Chapter 55

Ecosystems and Restoration Ecology

Lecture Outline

Overview: Cool Ecosystem

- An **ecosystem** is the sum of all the organisms that live in a community as well as all the abiotic factors with which they interact.
    - An ecosystem can encompass a large area, such as a lake or forest, or a microcosm, such as the area under a fallen log or a desert spring.
    - Many ecologists view the entire biosphere as a global ecosytem.
- The dynamics of an ecosystem involve two processes that cannot be fully described by population or community phenomena: energy flow and chemical cycling.
- Energy enters most ecosystems in the form of sunlight, which is converted to chemical energy by autotrophs, passed to heterotrophs as food, and dissipated as heat.
- Chemical elements are cycled among the abiotic and biotic components of the ecosystem.
    - Photosynthetic and chemosynthetic organisms assimilate inorganic elements from air, soil, and water, and incorporate them into their biomass, some of which is consumed by animals.
    - The elements are returned in inorganic form to the environment by the metabolism of plants and animals and by organisms such as bacteria and fungi, which break down organic wastes and dead organisms.
- Because energy, unlike matter, cannot be recycled, an ecosystem requires a continuous influx of energy from an external source, usually the sun.
- Energy flows through ecosystems, whereas matter cycles within and through them.

Concept 55.1 Physical laws govern energy flow and chemical cycling in ecosystems

- Ecosystem ecologists study the transformations of energy and matter within ecosystems and the amounts of both that cross the system's boundaries.
- Species in a community are grouped into trophic levels of feeding relationships.

Ecosystems obey physical laws.

- The first law of thermodynamics states that energy cannot be created or destroyed but only transformed or transferred.
    - Plants and other photosynthetic organisms convert solar energy to chemical energy, but the total amount of energy does not change.

- The total amount of energy stored in organic molecules must equal the total solar energy intercepted by the plant, minus the amounts reflected and dissipated as heat.

- One area of ecosystem ecology computes such energy budgets and traces energy flow through ecosystems in order to understand the factors that control these energy transfers.
  - Transfers help determine how many organisms a habitat can support and the amount of food that humans can harvest from a site.
- The second law of thermodynamics states that every exchange of energy increases the entropy of the universe.
  - Some energy is lost as heat in any conversion process.
- The efficiency of ecological energy conversions can be measured.
- According to the **law of conservation of mass**, matter, like energy, cannot be created or destroyed.
  - Because mass is conserved, we can determine how much of an element cycles within an ecosystem or is gained or lost by that ecosystem over time.
- Unlike energy, chemical elements are continuously recycled within ecosystems.
  - A carbon or nitrogen atom moves from one trophic level to another and eventually to the decomposers and back again.
- Chemical elements can be gained or lost from a particular ecosystem.
  - Nutrients enter a forest ecosystem as dust or as solutes dissolved in rainwater or leached from rocks in the ground.
  - Nitrogen is also supplied through the biological process of nitrogen fixation.
  - In terms of losses, some elements return to the atmosphere as gases, and others are carried out of the ecosystem by moving water.
- Like organisms, ecosystems are open systems, absorbing energy and mass and releasing heat and waste products.
  - Most gains and losses are small compared to the amounts recycled within ecosystems.
- The balance between inputs and outputs determines whether an ecosystem is a source or a sink for an element.
  - If an element's outputs exceed its inputs, it will eventually limit production in that system.
- Human activities may change the balance of inputs and outputs considerably.

Trophic relationships determine the routes of energy flow and chemical cycling in ecosystems.

- Ecologists assign species to trophic levels on the basis of their main source of nutrition and energy.
- Autotrophs, the **primary producers** of the ecosystem, ultimately support all other organisms.
  - Most autotrophs are photosynthetic organisms that use light energy to synthesize sugars and other organic compounds.
  - Chemosynthetic prokaryotes are the primary producers in deep-sea hydrothermal vents and places deep under ground or ice.
- Heterotrophs in trophic levels above the primary producers depend on them for energy.
  - Herbivores that eat primary producers are called **primary consumers**.
  - Carnivores that eat herbivores are called **secondary consumers**.

- Carnivores that eat other carnivores are called **tertiary consumers**.

Decomposition connects all trophic levels.

