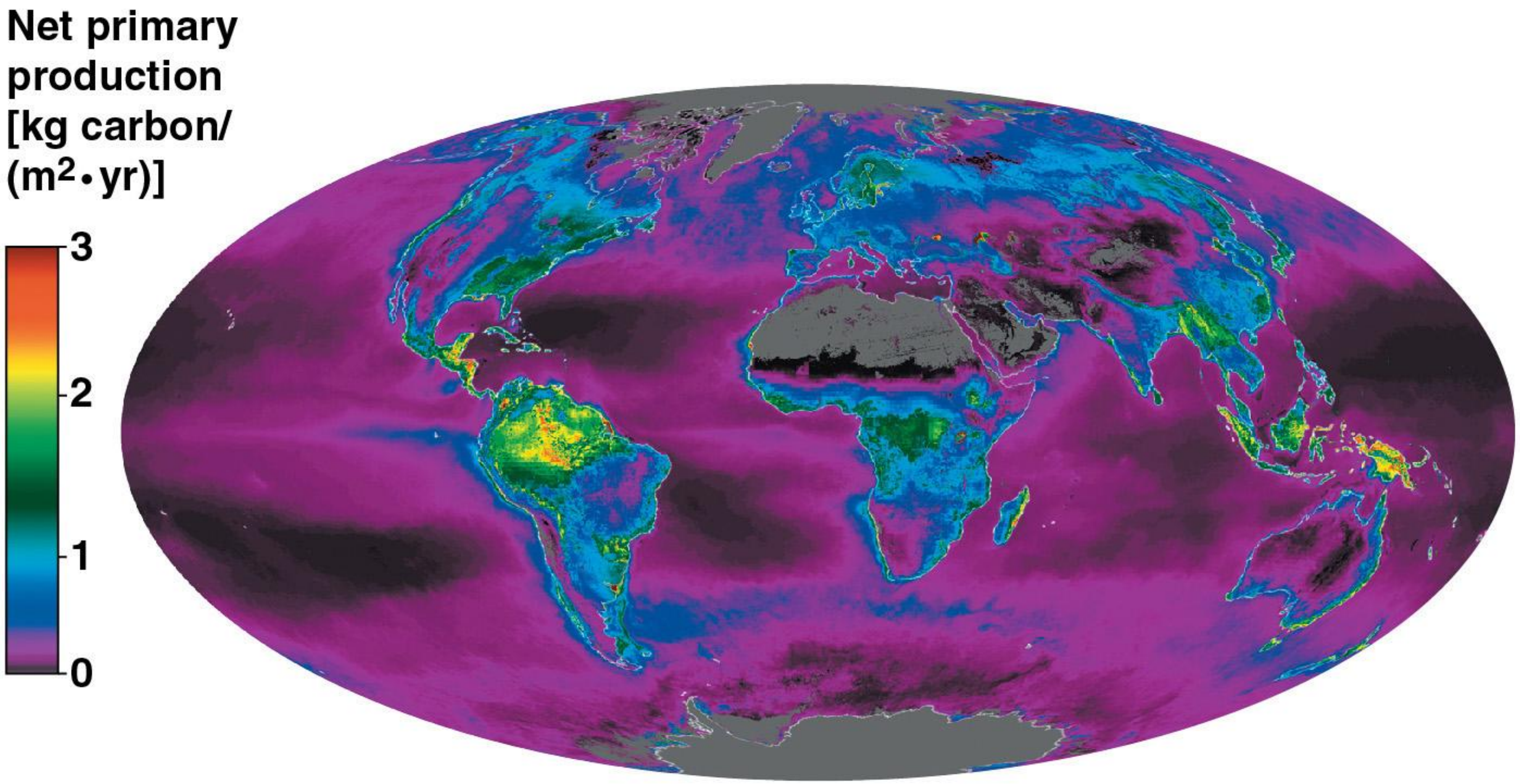
$$NPP = GPP - R_a$$

- **Net ecosystem production** (**NEP**) is a measure of total biomass accumulation during a given time. Total Respiration (R_T)

$$NEP = GPP - R_T$$

Figure 42.6

Global Net Primary Production



Primary Production in Aquatic Ecosystems

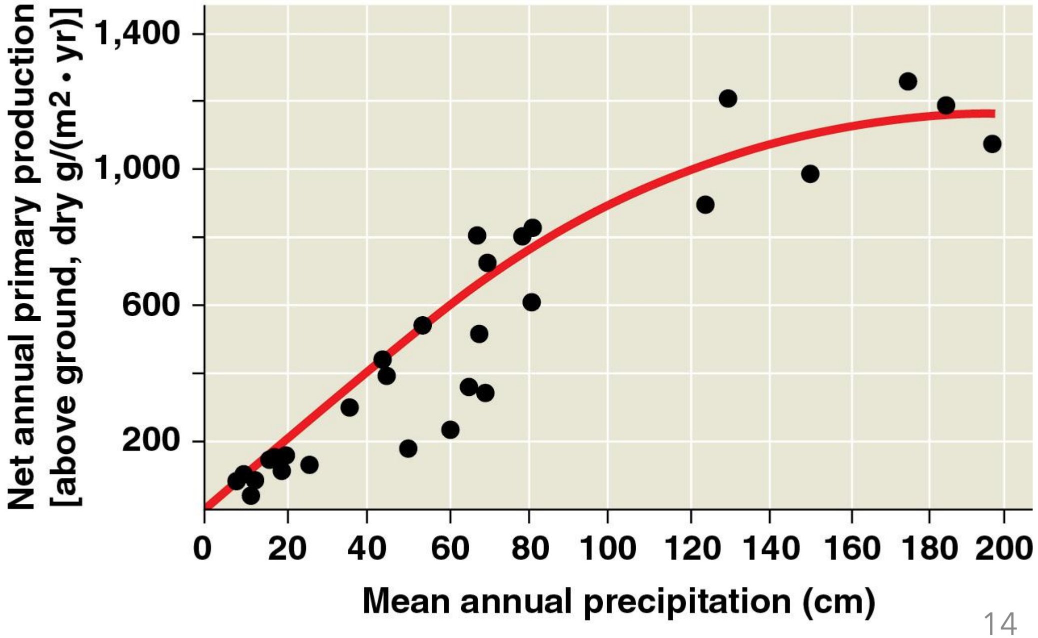
- In marine and freshwater ecosystems, both light and nutrients are important in controlling primary production
- Light Limitation: Depth of light penetration affects primary production in the photic zone of an ocean or lake
- A **limiting nutrient** is the element that must be added for production to increase in an area

- **Eutrophication** is the dramatic increase in primary production that occurs when aquatic ecosystems are converted from nutrient-poor to nutrient-rich

Primary Production in Terrestrial Ecosystems

- At regional and global scales, temperature and moisture are the main factors controlling primary production in terrestrial ecosystems
- NPP increases with annual precipitation, temperature, and the amount of solar radiation

A Global Relationship Between Net Primary Production and Mean Annual Precipitation for Terrestrial Ecosystems



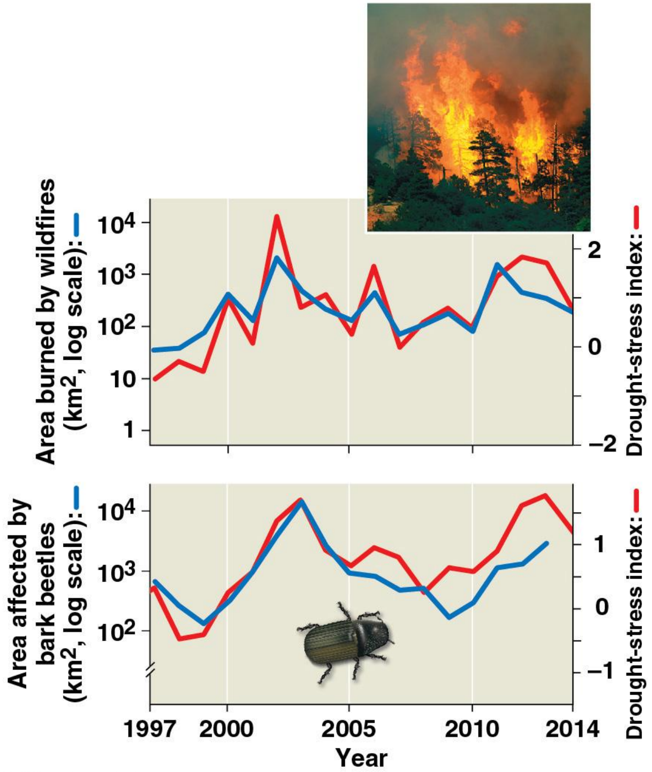
Nutrient Limitations and Adaptations That Reduce Them

- Soil nutrients also limit primary production in terrestrial ecosystems
- Globally, nitrogen limits plant growth most
- Phosphorus can also be a limiting, especially in older soils where water has leached it away
- Adding a limiting nutrient only increases production until some other nutrient becomes limiting

Effects of Climate Change on Production

- Climate change affects temperature and precipitation, which in turn affects terrestrial NPP
- Climate warming and changing precipitation patterns cause "hotter droughts" that impact wildfires and insect outbreaks
  - For example, droughts have led to increased outbreaks of mountain pine beetle, *Dendroctonus ponderosae*, causing widespread tree mortality

