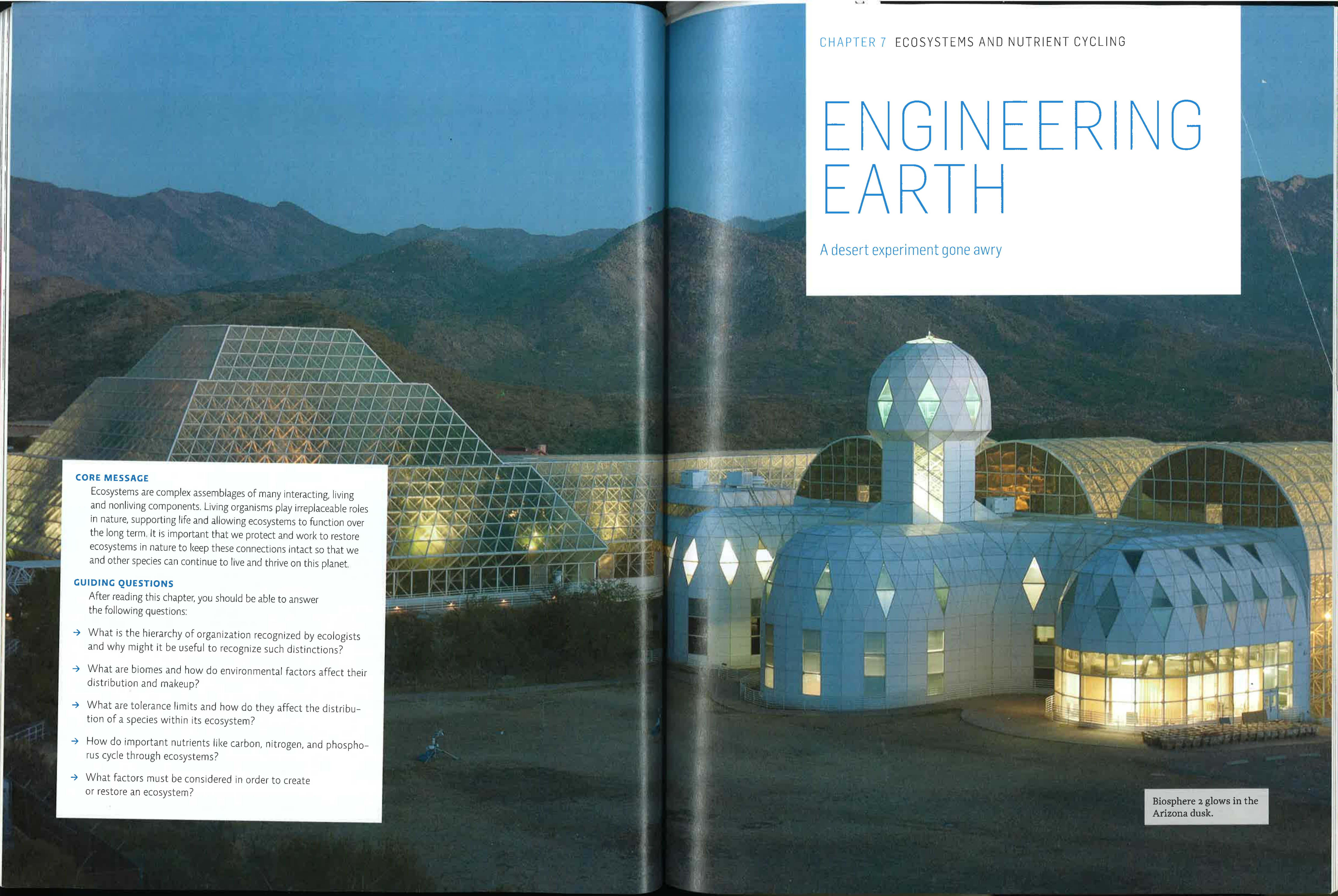
CHAPTER 7 ECOSYSTEMS AND NUTRIENT CYCLING

ENGINEERING EARTH

A desert experiment gone awry



Biosphere 2 glows in the Arizona dusk.