- **Detritivores**, or **decomposers**, are heterotrophs that get energy from **detritus**, nonliving organic material such as the remains of dead organisms, feces, fallen leaves, and wood.
  - Many detritivores are in turn eaten by secondary and tertiary consumers.
- Two important groups of detritivores are prokaryotes and fungi, organisms that secrete enzymes that digest organic material and then absorb the breakdown products, linking the primary producers and consumers in an ecosystem.
- Detritivores recycle chemical elements back to primary producers.
  - Detritivores convert organic matter from all trophic levels to inorganic compounds usable by primary producers, which then recycle these elements into organic compounds.
- If decomposition stopped, all life on Earth would cease as detritus piled up and the supply of ingredients needed for to synthesize new organic matter was exhausted.

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

- In most ecosystems, the amount of light energy converted to chemical energy by autotrophs in a given time period is the ecosystem's **primary production**.
  - Chemoautotrophs use inorganic chemicals instead of sunlight as their energy source.

An ecosystem's energy budget depends on its primary production.

- Most primary producers use light energy to synthesize organic molecules, which are broken down to generate ATP.
  - The amount of photosynthetic production sets the spending limit of the entire ecosystem.
- A global energy budget can be analyzed.
- Each day, Earth's atmosphere is bombarded by approximately 10^{22} joules of solar radiation.
  - The intensity of solar energy striking Earth varies with latitude, with the tropics receiving the greatest input.
  - Most radiation is scattered, absorbed, or reflected by clouds and dust in the atmosphere.
- Much of the solar radiation that reaches Earth's surface lands on bare ground or ice.
  - Only a small fraction of this solar radiation actually strikes photosynthetic organisms.
  - Only certain wavelengths are absorbed by photosynthetic pigments; the rest is transmitted, reflected, or lost as heat.
- Approximately 1% of the visible light that reaches photosynthetic organisms is converted to chemical energy by photosynthesis.
- Despite this small amount, Earth's primary producers produce about 150 billion metric tons (1.5×10^{14} kg) of organic material per year.
- The total primary production in an ecosystem is known as **gross primary production (GPP)**, the amount of light energy converted to chemical energy by photosynthesis per unit time.
- Producers use some of these molecules as fuel in their own cellular respiration.

- **Net primary production (NPP)** is equal to gross primary production minus the energy used by the primary producers for autotrophic respiration (R_a): NPP = GPP − R_a
  - On average, NPP is about half of GPP.
- To ecologists, net primary production is the key measurement because it represents the stored chemical energy that is available to consumers in the ecosystem.
  - Net primary production can be expressed as energy per unit area per unit time ($J/m^2 \cdot yr$), or as biomass of vegetation added to the ecosystem per unit area per unit time ($g/m^2 \cdot yr$).
- An ecosystem's NPP should not be confused with the *total* biomass of photosynthetic autotrophs present in a given time, which is called the *standing crop*.
  - Net primary production is the amount of *new* biomass added in a given period of time.
  - Although a forest has a large standing crop, its primary production may be less than that of grasslands, which do not accumulate as much biomass because animals consume the plants rapidly and because grasses and herbs decompose more quickly than trees do.
- Different ecosystems vary greatly in their net primary production.
  - Tropical rain forests are among the most productive terrestrial ecosystems and contribute a large portion of Earth's overall net primary production.
  - Estuaries and coral reefs have very high net primary production, but they cover only about one-tenth the area covered by tropical rain forests.
  - The open ocean is relatively unproductive but contributes as much global net primary production as terrestrial systems because of its vast size.
- **Net ecosystem production (NEP)** is a measure of the total biomass accumulation over time.
  - Net ecosystem production is defined as gross primary production minus the total respiration of all organisms in the system (R_T): NEP = GPP – R_T
  - The value of NEP determines whether an ecosystem gains or loses carbon through time.
  - A forest with a positive NPP may still lose carbon if heterotrophs release it as CO_2 more quickly than primary producers incorporate it into organic compounds.
- NEP can be estimated by measuring the net flux of CO_2 or O_2 entering or leaving the ecosystem.
  - If more CO_2 enters than leaves, the system is storing carbon.
  - Because O_2 release is directly coupled to photosynthesis and respiration, a system that is giving off O_2 is also storing carbon.
  - On land, ecologists typically measure only the net flux of CO_2 from ecosystems; detecting small changes in O_2 amidst a large atmospheric O_2 pool is difficult.
- Marine research shows high NEP in large areas of nutrient-poor waters, causing biologists to reevaluate estimates of ocean productivity.