Climate Change, Wildfires, and Insect Outbreaks



Production Efficiency

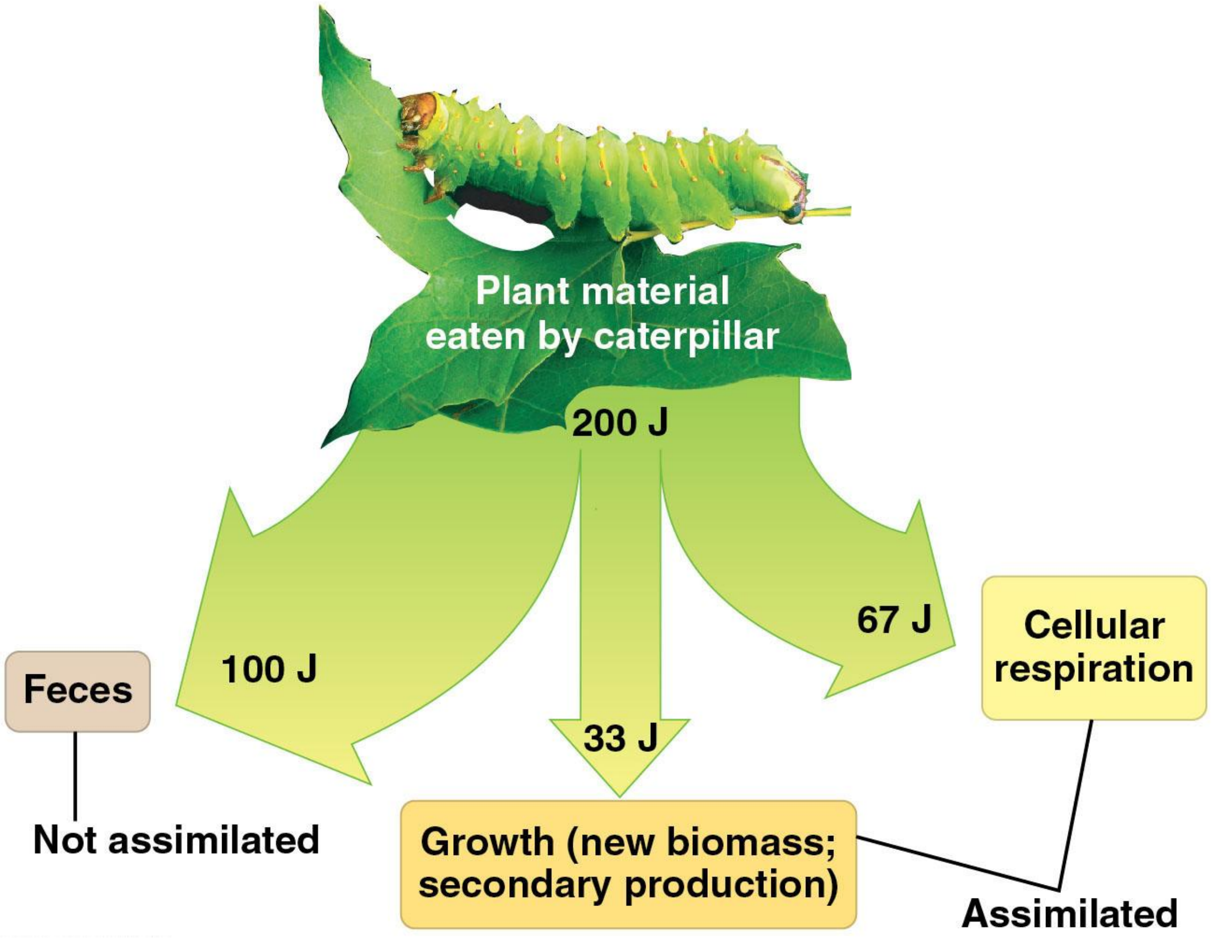
- An organism's **production efficiency** is the fraction of energy stored in food that is used for secondary production

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

  - 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 42.10

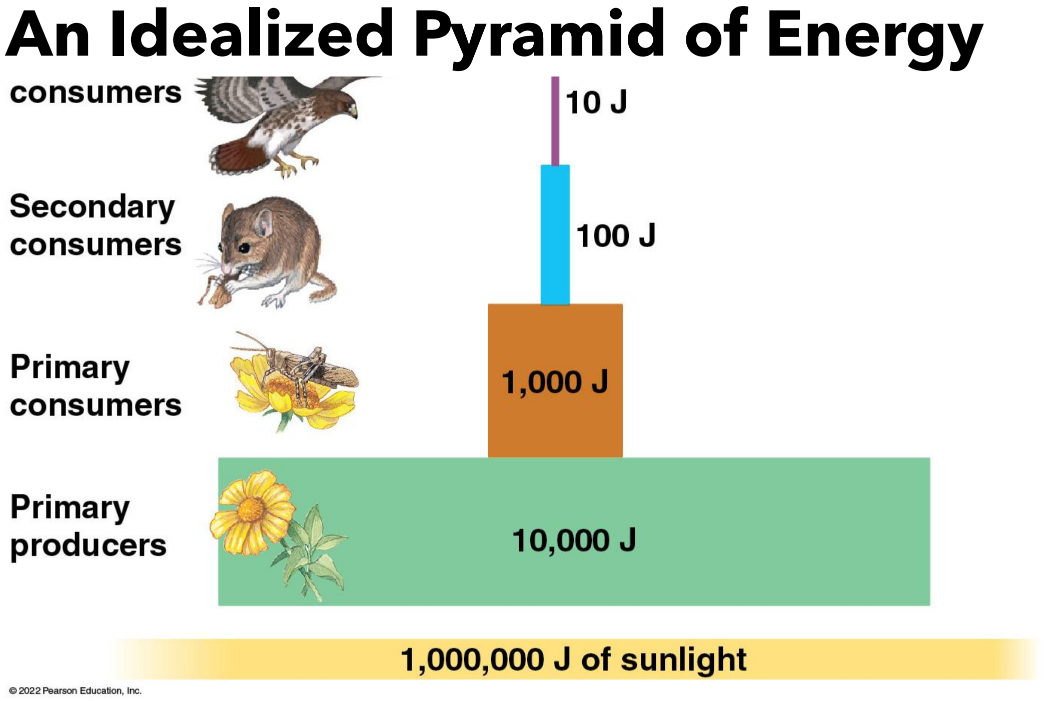
Energy Partitioning Within a Link of the Food Chain

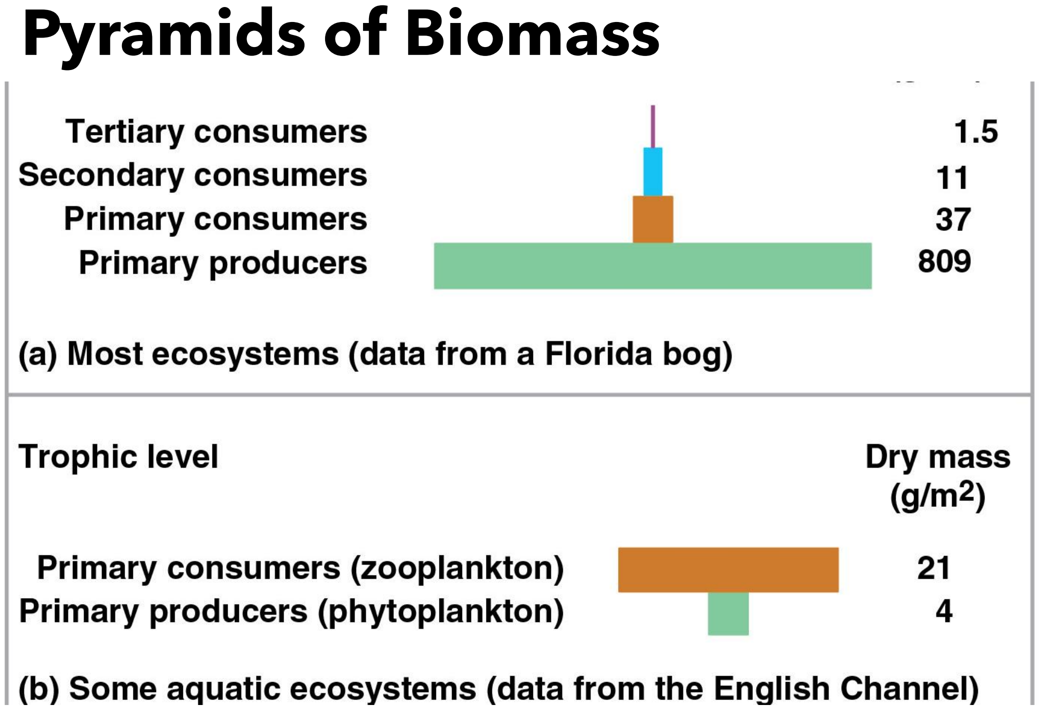


Trophic Efficiency and Ecological Pyramids

- **Trophic efficiency** is the percentage of production transferred from one trophic level to the next, on average about 10%
- Trophic efficiencies take energy stored in unconsumed biomass at lower trophic levels as well as energy lost to feces and respiration