CORE MESSAGE

Ecosystems are complex assemblages of many interacting, living and nonliving components. Living organisms play irreplaceable roles in nature, supporting life and allowing ecosystems to function over the long term. It is important that we protect and work to restore ecosystems in nature to keep these connections intact so that we and other species can continue to live and thrive on this planet.

GUIDING QUESTIONS

After reading this chapter, you should be able to answer the following questions:

- What is the hierarchy of organization recognized by ecologists and why might it be useful to recognize such distinctions?
- What are biomes and how do environmental factors affect their distribution and makeup?
- What are tolerance limits and how do they affect the distribution of a species within its ecosystem?
- How do important nutrients like carbon, nitrogen, and phosphorus cycle through ecosystems?
- What factors must be considered in order to create or restore an ecosystem?

On September 26, 1993, with their first mission complete, four men and four women emerged from Biosphere 2—a hulking dome of custom-made glass and steel—back into the Arizona desert, where throngs of spectators stood cheering. They had been sealed inside the facility, along with 3,000 other plant and animal species, for exactly 2 years and 20 minutes; it was the longest anyone had ever survived in an enclosed structure.

The feat was part of a grand experiment, the goals of which were twofold. First, scientists wanted to prove that an entirely self-contained, humanmade system—the kind they might one day use to colonize the Moon or Mars—could sustain life. Second, they hoped that by studying this mini-earth, which could be controlled and manipulated in ways the real Earth could not, they might better understand our own planet's delicate balance and how best to protect it.

Despite the fanfare surrounding the biospherians' emergence, it was tough to say whether the mission had been a success or a failure. More than one-third of the flora and fauna had become extinct, including most of the vertebrates and all of the pollinating insects. Morning glory vines had overrun other plants, including food crops. Cockroaches and "crazy ants" were thriving. Too little wind had prevented trees from developing stress wood—wood that grows in response to mechanical stress and helps trunks and branches shift into an optimal position; without stress wood, the trees were brittle and prone to collapse. And too many sweet potatoes had turned the biospherians themselves bright orange (a string of plant diseases had decimated other crops).

◉WHERE IS BIOSPHERE 2?

On top of that, nitrous oxide (laughing gas) had grown concentrated enough to "reduce vitamin B12 synthesis to a level that could impair or damage the brain," according to one interim report. And oxygen levels had plummeted from 21% (roughly the same as Earth's atmosphere) to 14% (just barely enough to sustain human life). To fix this, project engineers had been forced to pump in 600,000 cubic feet of outside air, violating the facility's sanctity as a closed system.

Worst of all, missteps and course corrections had been mired in secrecy—each one leaked to the press only months after the fact. Rumors had begun to circulate that the eight people sealed inside—not to mention the ones they took their orders from—were more interested in creating a futuristic utopia than in conducting rigorous scientific research. As evidence for this theory mounted, the scientific community grew suspicious. Was Biosphere 2 legitimate science, a publicity stunt, or some bizarre mix of the two?

To be sure, the eight biospherians had survived, and many experts agreed that in principle at least, the facility still held enormous potential as a scientific tool. But before that potential could be realized, the scientific community and the public at large would need to know exactly what had happened inside the desert dome.

To answer that question, we need to answer a few others first: What exactly is a biosphere, and just how did Biosphere 2's creators set about building one?

Organisms and their habitats form complex systems.