In aquatic ecosystems, light and nutrients limit primary production.

- What limits production in ecosystems? What factors could we change to increase or decrease primary production for a given ecosystem?
- Light is a key variable controlling primary production in oceans and lakes because solar radiation can penetrate to only a certain depth known as the photic zone.
  - The first 15 m of water absorbs more than half of the solar radiation.
  - Even in "clear" water, only 5–10% of the radiation may reach a depth of 75 m.

- If light were the main variable limiting primary production in the ocean, we would expect production to increase along a gradient from the poles toward the equator, which receives the greatest intensity of light.
    - There is no such gradient. Some parts of the ocean in the tropics and subtropics exhibit low primary production, while some high-latitude ocean regions are relatively productive.
- More than light, nutrients limit primary production in most oceans and lakes.
- A **limiting nutrient** is an element that must be added for production to increase in a particular area.
    - The nutrient that most often limits marine production is either nitrogen or phosphorus.
    - Levels of these nutrients are very low in the photic zone because they are rapidly taken up by phytoplankton and because detritus tends to sink.
    - Nutrient levels are higher in deeper water, where light does not penetrate.
- Nutrient enrichment experiments confirmed that nitrogen is limiting phytoplankton growth off the south shore of Long Island, New York.
    - This knowledge can be used to prevent algal blooms by limiting nitrogen runoff that fertilizes phytoplankton.
    - Eliminating phosphates from sewage will not solve the problem unless nitrogen pollution is also controlled.
- Some areas of the ocean have low phytoplankton density despite relatively high nitrogen concentrations.
    - For example, the Sargasso Sea has a very low density of phytoplankton.
    - Nutrient-enrichment experiments showed that iron availability limits primary production in this area.
    - Windblown dust from the land, the main input of iron to the ocean, is scarce here.
- Marine ecologists carried out large-scale ocean-fertilization experiments in the Pacific Ocean, spreading low concentrations of dissolved iron over 72 km^2 of ocean and measuring the change in phytoplankton density over a seven-day period.
    - A massive phytoplankton bloom occurred, with increased chlorophyll concentration in water samples from test sites.
    - Adding iron stimulates the growth of cyanobacteria that fix atmospheric nitrogen, and the extra nitrogen stimulates the proliferation of phytoplankton.
- Iron fertilization is unlikely to be widely applied anytime soon.
    - There is little evidence that organic carbon sinks into deep-ocean water and sediments.
    - It tends to be recycled by secondary consumers and decomposers in shallow waters, returning eventually to the atmosphere.
    - The overall effects of large-scale fertilization on marine communities are uncertain.
- In areas of upwelling, deep nutrient-rich waters circulate to the ocean surface.
- These areas have exceptionally high primary production, supporting the hypothesis that nutrient availability determines marine primary production.
    - Because upwelling stimulates growth of phytoplankton that form the base of marine food webs, upwelling areas support productive, diverse ecosystems with many fish.
    - The largest areas of upwelling occur in the Southern Ocean (also called the Antarctic Ocean) and the coastal waters off Peru, California, and parts of western Africa.
- Nutrient limitation is also common in freshwater lakes.

- Sewage and fertilizer runoff from farms and lawns adds large amounts of nutrients to lakes.
  - Cyanobacteria and algae grow rapidly in response to these added nutrients, reducing oxygen concentrations and visibility in the water.
  - This process, called **eutrophication**, has a wide range of ecological impacts, including the loss of many fish species.
- A series of whole-lake experiments identified phosphorus as the nutrient that limited cyanobacterial growth.
  - This research led to the use of phosphate-free detergents and other water quality reforms.

In terrestrial ecosystems, temperature and moisture are key factors limiting primary production.