Pyramid Energy and Biomass





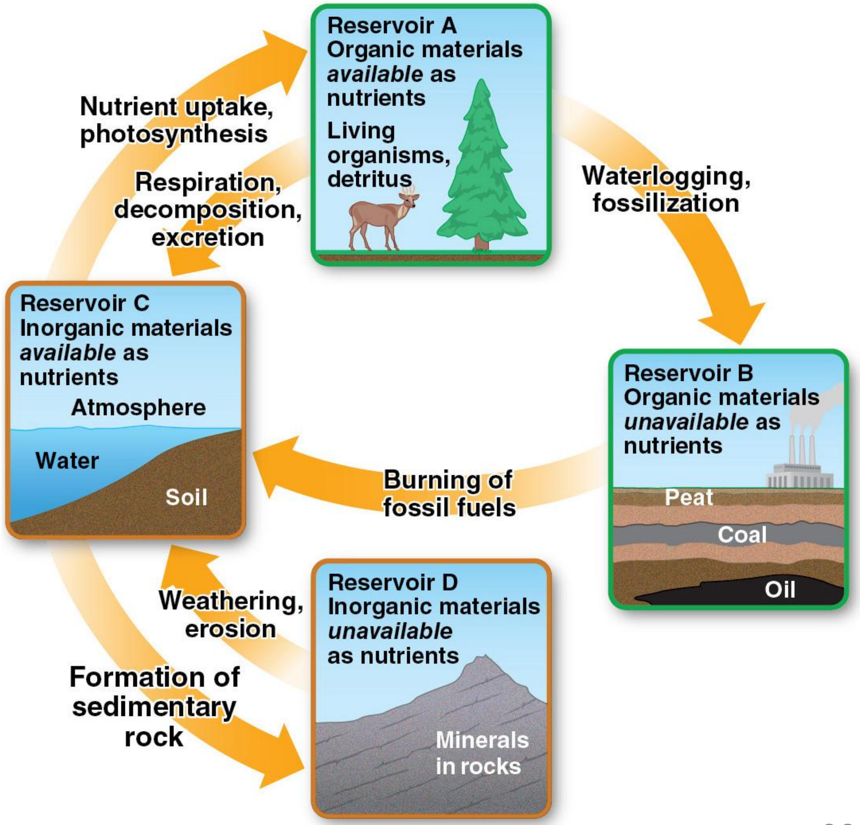
Concept 42.4: Biological and Geochemical Processes Cycle Nutrients and Water in Ecosystems

- Life depends on the recycling of limited essential chemical elements
- Decomposers play a key role in chemical cycling
- Decomposer growth and rate of decomposition are controlled by temperature, moisture, and nutrient availability

Biogeochemical Cycles

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

Visualizing Biogeochemical Cycles



Biogeochemical Cycles: The Water Cycle

- **Biological importance**: Essential to all organisms
- **Forms available to life**: Primarily liquid, some harvest water vapor
- **Reservoirs**: 97% of biosphere's water is in oceans; 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

Biogeochemical Cycles: The Carbon Cycle

The Carbon Cycle

- **Biological importance**: All organic molecules contain carbon
- **Forms available to life**: Photosynthetic organisms convert CO_2 to organic forms used by consumers
- **Reservoirs**: Fossil fuels, soils, sediments, solutes in oceans, plant and animal biomass, the atmosphere, and sedimentary rocks
- **Key processes**: Photosynthesis takes up CO_2 and respiration releases it; volcanic activity and burning fossil fuels and wood also release CO_2

Biogeochemical Cycles: The Nitrogen Cycle

The Nitrogen Cycle

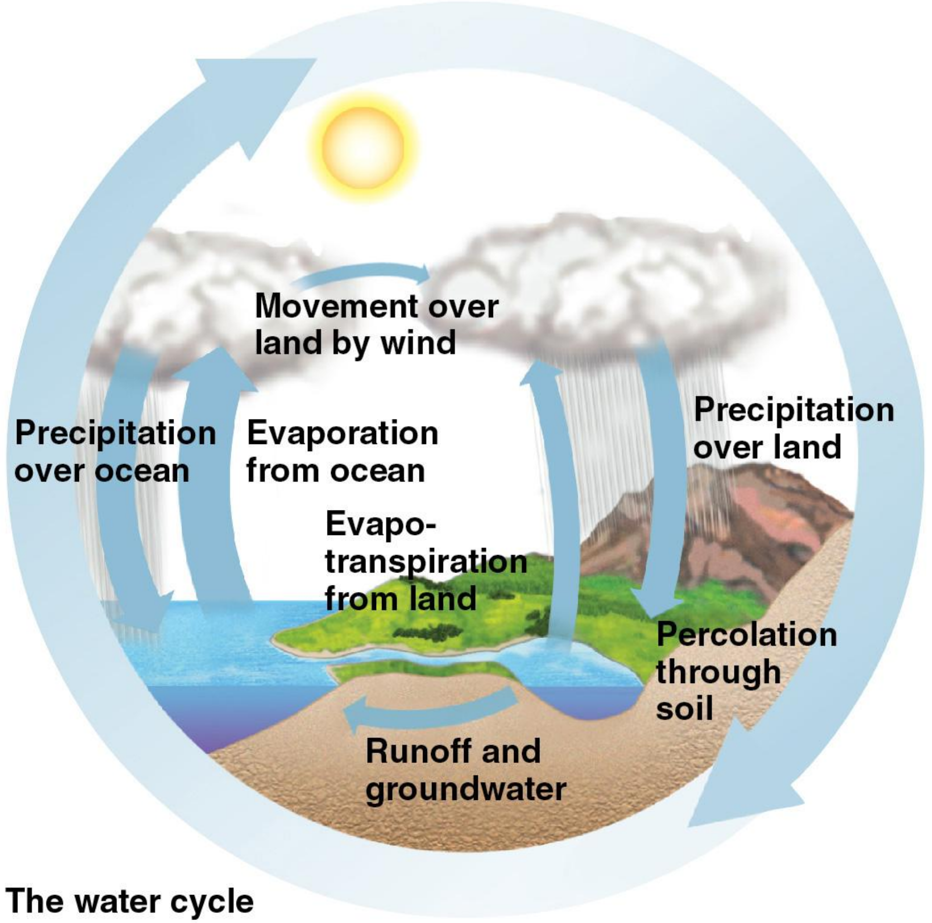
- **Biological importance**: Amino acids, proteins, and nucleic acids contain nitrogen
- **Forms available to life**: Plants use ammonium (NH_4^+) and nitrate (NO_3^-); bacteria use nitrite (NO_2^-); animals use organic forms
- **Reservoirs**: Atmosphere (N_2), soils, sediments, surface and groundwater, organisms
- **Key processes**: Fixation (N_2 to NH_3), nitrification (NH_4^+ to NO_3^-), denitrification (NO_3^- to N_2), industrial fertilizers, legume crops, reactive gas emissions

Biogeochemical Cycles: The Phosphorus Cycle

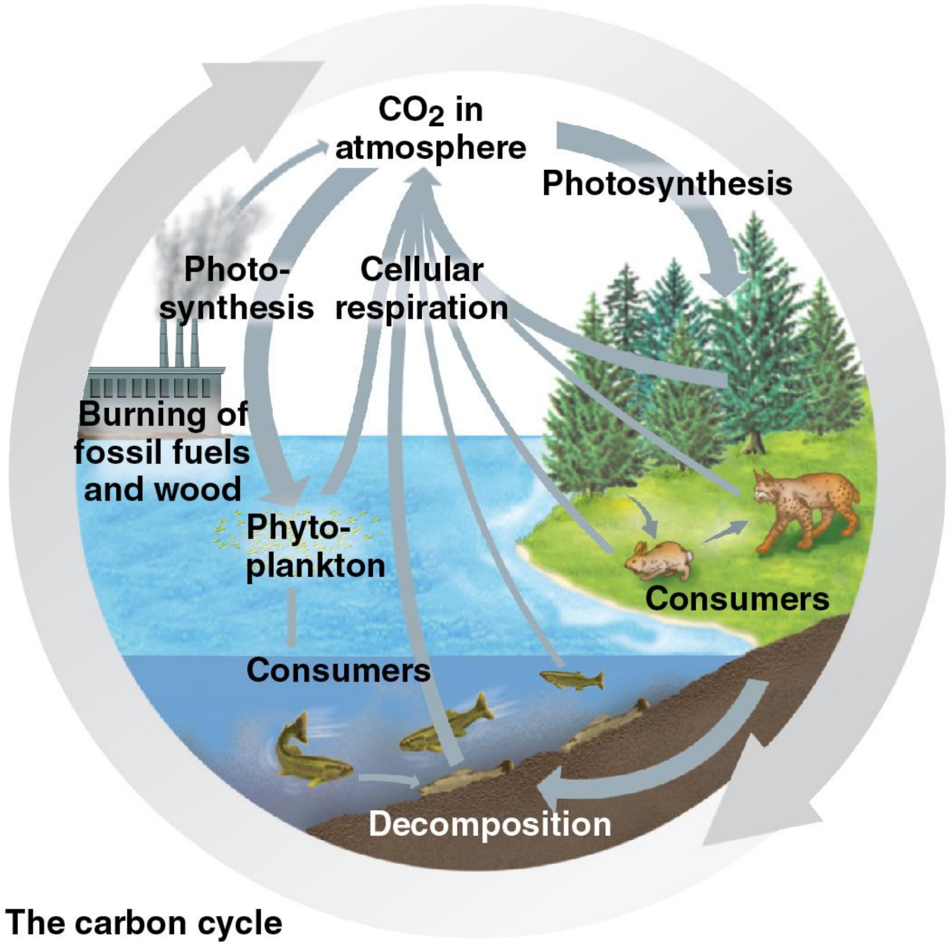
- **Biological importance**: Nucleic acids, phospholipids, and ATP contain phosphorus
- **Forms available to life**: Phosphate(PO_4^{3-}) is the most important inorganic form of phosphorus
- **Reservoirs**: Sedimentary rocks of marine origin, soil, oceans (dissolved form), organisms
- **Key processes**: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

Figure Biogeochemical Cycles (1 of 2)