The term **biosphere** refers to the total area on Earth where living things are found—the sum total of all its ecosystems. An **ecosystem** includes all the organisms in a given area plus the nonliving components of the

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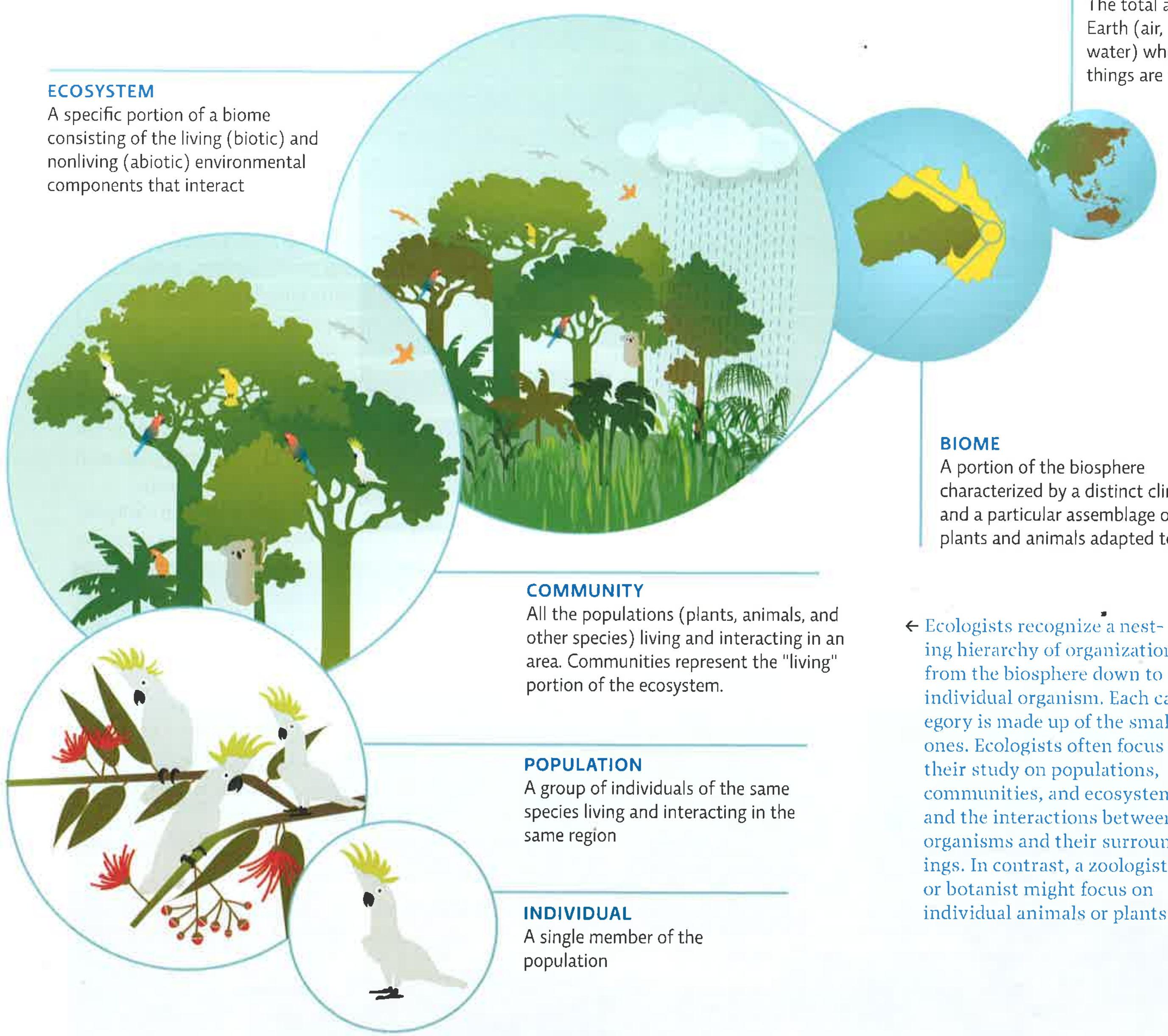
biosphere The sum total of all of Earth's ecosystems.
ecosystem All of the organisms in a given area plus the physical environment in which they interact.

← The eight biospherians emerge from Biosphere 2 after living there for two years.

↓ Visitors can tour the facility. Here they view the desert biome.