- Tropical rain forests, with warm, wet conditions, are the most productive of all terrestrial ecosystems.
  - Low-productivity ecosystems are generally dry (deserts) or dry and cold (arctic tundra).
  - Temperate forest and grassland ecosystems have moderate climates and intermediate productivity.
- Several climate variables are useful for predicting NPP in terrestrial ecosystems.
  - NPP increases with annual precipitation.
  - *Actual evapotranspiration*, the total amount of water transpired by plants and evaporated from a landscape, is a useful predictor of NPP.
  - Actual evapotranspiration increases with precipitation, temperature, and the amount of solar energy available to drive evaporation and transpiration.
- Mineral nutrients in the soil also limit primary production in terrestrial ecosystems.
  - Nitrogen and phosphorus are the most common limiting nutrients.
  - Nitrogen most often limits plant growth globally.
  - Phosphorus limitations are common in older soils (where phosphate molecules have been leached away by water) and in high pH desert soils (where phosphorus precipitates in forms that are unavailable to plants).
- Adding a nonlimiting nutrient, even one that is scarce, will not stimulate production.
  - Adding more of a limiting nutrient increases production until another nutrient becomes limiting.
- Various adaptations increase plant uptake of limiting nutrients.
  - Some plants have a mutualistic relationship with nitrogen fixing prokaryotes.
  - Mycorrhizal associations between plant roots and fungi supply phosphorus and other limiting elements to plants.
- Plants roots have root hairs that increase their surface area and release enzymes and other substances into the soil to increase availability of limiting nutrients.
  - Phosphatases cleave a phosphate group from larger molecules.
  - Chelating agents make micronutrients such as iron more soluble in the soil.
- Studies relating nutrients to terrestrial primary production have practical applications in agriculture.
  - Farmers maximize crop yields by using fertilizers with the right balance of nutrients for the local soil and type of crop.

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

- The amount of chemical energy in consumers' food that is converted to their own new biomass during a given time period is called the **secondary production** of an ecosystem.
  - Globally, herbivores eat only one sixth of total plant production. In addition, herbivores cannot digest all the plant material that they *do* eat.
  - The vast majority of an ecosystem's production is eventually consumed by detritivores.
- We can measure the efficiency of animals as energy transformers with this equation:
  - Production efficiency = Net secondary production × 100% / Assimilation of primary production
- Net secondary production is the energy stored in biomass represented by growth and reproduction.
  - Assimilation is the total energy taken in, not lost as feces, that is used for growth, reproduction, and respiration.
- **Production efficiency** is the percentage of food energy that is *not* used for respiration.

Production efficiencies differ among organisms.

- Birds and mammals typically have low production efficiencies of 1–3% because they use so much energy to maintain a constant body temperature.
  - Fishes, which are ectotherms, have production efficiencies of around 10%.
  - Insects and microorganisms are even more efficient, with production efficiencies averaging 40%.
- **Trophic efficiency** is the percentage of production transferred from one trophic level to the next.
  - Trophic efficiencies are always less than production efficiencies because they include energy lost through respiration and contained in feces and also the energy in organic material at lower trophic levels that is not consumed.
- Trophic efficiencies are generally about 10% and range from approximately 5% to 20%, depending on the type of ecosystem.
  - 90% of the energy available at one trophic level is typically *not* transferred to the next.
- This loss is multiplied over the length of a food chain.
  - If 10% of energy is transferred from primary producers to primary consumers, and 10% of that energy is transferred to secondary consumers, then only 1% of net primary production is available to secondary consumers.

The progressive loss of energy along a food chain limits the abundance of top-level carnivores.

- Only about 0.1% of the chemical energy fixed by photosynthesis can flow all the way through a food web to a tertiary consumer, such as a snake or a shark.
- This limits most food webs to four or five trophic levels.
- *Pyramids of net production* represent the multiplicative loss of energy in a food chain.
  - The width of each tier in the pyramid is proportional to the net production of each trophic level, expressed in joules.
  - The highest level, which represents top-level predators, contains few individuals.

- Because populations of top predators are typically small and the animals may be widely spaced within their habitats, many predator species are highly susceptible to extinction.

- *Biomass pyramids* represent the ecological consequences of low trophic efficiencies.
    - Each tier represents standing crop (total dry mass of all organisms) in one trophic level.
    - Most biomass pyramids narrow sharply from primary producers to top-level carnivores because energy transfers are so inefficient.
- In some aquatic ecosystems, the biomass pyramid is inverted and primary consumers outweigh producers.
    - Inverted biomass pyramids occur because producers (phytoplankton) grow, reproduce, and are consumed by zooplankton too rapidly to develop a large standing crop.
    - Phytoplankton have a short **turnover time**, with a small standing crop biomass compared to production: Turnover time = Standing crop biomass (g/m^2) / Production ($g/m^2 \cdot day$)
- Because phytoplankton replace their biomass at such a rapid rate, they can support a biomass of zooplankton much greater than their own biomass.
    - However, the pyramid of *production* for this ecosystem is still bottom-heavy.
- The dynamics of energy flow through ecosystems have important implications for humans.
    - Eating meat is an inefficient way of tapping photosynthetic production.
    - Worldwide agriculture could feed many more people if all humans fed as primary consumers, eating plant material.
- Estimates of Earth's human carrying capacity depend greatly on our diet and on the amount of resources each of us consumes.