Exploring Water and Nutrient Cycling



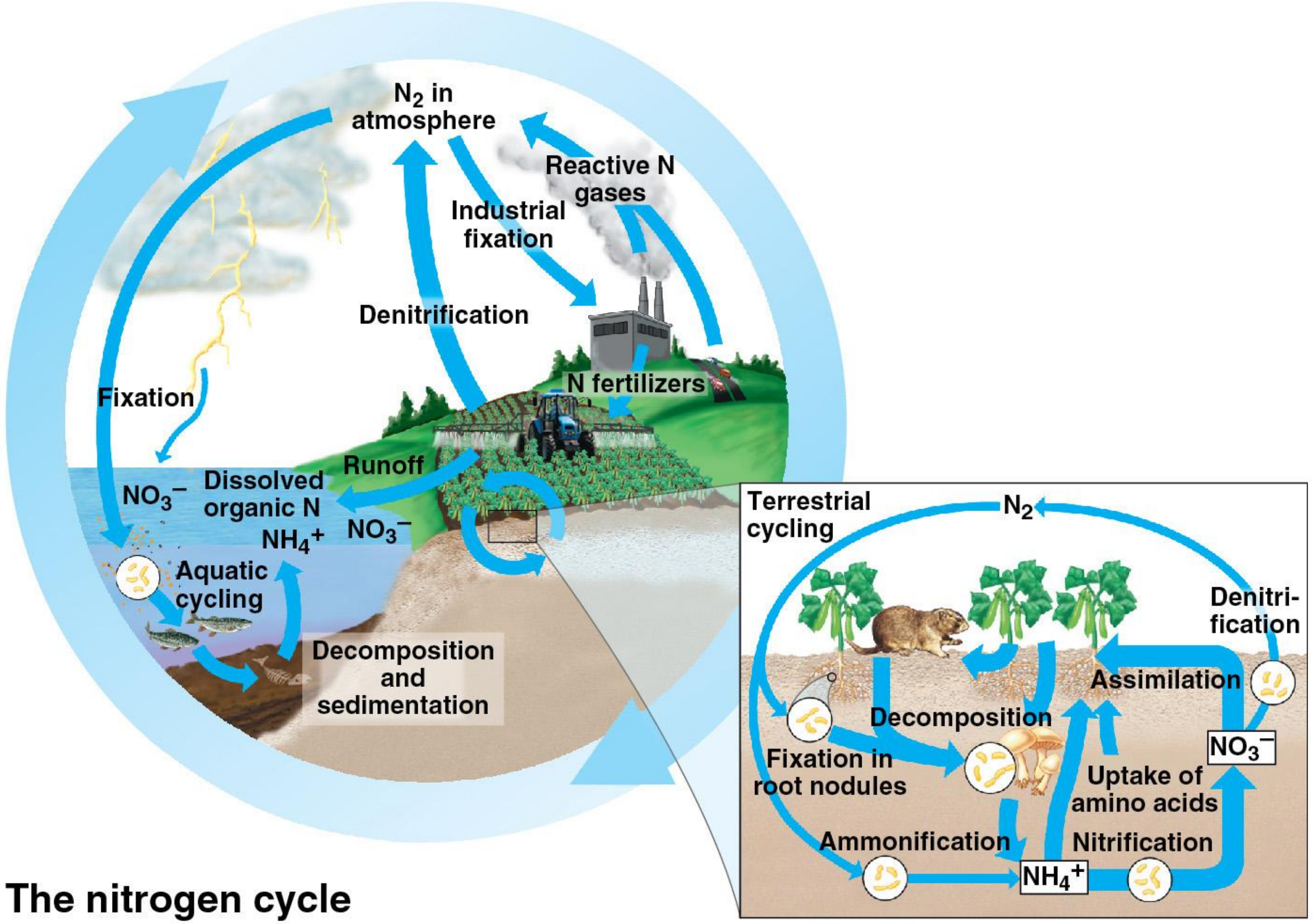
The water cycle



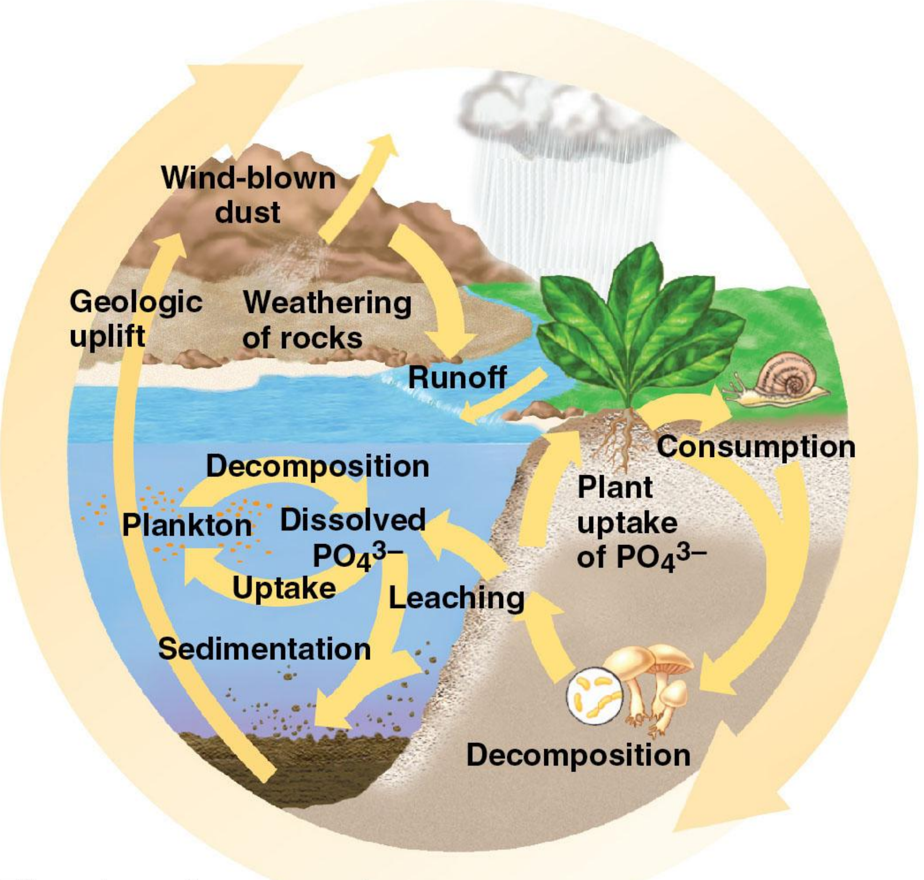
The carbon cycle

Figure Biogeochemical Cycles (2 of 2)

Exploring Water and Nutrient Cycling



The nitrogen cycle



The phosphorus cycle

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 ecologists seek to initiate or speed up the recovery of degraded ecosystems
- In extreme cases, the physical structure of the ecosystem must be restored before biological restoration can occur

- **Bioremediation** is the use of organisms—typically prokaryotes, fungi, or plants—to detoxify ecosystems
- **Biological augmentation** uses organisms to add essential materials to a degraded ecosystem

Figure 42.18

Exploring Restoration Ecology Worldwide

Kissimmee River, Florida

Succulent Karoo, South Africa

Maungatautari, New Zealand

Coastal Indonesia

Campbell Biology in Focus

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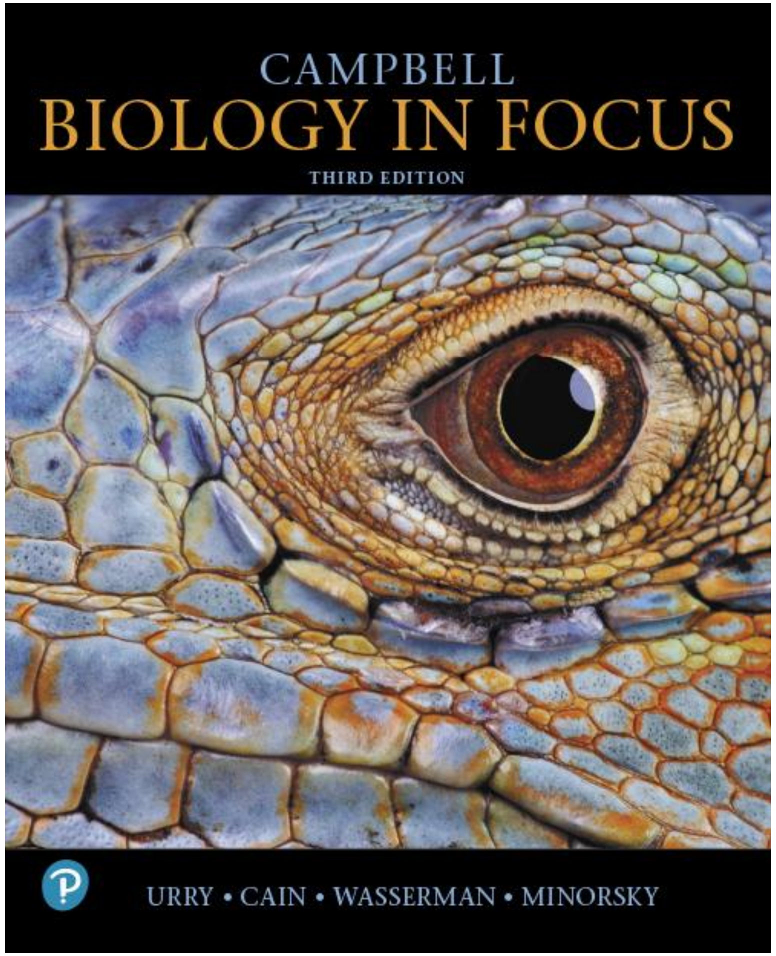