Infographic 7.1 **ORGANIZATION OF LIFE: FROM BIOSPHERE TO INDIVIDUAL**



BIOSPHERE
The total area on Earth (air, land, or water) where living things are found

ECOSYSTEM
A specific portion of a biome consisting of the living (biotic) and nonliving (abiotic) environmental components that interact

BIOME
A portion of the biosphere characterized by a distinct climate and a particular assemblage of plants and animals adapted to it

COMMUNITY
All the populations (plants, animals, and other species) living and interacting in an area. Communities represent the "living" portion of the ecosystem.

POPULATION
A group of individuals of the same species living and interacting in the same region

INDIVIDUAL
A single member of the population

← Ecologists recognize a nesting hierarchy of organization from the biosphere down to the individual organism. Each category is made up of the smaller ones. Ecologists often focus their study on populations, communities, and ecosystems, and the interactions between organisms and their surroundings. In contrast, a zoologist or botanist might focus on individual animals or plants.

Infographic 7.2 **HABITAT AND NICHE**

↓ Species depend on suitable habitats in which to live. Species fill a specific niche in their community.

SPECIES
A group of plants or animals that have a high degree of similarity and can generally only interbreed among themselves

HABITAT
The physical environment in which individuals of a particular species can be found

NICHE
The role a species plays in its community, including how it gets its energy and nutrients, its habitat requirements, and what other species and parts of the ecosystem it interacts with

physical environment in which they interact. This physical environment is often referred to as an organism's **habitat**. Ecologists study how ecosystems function by focusing on **species'** interactions with their surroundings and with other species in their communities. They also study interactions between members of the same species within a population. Individuals of each species in a community occupy a specific ecological **niche** shared by no other species in that community. In the natural world, ecosystems assume a range of shapes and sizes—a single, simple tide pool qualifies as an ecosystem; so does the entire Mojave Desert. [INFOGRAPHIC 7.1, 7.2]

All ecosystems function through two fundamental processes collectively referred to as ecosystem processes, namely nutrient cycling and **energy flow**. The term **nutrient cycles**, or biogeochemical cycles, refers to the movement of life's essential chemicals or nutrients through an ecosystem. Energy, on the other hand, enters as solar radiation and is passed along from organism to organism, some released as heat, until there is no more usable energy left. Therefore we can say that matter *cycles* but energy *flows*—a one-way trip.

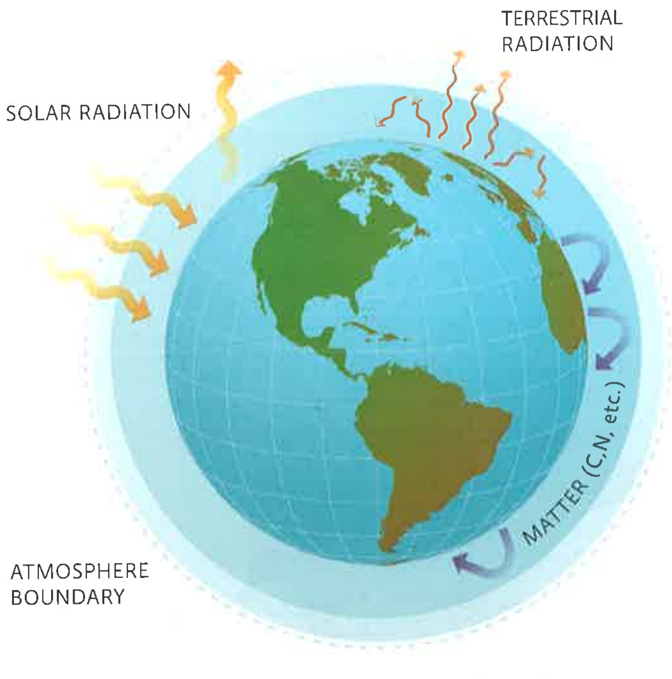
Earth—or "Biosphere 1," as the creators of Biosphere 2 liked to call it—is materially closed but energetically open. [INFOGRAPHIC 7.3] In other words, the plants and other organic material that make up an ecosystem, called **biomass**, cannot enter or leave the system, but energy can: some leaves as heat or light and new energy is absorbed from outside. In fact, plant biomass is produced with energy from the Sun through photosynthesis.