Concept 55.4 Biological and geochemical processes cycle nutrients and water in ecosystems

- Because chemical elements are available to ecosystems in only limited amounts, life on Earth depends on the recycling of essential chemical elements.

Biogeochemical cycles involve both biotic and abiotic components of ecosystems.

- Human activities increasingly alter biogeochemical cycles.
- There are two general categories of **biogeochemical cycles:** global and local.
- Gaseous forms of carbon, oxygen, sulfur, and nitrogen occur in the atmosphere, and cycles of these elements are global.
    - For example, carbon and oxygen atoms a plant acquires from the air as CO_2 may have been released into the atmosphere by the respiration of an organism in a distant locale.
- Elements such as phosphorus, potassium, and calcium are too heavy to occur as gases, although they are transported in dust.
    - In terrestrial ecosystems, these elements cycle locally, absorbed from the soil by plant roots and returned to the soil by decomposers.
    - In aquatic systems, they cycle more broadly as dissolved forms carried in currents.
- We will consider a general model of chemical cycling that includes the main reservoirs of elements and the processes that transfer elements between reservoirs.

- Each reservoir is defined by two characteristics: whether it contains organic or inorganic materials and whether or not the materials are directly available for use by organisms.
- Reservoir A includes the nutrients in living organisms and in detritus.
  - These nutrients are available to other organisms when consumers feed and when detritivores consume nonliving organic material.
- Reservoir B includes materials that move to the fossilized organic reservoir as dead organisms and are buried by sedimentation over millions of years.
  - Some fossilized organisms become coal, oil, or peat.
  - Nutrients in fossilized deposits cannot be assimilated directly.
- Reservoir C includes inorganic elements and compounds that are dissolved in water or present in soil or air.
  - These materials are available for use by organisms and returned to the reservoir through relatively rapid processes of cellular respiration, excretion, and decomposition.
- Reservoir D includes inorganic elements present in rocks.
  - These nutrients are not directly available for use by organisms, but may gradually become available through erosion and weathering.
- Unavailable organic materials move into the available reservoir of inorganic nutrients when fossil fuels are burned, releasing exhaust into the atmosphere.
- Ecologists study chemical cycling by adding tiny amounts of radioactive isotopes to the elements they are tracing and by following the movement of naturally occurring stable, nonradioactive isotopes through the various biotic and abiotic components of an ecosystem.

There are several important biogeochemical cycles.

- We will consider the cycling of water, carbon, nitrogen, and phosphorus.

The water cycle

- **Biological importance:** Water is essential to all organisms, and its availability influences the rates of ecosystem processes.
- **Biologically available forms:** Liquid water is the primary form in which water is used.
- **Reservoirs:**
  - The oceans contain 97% of the water in the biosphere.
  - Two percent is bound as ice.
  - One percent is in lakes, rivers, and groundwater.
  - A negligible amount is in the atmosphere.
- **Key processes:**
  - The main processes driving the water cycle are evaporation of liquid water by solar energy, condensation of water vapor into clouds, and precipitation.
  - Transpiration by terrestrial plants moves significant amounts of water.
  - Surface and groundwater flow returns water to the oceans.

The carbon cycle

- **Biological importance:** Organic molecules have a carbon framework.

- **Biologically available forms:** Autotrophs convert carbon dioxide to organic molecules that are used by heterotrophs.
- **Reservoirs:** The major reservoirs of carbon are fossil fuels, soils, aquatic sediments, the oceans, plant and animal biomass, and the atmosphere (CO_2).
- **Key processes:**
  - Photosynthesis by plants and phytoplankton fixes atmospheric CO_2.
  - CO_2 is added to the atmosphere by cellular respiration of producers and consumers.
  - Volcanoes and the burning of fossil fuels add CO_2 to the atmosphere.