Chapter 43

Conservation Biology and Global Change

Lecture Presentations by

Kathleen Fitzpatrick and Nicole Tunbridge,

Simon Fraser University

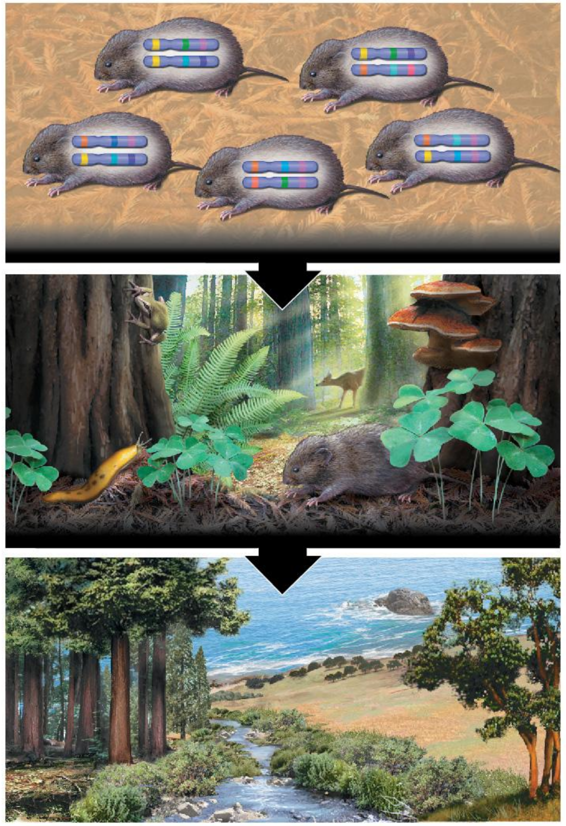
Overview

- **Conservation biology** integrates several fields to conserve biological diversity
  - Ecology
  - Physiology
  - Molecular biology
  - Genetics
  - Evolutionary biology

Three Levels of Biodiversity

- Biodiversity can be considered at three main levels: genetic diversity, species diversity, and ecosystem diversity

Three Levels of Biodiversity



Genetic diversity in a vole population

Species diversity in a coastal redwood ecosystem

Community and ecosystem diversity across the landscape of an entire region

Genetic Diversity

- Genetic diversity comprises genetic variation within a population and between populations
- Population extinctions reduce genetic diversity, which in turn reduces the adaptive potential of the entire species

Species Diversity

- Species diversity is the number of species in an ecosystem or across the biosphere
- An **endangered species** is in danger of becoming extinct throughout all or much of its range
- A **threatened species** is likely to become endangered in the near future

Ecosystem Diversity

- Human activity is reducing ecosystem diversity, the variety of ecosystems in the biosphere
  - For example, more than 50% of wetlands in the contiguous United States have been drained and converted to agricultural or other use

Biodiversity and Human Welfare

- There are moral and philosophical reasons to care about the loss of biodiversity
  - Our sense of connection to nature (biophilia)
  - The belief that other species are entitled to life
  - Concern for future generations
- Species and genetic diversity also have many practical benefits

Ecosystem Services

- **Ecosystem services** encompass all the processes through which natural ecosystems help sustain human life
- Some examples of ecosystem services
  - Purification of air and water
  - Detoxification and decomposition of wastes
  - Crop pollination, pest control, and soil preservation
- Ecosystem services have an estimated value of $33 trillion per year but are provided for free

Threats to Biodiversity

- Most species loss can be traced to four major threats
  - Habitat loss.
    - Habitat destruction and fragmentation result from factors such as agriculture, urban development, forestry, mining, and pollution
  - Introduced species
    - **Introduced species** are those that humans move from native locations to new geographic regions
  - Overharvesting
    - Overharvesting is harvesting of wild organisms at rates exceeding the population's ability to rebound
  - Global change
    - Global change includes alterations in climate, atmospheric chemistry, and broad ecological systems

Concept 43.2: Population Conservation Focuses on Population Size, Genetic Diversity, and Critical Habitat

- Biologists focusing on conservation at the population and species levels follow two main approaches
  - The small-population approach
  - The declining-population approach

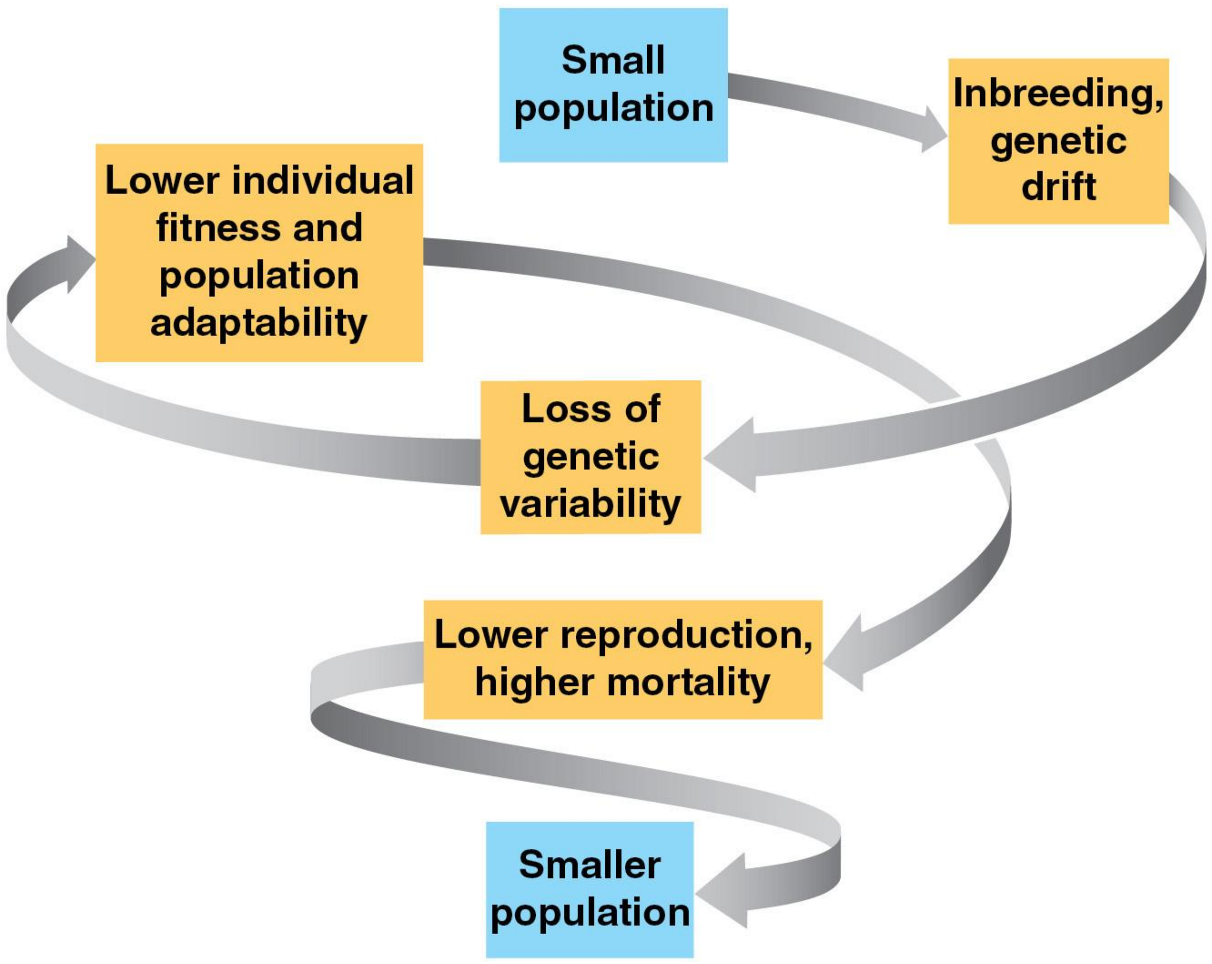
- Factors specific to small populations can cause extinctions once population sizes have been greatly reduced

The Extinction Vortex: Evolutionary Implications of Small Population Size

- A small population is prone to inbreeding and genetic drift, which draw it down an **extinction vortex** toward increasingly small population size
- A key factor driving the extinction vortex is loss of the genetic variation necessary to enable evolutionary responses to environmental change

Figure 43.11

Processes Driving an Extinction Vortex



Minimum Viable Population Size

- **Minimum viable population** (**MVP**) is the minimum population size at which a species can survive
- Estimates of MVP depend on many factors that affect a population's chances for survival
  - For example, the number of individuals likely to be killed in a natural catastrophe such as a storm
- A meaningful estimate of MVP requires determining the **effective population size**, which is based on the population's breeding potential
- Effective population size (N_e) $N_e = \dfrac{4N_f N_m}{N_f + N_m}$

N_f and N_m are, respectively, the number of females and the number of males that breed successfully

Critical Habitat and Population Decline

- A loss of critical habitat can cause a threatened or endangered population to show a downward trend, even if the population is far above its minimum viable population size
- A critical-habitat approach emphasizes the environmental factors that can cause a population decline

Weighing Conflicting Demands

- Conserving species often requires resolving conflicts between habitat needs of endangered species and human demands
    - For example, in the western United States, habitat preservation for many species is at odds with grazing and resource extraction industries

Landscape Structure and Biodiversity

- The physical structure of a landscape can strongly influence biodiversity
- Many species use more than one type of ecosystem or live in the borders between ecosystems

Fragmentation and Edges

- The boundaries, or edges, between ecosystems are defining features of landscapes
- Abiotic conditions in edges are distinct from those in the surrounding landscapes
- Some species take advantage of edge communities to access resources from both adjacent areas

Figure 43.16

Amazon Rain Forest Fragments Created as Part of the Biological Dynamics of Forest Fragments Project

Corridors That Connect Habitat Fragments

- A **movement corridor** is a narrow strip of habitat connecting otherwise isolated patches
- Movement corridors promote dispersal and reduce inbreeding
- Corridors can also have harmful effects, for example, promoting the spread of disease
- Artificial corridors can be constructed in areas of heavy human use