Biomes are specific portions of the biosphere determined by climate and identified by the predominant vegetation and organisms adapted to live there. Biomes can be divided into three broad categories—marine, freshwater, and terrestrial. Within those three categories are several narrower groups, and within those, a variety of subgroups. An entire biome itself may be considered an ecosystem, as are the smaller groups and subgroups. For example, forests, deserts, and grasslands are the three main types of terrestrial biomes. Within the forest biome category are different types of forests, such as tropical, temperate, or boreal forest, and within each of those groups are subgroups (for example, dry tropical forest and tropical rain forest.) [INFOGRAPHIC 7.4]

When ecologists study entire ecosystems, they are limited to making observations and trying to discern cause and effect from those observations. This is no small challenge; even the simplest phenomenon is impacted by a myriad of factors. Precise, systemwide measurements are exceedingly difficult to come by. And unlike laboratory science, field research doesn't often accommodate rigorous controls.

Biosphere 2 would offer ecologists an unprecedented research tool: a mini-planet where a variety of environmental variables—from temperature and water availability to the relative proportions of oxygen and carbon dioxide (CO_2) at any given moment—could be tightly controlled and precisely measured. "Manipulating these variables and tracking the outcomes could greatly

Infographic 7.3 **EARTH IS A CLOSED SYSTEM FOR MATTER BUT NOT FOR ENERGY**



↑ Energy can enter and leave Earth as light (solar radiation) and heat (terrestrial radiation) but matter stays in the biosphere, cycling in and out of organisms and environmental components.

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habitat The physical environment in which individuals of a particular species can be found.

species A group of plants or animals that have a high degree of similarity and can generally only interbreed among themselves.

niche The role a species plays in its community, including how it gets its energy and nutrients, what habitat requirements it has, and what other species and parts of the ecosystem it interacts with.

energy flow The one-way passage of energy through an ecosystem.