The nitrogen cycle

- **Biological importance:** Nitrogen is a component of amino acids, proteins, and nucleic acids.
  - Nitrogen may be a limiting plant nutrient.
- **Biologically available forms:**
  - Plants and algae can use ammonium (NH_4^+) or nitrate (NO_3^-).
  - Various bacteria can use NH_4^+, NO_3^-, or NO_2.
  - Animals can use only organic forms of nitrogen.
- **Reservoirs:**
  - The major reservoir of nitrogen is the atmosphere, which is 80% nitrogen gas (N_2).
  - Nitrogen is also bound in soils and the sediments of lakes, rivers, and oceans.
  - Some nitrogen is dissolved in surface water and groundwater.
  - Nitrogen is stored in living biomass.
- **Key processes:**
  - Nitrogen enters ecosystems primarily through bacterial nitrogen fixation.
  - Some nitrogen is fixed by lightning and industrial fertilizer production.
  - *Ammonification* by bacteria decomposes organic nitrogen.
  - In *nitrification,* bacteria convert NH_4^+ to NO_3^-.
  - In *denitrification,* bacteria use NO_3^- for metabolism instead of O_2, thus releasing N_2.

The phosphorus cycle

- **Biological importance:** Phosphorus is a component of nucleic acids, phospholipids, and ATP and other energy-storing molecules.
  - Phosphorus is a mineral constituent of bones and teeth.
- **Biologically available forms:** The only biologically important inorganic form of phosphorus is phosphate (PO_4^{3-}), which plants absorb and use to synthesize organic compounds.
- **Reservoirs:**
  - The major reservoir of phosphorus is sedimentary rocks of marine origin.
  - There are also large quantities of phosphorus in soils, dissolved in the oceans, and in organisms.
- **Key processes:**
  - Weathering of rocks gradually adds phosphate to soil.
  - Some phosphate leaches into groundwater and surface water and moves to the sea.
  - Phosphate may be taken up by producers and incorporated into organic material.

- Phosphate is returned to soil or water through decomposition of biomass or excretion by consumers.

Decomposition rates largely determine the rates of nutrient cycling.

- The rates at which nutrients cycle in different ecosystems are extremely variable as a result of variable rates of **decomposition**.
- Decomposition is controlled by the same factors that limit primary production in aquatic and terrestrial ecosystems: temperature, moisture, and nutrient availability.
  - Decomposition takes an average of four to six years in temperate forests, whereas in tropical rain forests, most organic material decomposes in a few months to a few years.
  - The difference is largely due to the warmer temperatures and more abundant precipitation in tropical rain forests.
- In tropical rain forests, relatively little organic material accumulates as leaf litter on the forest floor. The woody trunks of trees contain 75% of the nutrients and the soil contains only 10%.
  - The relatively low concentrations of some nutrients in the soil of tropical rain forests result from a short cycling time, not from a lack of these elements in the ecosystem.
- In temperate forests, with slower decomposition, soil may contain 50% of organic material.
  - Nutrients remain in temperate forest detritus and soil for a long time before plants assimilate them.
- Decomposition on land slows when conditions are too dry for decomposers to thrive or too wet to supply them with enough oxygen.
  - Ecosystems that are both cold and wet, such as peatlands, store much organic matter.
  - Decomposers grow poorly year-round, and net primary production greatly exceeds decomposition.
- In aquatic ecosystems, decomposition in anaerobic muds can take 50 years or longer.
  - Algae and aquatic plants usually assimilate nutrients directly from the water, and aquatic sediments may constitute a nutrient sink.
  - Mixing of the bottom and surface layers of water increases aquatic productivity.

Nutrient cycling is strongly regulated by vegetation.

- Since 1963, researchers have been studying nutrient cycling at the Hubbard Brook Experimental Forest in the White Mountains of New Hampshire.
  - The research site is a deciduous forest with several valleys, each drained by a small creek that is a tributary of Hubbard Brook.
  - Bedrock impenetrable to water is close to the surface of the soil, and each valley constitutes a watershed that can drain only through its creek.
- The research team first determined the mineral budget for each valley by measuring the input and outflow of several key nutrients.
  - They collected rainfall at several sites to measure the amount of water and dissolved minerals added to the ecosystem.
  - To monitor the loss of water and minerals, they constructed a small concrete dam with a V-shaped spillway across the creek at the bottom of each valley.
  - About 60% of the water added to the ecosystem as rainfall and snow exits through the stream, and the remaining 40% is lost by evapotranspiration.
- Preliminary studies confirmed that internal cycling conserves most of the mineral nutrients.