Figure 43.17

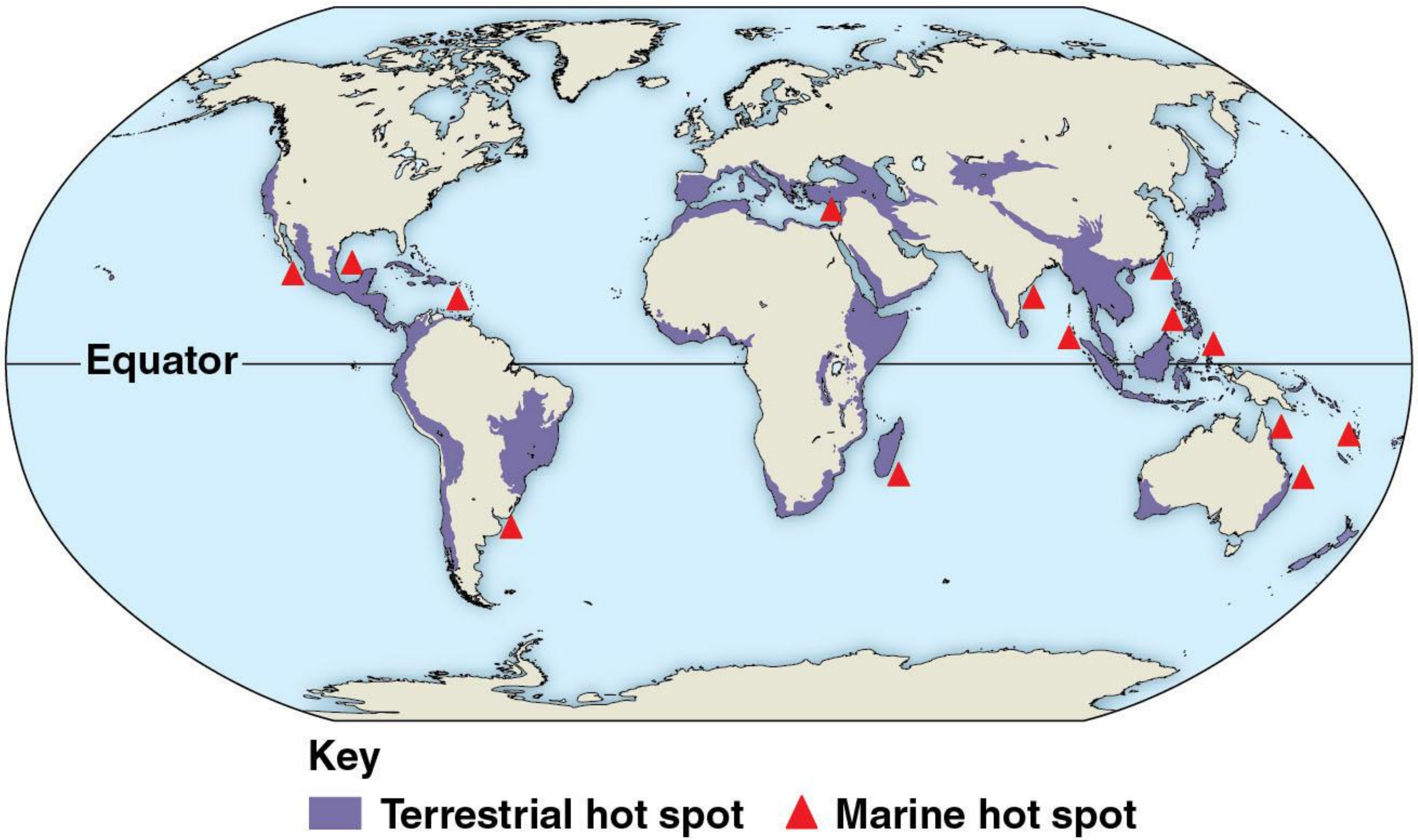
An Artificial Corridor

Establishing Protected Areas

- About 7% of the world’s land has been protected in various forms of reserves
- The design, placement, and management of protected areas are controversial topics in conservation biology

Preserving Biodiversity Hot Spots

- A **biodiversity hot spot** is a relatively small area with a great concentration of endemic species and many endangered and threatened species



Philosophy of Nature Reserves

- Nature reserves are protected “islands” of biodiversity in a sea of habitat altered or degraded by human activity
- Successful nature reserves allow natural disturbance to occur as a functional component of the ecosystem

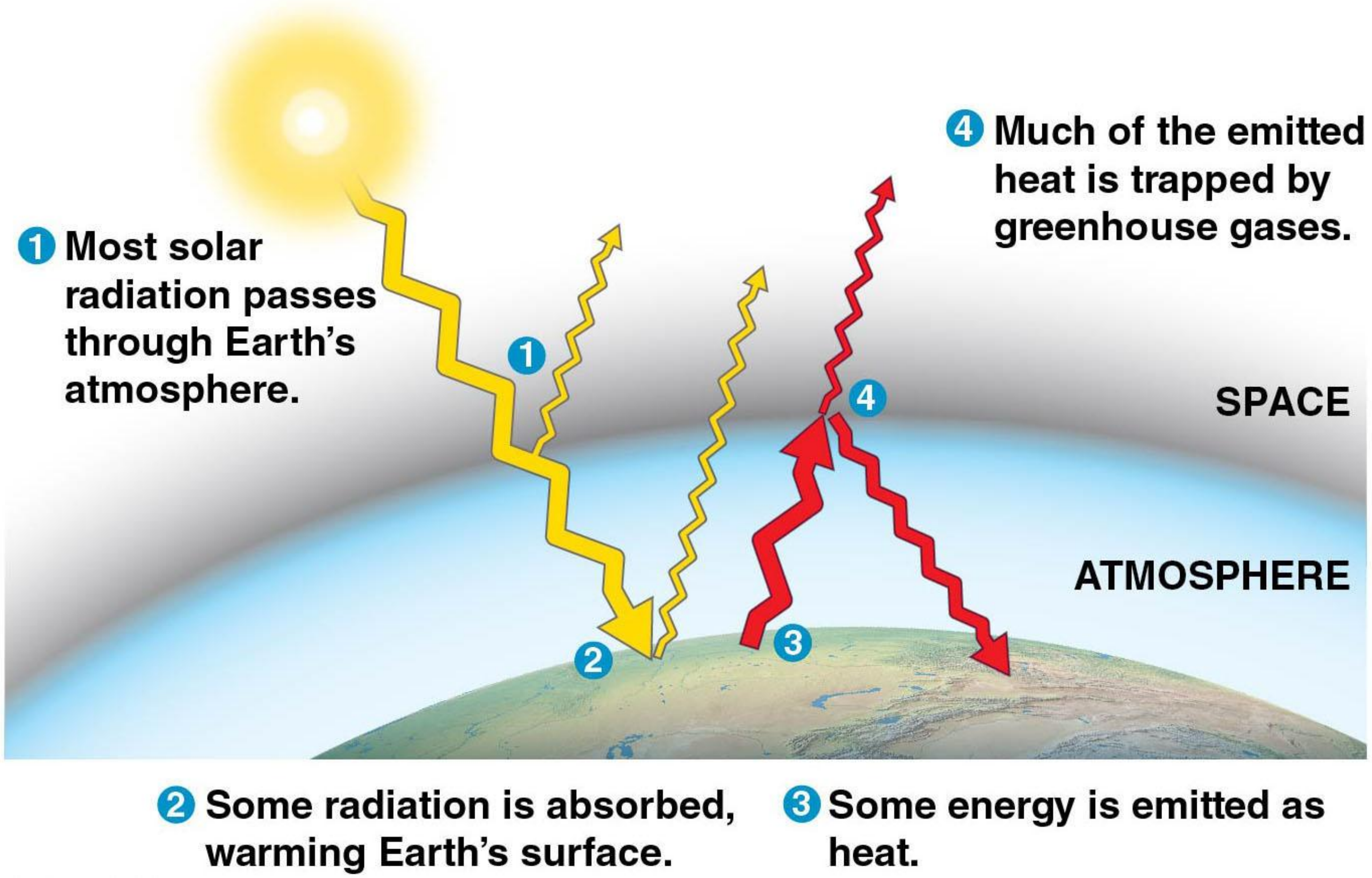
- A **zoned reserve** includes relatively undisturbed areas surrounded by human-modified areas of economic value

Concept 43.4: Earth is Changing Rapidly as a Result of Human Actions

- The locations of reserves today may be unsuitable for their species in the future
- Three types of environmental change that threaten biodiversity are
  - Nutrient enrichment
    - Human activities transport nutrients from one part of the biosphere to another
  - Accumulation of toxins
    - Humans release many toxic chemicals, including synthetics previously unknown in nature
  - Climate change
    - Changing concentrations of atmospheric CO_2 are correlated with **climate change**