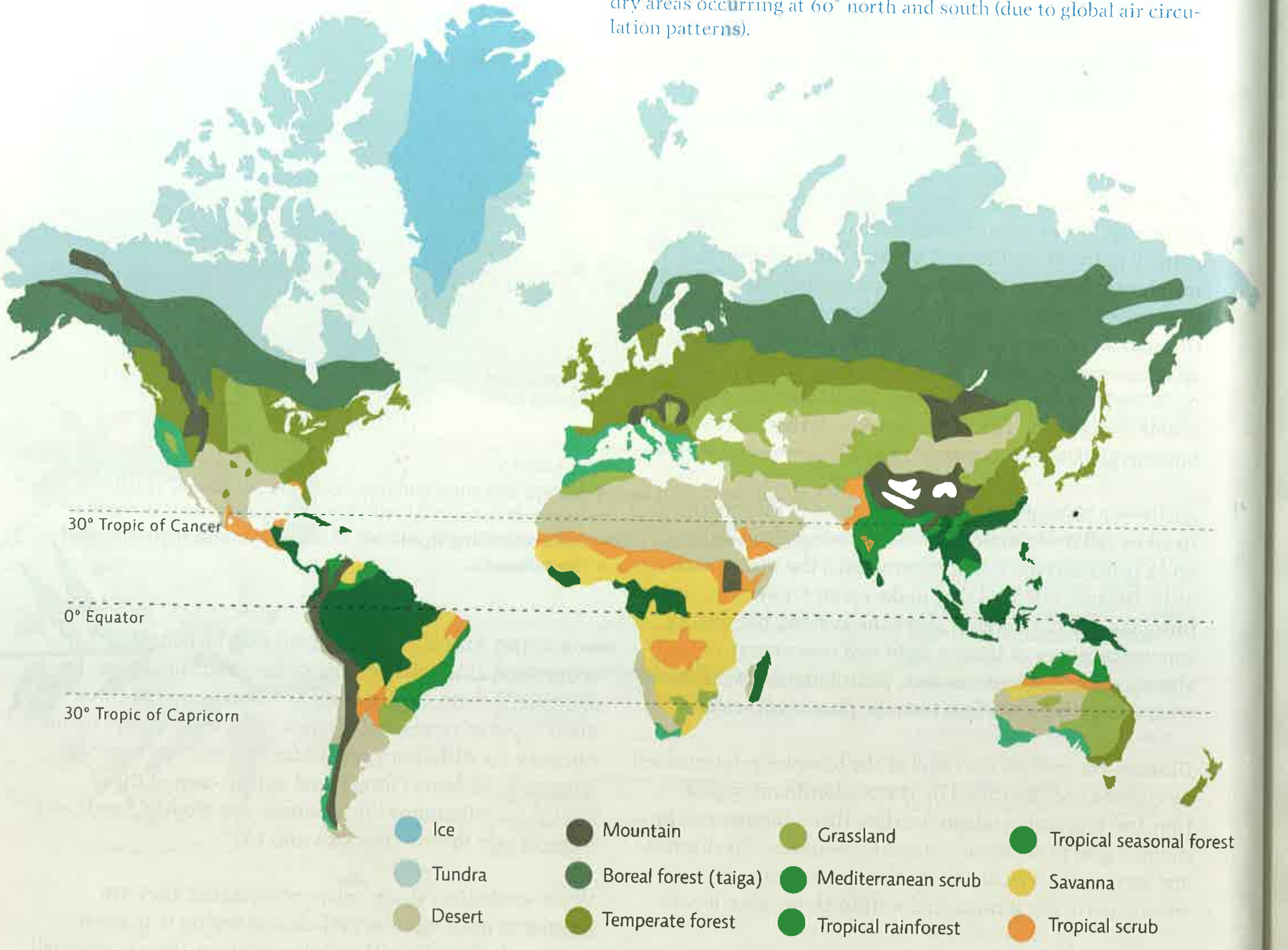
nutrient cycles Movement of life's essential chemicals or nutrients through an ecosystem (also known as biogeochemical cycles).

biomass The sum of all organic material—plant and animal matter—that make up an ecosystem.

biome One of many distinctive types of ecosystems determined by climate and identified by the predominant vegetation and organisms that have adapted to live there.

Infographic 7.4 **GLOBAL TERRESTRIAL BIOMES**

↓ Biomes are specific types of terrestrial ecosystems with characteristic temperature and precipitation conditions. Temperature varies with latitude (decreasing as one moves away from the equator) and altitude (decreasing as elevation increases); thus a cold climate can be found above 60° north and south latitudes, as well as on an equatorial mountaintop. Latitude also affects precipitation, with wet areas occurring at the equator and at 30° north and south and dry areas occurring at 60° north and south (due to global air circulation patterns).