- Only about 0.3% more calcium (Ca^{2+}) left a valley via its creek than was added by rainwater. This net loss is probably replaced by chemical decomposition of the bedrock.
- During most years, the forest actually registered small net gains of a few mineral nutrients, including nitrogen.

- Experimental deforestation of a watershed dramatically increased the flow of water and minerals leaving the watershed.
  - Water runoff from the deforested watershed was 30–40% greater than in a control watershed, because there were no plants to absorb and transpire water from the soil.
- Net losses of minerals from the altered watershed were huge.
  - The concentration of Ca^{2+} in the creek increased fourfold, for example, and the concentration of K^+ increased by a factor of 15.
  - Nitrate concentrations in the creek increased 60-fold, reaching levels considered unsafe for drinking water.
- This study demonstrates that the amount of nutrients leaving an intact forest ecosystem is controlled mainly by the plants.
  - Retaining nutrients in ecosystems maintains the productivity of the systems and reduces problems cause by excess nutrient runoff.

Concept 55.5 Restoration ecology restores degraded ecosystems to a more natural state

- Ecosystems can recover naturally from most disturbances, although recovery may take centuries.
  - Tropical areas cleared for farming become unproductive because of nutrient losses.
  - Lands abandoned after mining activities are often in a degraded state.
  - Ecosystems are damaged by salts that build up in soils from irrigation and by releases of toxic chemicals or oil spills.

Restoration ecology seeks to initiate or speed up the recovery of degraded ecosystems.

- The basic assumption of restoration ecology is that some environmental damage is reversible.
  - However, ecosystems are not infinitely resilient.
- Restoration ecologists work to identify and manipulate the processes that limit the speed of recovery of ecosystems from disturbances.
- In extreme cases, the physical structure of an ecosystem may need restoration before biological restoration can occur.
  - If a stream was straightened, restoration ecologists may reconstruct a meandering channel to slow down the flow of water eroding the stream bank.
  - To restore an open-pit mine, engineers first grade the site with heavy equipment to reestablish a gentle slope, spreading topsoil when the slope is in place.
- Two key strategies in biological restoration are bioremediation and biological augmentation.
- The use of organisms to detoxify polluted ecosystems is known as **bioremediation**.
  - Some plants and lichens adapted to soils containing heavy metals can accumulate high concentrations of potentially toxic metals such as zinc, nickel, lead, and cadmium in their tissues.

- For instance, researchers in the United Kingdom discovered a lichen species that grows on soil polluted with uranium dust left over from mining.
- The lichen concentrates uranium in a dark pigment, making it useful as a biological monitor and potentially as a remediator.

- Scientists have sequenced the genomes of ten prokaryotic species specifically for their bioremediation potential.
- The bacterium *Shewanella oneidensis* can metabolize a dozen elements under aerobic and anaerobic conditions.
    - It converts soluble uranium, chromium, and nitrogen to insoluble forms that are unlikely to leach into streams or groundwater.
- While bioremediation is a strategy for removing harmful substances from an ecosystem, **biological augmentation** uses organisms to *add* essential materials to a degraded ecosystem.
- To augment ecosystem processes, restoration ecologists need to determine which factors, such as chemical nutrients, have been lost from a system and are limiting its recovery.
- Encouraging the growth of plants that thrive in nutrient-poor soils often speeds up succession and ecosystem recovery.
    - In alpine ecosystems of the western United States, nitrogen-fixing herbs such as lupines increase nitrogen concentrations in soils disturbed by mining and other uses.
    - Once these plants become established, other native species are better able to survive.
    - Ecologists restoring a tallgrass prairie in Minnesota enhanced the recovery of native species by adding mycorrhizal symbionts to the soil they seeded.
- Because animals aid critical ecosystem services, including pollination, seed dispersal, and herbivory, restoration ecologists sometimes help wildlife reach and use restored ecosystems.
    - They might release animals at a site or establish habitat corridors that connect a restored site to other places where the animals are found.
    - They sometimes establish artificial perches for birds or dig burrows for other animals to use at the site.
- Restoration ecology is a relatively new discipline and ecosystems are complex.
    - Many restoration ecologists advocate adaptive management: experimenting with several promising types of management to learn what works best.
- The long-term objective of restoration is to return an ecosystem as much as possible to its predisturbance state.