Figure 43.26

The Greenhouse Effect



Biological Effects of Climate Change

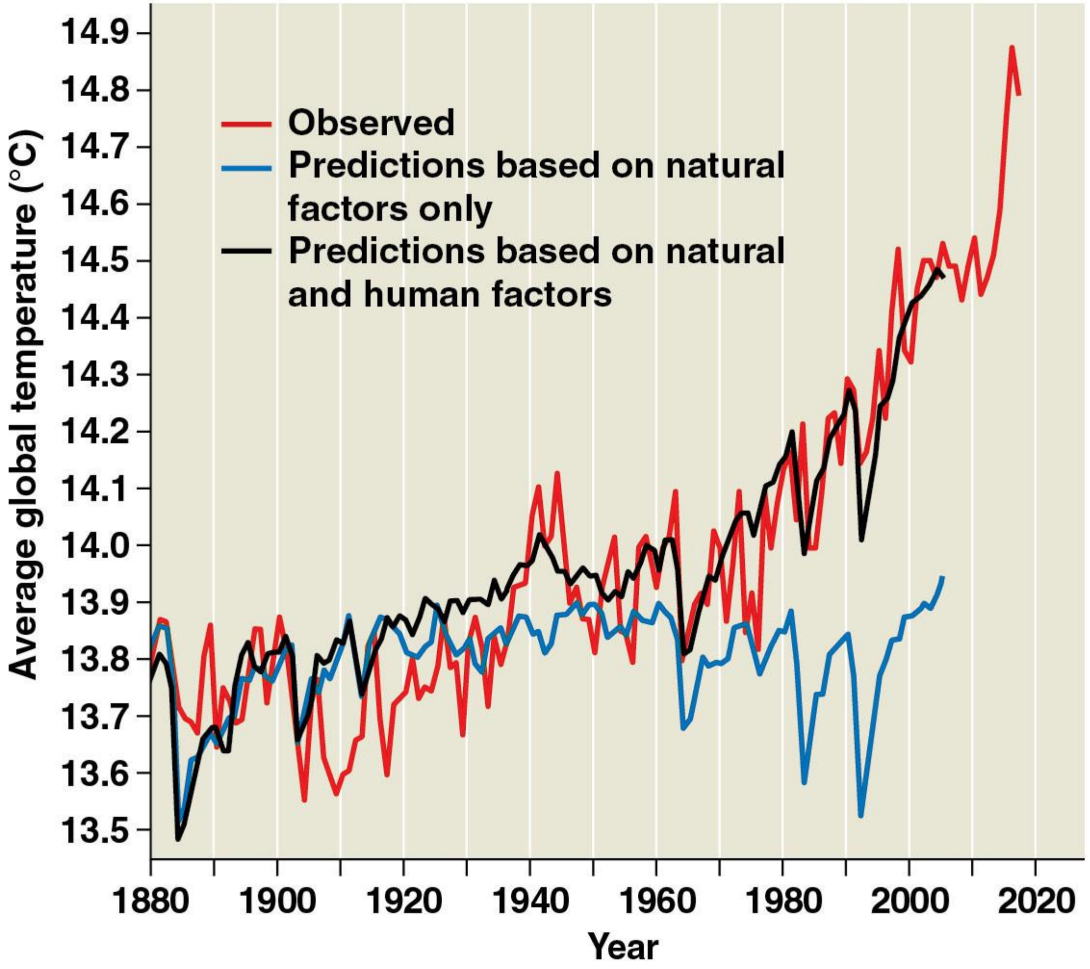
- Many organisms will not be able to disperse rapidly enough to survive climate change
- Examining changes in the fossil pollen record following the last ice age can help make predictions about future change
  - For example, the historical dispersal rate of the American beech will not be fast enough to keep pace with the warming climate

Modeling Climate Change

- Global models predict an additional 3°C (5°F) rise in temperature by the end of the 21st century
- The models are constructed using data on factors that affect surface absorption of solar radiation
- Natural factors affecting absorption include the 11-year solar cycle and volcanic explosions

Figure 43.28X

Factors contributing to rising global temperatures



Finding Solutions to Address Climate Change

- Global warming can be slowed by reducing energy consumption and converting to renewable energy
- Stabilizing CO_2 emissions will require international effort and changes in personal lifestyles and industrial processes
- Reduced deforestation would also decrease greenhouse gas emissions

Concept 43.5: The Human Population is No Longer Growing Exponentially but is Still Increasing Rapidly

- Global environmental problems arise from growing consumption and the increasing size of the human population
- No population can grow indefinitely, and humans are no exception

Global Carrying Capacity

- The most important ecological issue today is the future size of the human population
- How many humans can the biosphere support?

- The human carrying capacity of Earth is uncertain
- Estimates have varied from 1 billion to 1 trillion, with an average of 10–15 billion

Limits on Human Population Size

- The **ecological footprint** concept summarizes the aggregate land and water area needed to sustain a person, city, or nation
- It is one measure of how close we are to the carrying capacity of Earth
- Countries vary greatly in footprint size and available ecological capacity

Sustainable Development

- **Sustainable development** is development that meets the needs of people today without limiting the ability of future generations to meet their needs
- Connections between life sciences, social sciences, economics, and humanities must be made to achieve sustainable development

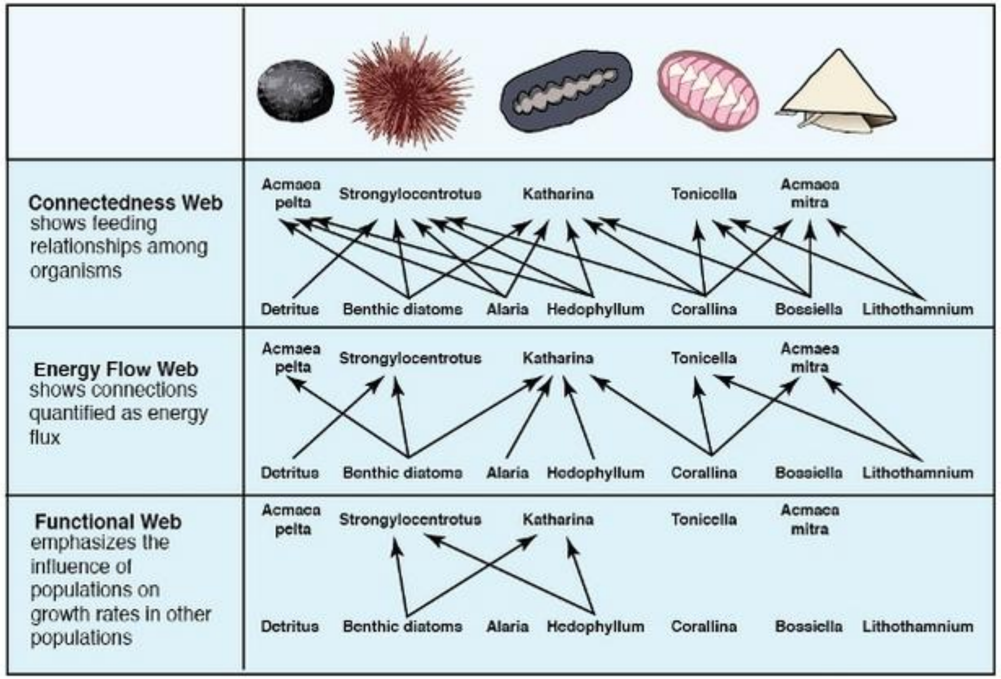
The Future of the Biosphere

- Our modern lives differ greatly from those of our hunter-gatherer ancestors
- Our behavior reflects remnants of our ancestral attachment to nature and the diversity of life—the concept of biophilia
- Our sense of connection to nature may motivate realignment of our environmental priorities

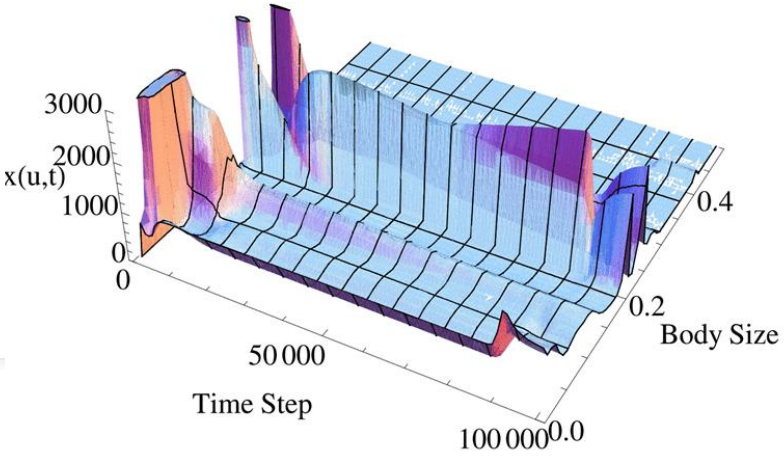
Computational

Modeling Ecosystems as Energy Flow Networks

- **Ecosystem as a Network -** An ecosystem can be viewed as a network where species (nodes) are connected by energy flows (edges) along food web links.
- **Energy Flow Dynamics -** The model focuses on both the fast dynamics of energy transfer between species and the slow evolution of the food web structure itself.
- **Simple Equation Approach: -** The paper introduces a reaction-diffusion equation to describe the co-evolution of energy flows and food web structure.
- Refence
  - J. Zhang, "Modeling Multi-species Interacting Ecosystem by a Simple Equation," *2009 International Joint Conference on Computational Sciences and Optimization*, Sanya, China, 2009, pp. 1003-1007, doi: 10.1109/CSO.2009.469.
  - https://ieeexplore.ieee.org/document/5193863



The Reaction-Diffusion Model



The evolution of biomass distribution on the body size space

- **Model Equation:**
  The model uses a reaction-diffusion equation that depends on the energy or biomass of species, local interactions (e.g., predation, growth), and the diffusion coefficient modeling energy flow between connected species.
- **Statistical Indicators:**
  - **Total System Throughflow (TST):** Measures the total energy flow in the system.
  - **Shannon Entropy:** Quantifies the diversity and complexity of the food web.
- **Simulation Results:**
  The model can simulate how energy distribution and food web structure change over time, revealing patterns such as stability, collapse, or reorganization.

Implications and Applications

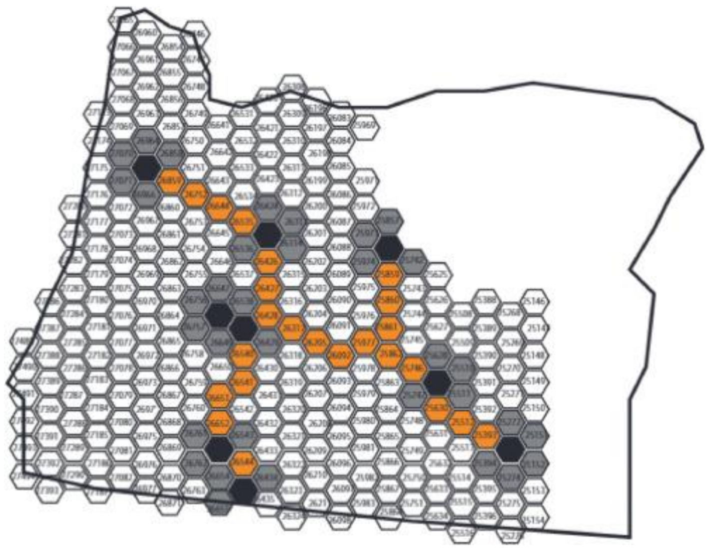
- **Understanding Ecosystem Stability:**
  The model helps explain how energy flow and network structure contribute to ecosystem stability or vulnerability.
- **Practical Applications:**
  - Predicting the impact of species removal or introduction.
  - Assessing the resilience of ecosystems to disturbances.
  - Informing conservation and management strategies.
- **Broader Impact:**
  This computational approach can be extended to other complex systems beyond ecology, such as social or technological networks.