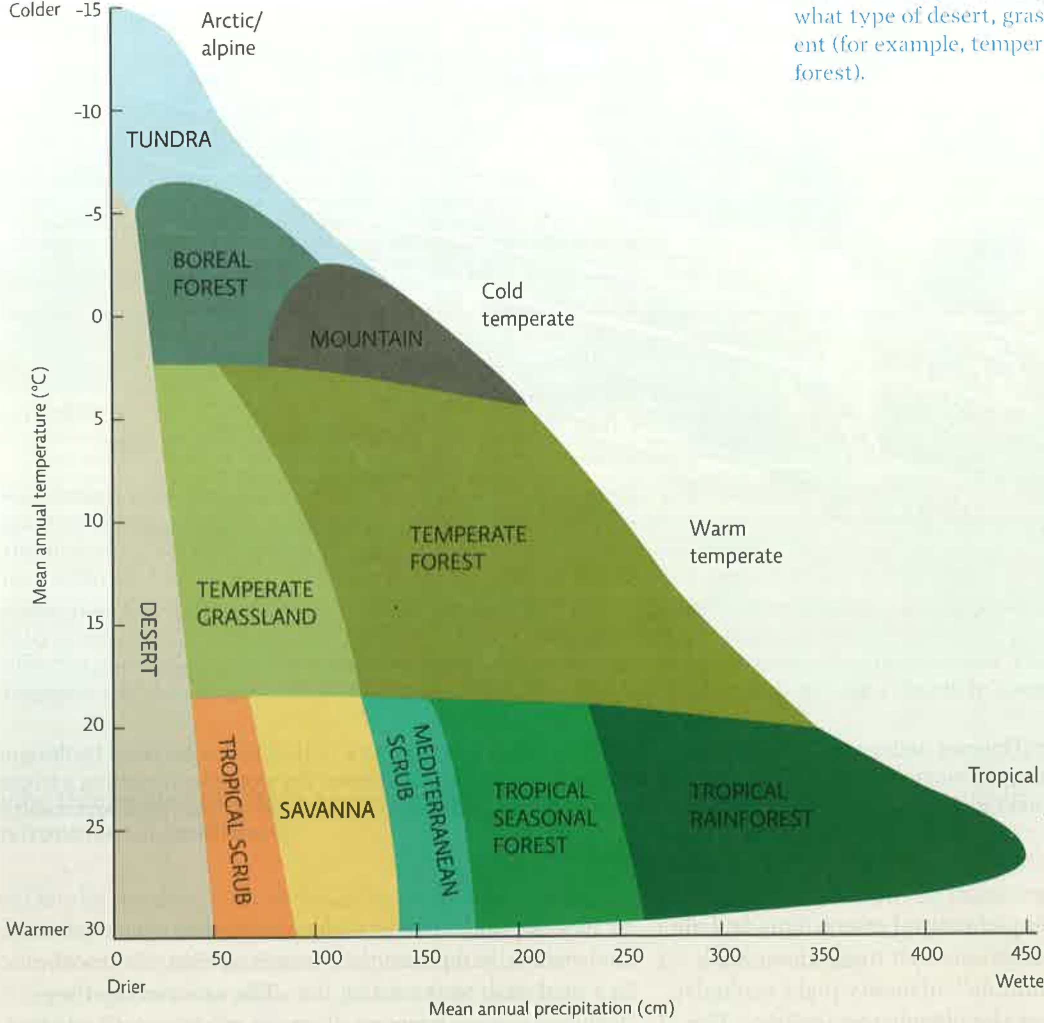


TUNDRA

TROPICAL RAINFOREST

BOREAL FOREST

↓ This biome climograph shows the approximate distribution of biomes with regard to annual precipitation and temperature. As precipitation increases and more plant life is able to be supported, deserts, scrublands, or grasslands give way to forests. The temperature also influences what type of desert, grassland, or forest is present (for example, temperate forest versus boreal forest).



MEDITERRANEAN SCRUB

DESERT

SAVANNA

Infographic **7.5** | **MAP OF BIOSPHERE 2**

↑ Biosphere 2 houses several biomes under one roof, each contributing to overall function. One of the challenges faced by designers was how to include a variety of biomes in the close quarters of the 3-acre Biosphere 2 structure. For example, in nature, a tropical rainforest would not be next to an arid desert. To deal with this, an ocean was placed between the desert and rainforest to serve as a temperature buffer.

advance our understanding of natural ecosystems and all the minute, complex interactions that make them work,” says Kevin Griffin, a Columbia University plant ecologist who conducted research at the Biosphere 2 facility. “The plan was to use that knowledge to figure out how to repair degraded ecosystems in the real world, so that they continue to provide the services so essential to our survival.”