Multi-Species Ecosystem Modeling in the Gulf of Mexico

- **Study Focus -** Development and application of a multi-species ecosystem model to evaluate the effects of fishing and environmental changes in the northern Gulf of Mexico.
- **Modeling Approach -** The model integrates biological, ecological, and environmental data to simulate interactions among multiple fish species and their responses to external pressures. This paper formulates spatial integer programming (set covering) models to protect both rare species (arbitrarily defined here as species breeding in 1% or less of the territory) and common species.
- To provide a tool for ecosystem-based fisheries management, supporting sustainable use and conservation of marine resources.
- Reference
  - Hamaide, Valentin, Bertrand Hamaide, and Justin C. Williams. "Nature reserve optimization with buffer zones and wildlife corridors for rare species." *Sustainability Analytics and Modeling* 2 (2022): 100003.
  - https://doi.org/10.1016/j.samod.2022.100003

Model Structure and Key Features

- **Model Components:**
  - **Species Groups:** Includes multiple fish species, invertebrates, and primary producers.
  - **Trophic Interactions:** Simulates predation, competition, and energy flow among species.
  - **Environmental Drivers:** Incorporates variables such as temperature, nutrient input, and fishing pressure.
- **Simulation Scenarios:**
  - Baseline (current conditions)
  - Increased fishing pressure
  - Environmental change (e.g., hypoxia events)
- **Outputs:**
  - Biomass trends for each species group
  - Changes in food web structure
  - Ecosystem indicators (e.g., trophic level, diversity)



Results, Implications, and Applications

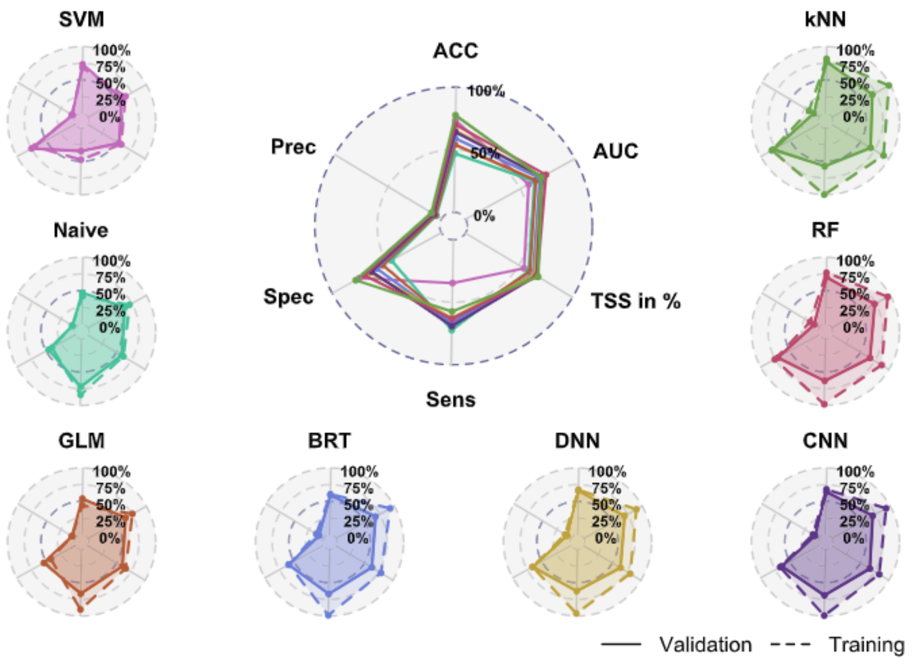
- **Key Findings:**
  - Fishing and environmental changes can have cascading effects throughout the ecosystem.
  - Some species are more sensitive to changes, leading to shifts in community structure and ecosystem function.
  - The model highlights trade-offs between fisheries yield and ecosystem health.
- **Management Applications:**
  - Supports ecosystem-based fisheries management (EBFM).
  - Helps predict outcomes of different management strategies and environmental scenarios.
  - Informs policy decisions for sustainable resource use.
- **Broader Impact:**
  - Demonstrates the value of computational ecosystem models in marine conservation and resource management.
  - Can be adapted to other regions and ecosystems.

Machine Learning for Wildlife Monitoring

- **Challenge in Ecology -** Camera traps generate millions of images, making manual species identification time-consuming and costly.
- **Machine Learning Solution -** Deep learning, especially convolutional neural networks (CNNs), can automate the classification of animal species in camera trap images.
- **Study Focus -** The paper demonstrates the use of machine learning to accurately classify multiple animal species from real-world camera trap datasets.
- Reference
  - Pichler, Maximilian, Virginie Boreux, Alexandra-Maria Klein, Matthias Schleuning, and Florian Hartig. "Machine learning algorithms to infer trait-matching and predict species interactions in ecological networks." *Methods in Ecology and Evolution* 11, no. 2 (2020): 281-293.
  - https://doi.org/10.1111/2041-210X.13329

Model Development and Performance

- **Model Used:**
  The study used a ResNet-18 convolutional neural network, trained on over 3 million labeled images from camera traps.
- **Training and Validation:**
  - Images were labeled by experts and citizen scientists.
  - The model was trained to recognize 27 different animal species/groups.
- **Results:**
  - Achieved over 97% accuracy in species classification.
  - Outperformed traditional manual and semi-automated methods in speed and scalability.



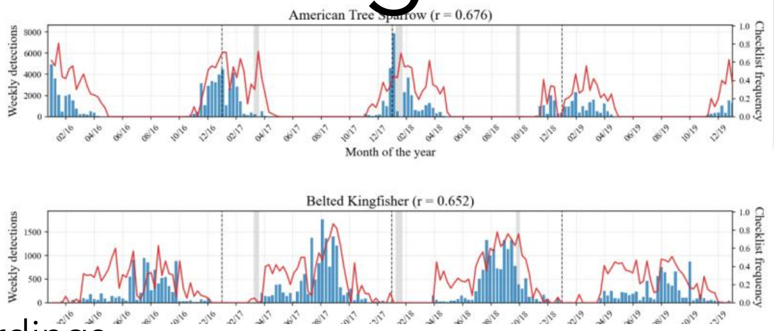
Implications and Applications in Ecology

- **Ecological Impact:**
  - Enables large-scale, real-time wildlife monitoring.
  - Facilitates studies on species distribution, abundance, and behavior.
- **Broader Applications:**
  - Can be adapted for other regions, species, and ecological questions.
  - Supports conservation efforts by providing rapid, accurate data.
- **Future Directions:**
  - Integrating ML models with citizen science platforms.
  - Expanding to video data and rare species detection.

BirdNET – Deep Learning for Avian Diversity Monitoring

- **Motivation -** Monitoring bird diversity is crucial for assessing ecosystem health and guiding conservation. Traditional methods (e.g., point counts) are labor-intensive and limited in scale.
- **BirdNET Solution** is a deep neural network (DNN) designed to identify 984 North American and European bird species from audio recordings, enabling large-scale, automated avian monitoring.
- **Technological Highlights:**
  - Based on a 157-layer ResNet architecture with over 27 million parameters.
  - Trained on nearly 1,000 bird and non-bird classes using millions of spectrograms.
  - Incorporates domain-specific data augmentation for robustness to noise and overlapping calls.
- Reference
  - Kahl, Stefan, Connor M. Wood, Maximilian Eibl, and Holger Klinck. "BirdNET: A deep learning solution for avian diversity monitoring." *Ecological Informatics* 61 (2021): 101236.
  - https://doi.org/10.1016/j.ecoinf.2021.101236
  - https://birdnet.cornell.edu/

Data, Model Architecture, and Training



- **Data Sources:**
  - Xeno-canto and Macaulay Library: Over 226,000 high-quality bird recordings.
  - Non-bird sounds (e.g., insects, human, environmental noise) included to reduce false positives.
  - Evaluation on both single-species (focal) and complex soundscape recordings.
- **Model Architecture:**
  - Input: 3-second mel-spectrograms (64 frequency bands × 384 time steps).
  - Wide ResNet with residual blocks, batch normalization, and ReLU activations.
  - Classification block outputs probabilities for all species and non-bird classes.
- **Training Strategies:**
  - Data augmentation: Frequency/time shifts, warping, and noise addition.
  - Mixup training: Combines multiple spectrograms to simulate overlapping calls.
  - Oversampling for rare species; knowledge distillation for improved performance.

Results, Applications, and Impact

- **Performance:**
  - Mean average precision (mAP) of 0.791 on single-species recordings.
  - F0.5 score of 0.414 on fully annotated soundscapes (real-world field data).
  - Detected seasonal and migratory patterns closely matching human observations (eBird data).
- **Applications:**
  - Enables efficient, large-scale monitoring of bird communities.
  - Supports conservation, biodiversity research, and environmental impact assessments.
  - Open-source and available for real-time analysis.
- **Broader Impact:**
  - Demonstrates the power of deep learning for ecological monitoring.
  - Can be adapted for other taxa and environmental sound recognition tasks.
  - Reduces manual labor and enables new scales of ecological research.