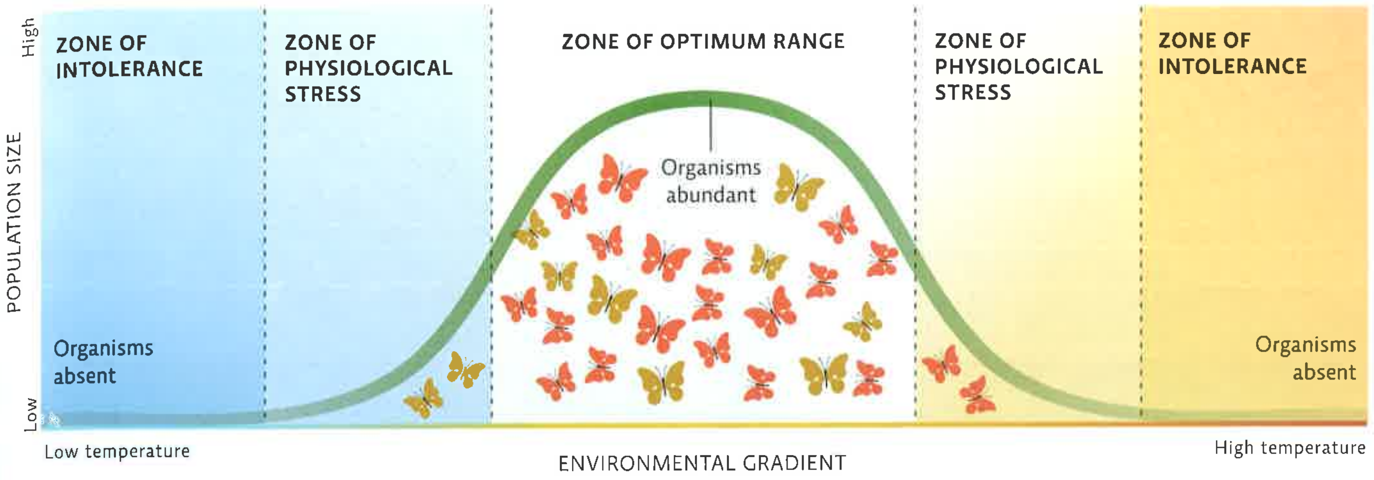
On top of all that, proving humans could survive in a completely enclosed, manufactured system would take us one giant step closer towards colonizing space.

But would it work?

The concept of enclosed ecosystems was not a new one. Since before they put a person on the moon, in fact, astronauts and engineers had been tinkering with their own artificial ecosystems—systems they hoped could one day be used to colonize space. The earliest versions of this technology were developed in the 1960s and 1970s by Russian and American scientists who, in the spirit of their times, had pitted themselves against one another in a mad dash to the finish line. The ecosystems they designed ranged from small, crude structures in which a single person might last for a single day, to larger, more sophisticated enterprises that could sustain a few people for a few months.

Biosphere 2 is by far the most elaborate. At 2½ football fields in diameter, it remains the largest enclosed ecosystem ever created and the only one to house several biomes under one roof. [INFOGRAPHIC 7.5] From a mountain under the dome’s 91-foot zenith, a stream rushes down through a tropical rainforest before snaking southward into a savanna. From there, the stream wends its way through a mangrove swamp into a million-gallon ocean complete with a coral reef. On the other side of the ocean lies a desert. Biosphere 2 also includes a human habitat and an agricultural biome.

Infographic **7.6** | **RANGE OF TOLERANCE FOR LIFE**



↑ Populations have a range of tolerance for a given environmental factor (such as temperature). Every species has an upper and a lower limit beyond which it cannot survive (in this example, temperatures that are too cool or too hot). Most individuals, like the butterflies in this population, can be found around the optimum temperature, though what is “optimum” for each individual may differ slightly because of genetic variability. Some individuals may find themselves in areas of the habitat that are warmer or colder than the optimum. They can tolerate these conditions but may be physiologically stressed and not grow well or successfully breed. Genetic differences that allow some individuals to tolerate or even thrive at the edges of the population’s tolerance offer the population a chance to adapt to changing conditions (such as a warmer climate) if needed. The more narrow the range of tolerance and the less genetically diverse the population, the less likely it will survive a change in conditions.

Living things survive within a specific range of environmental conditions.

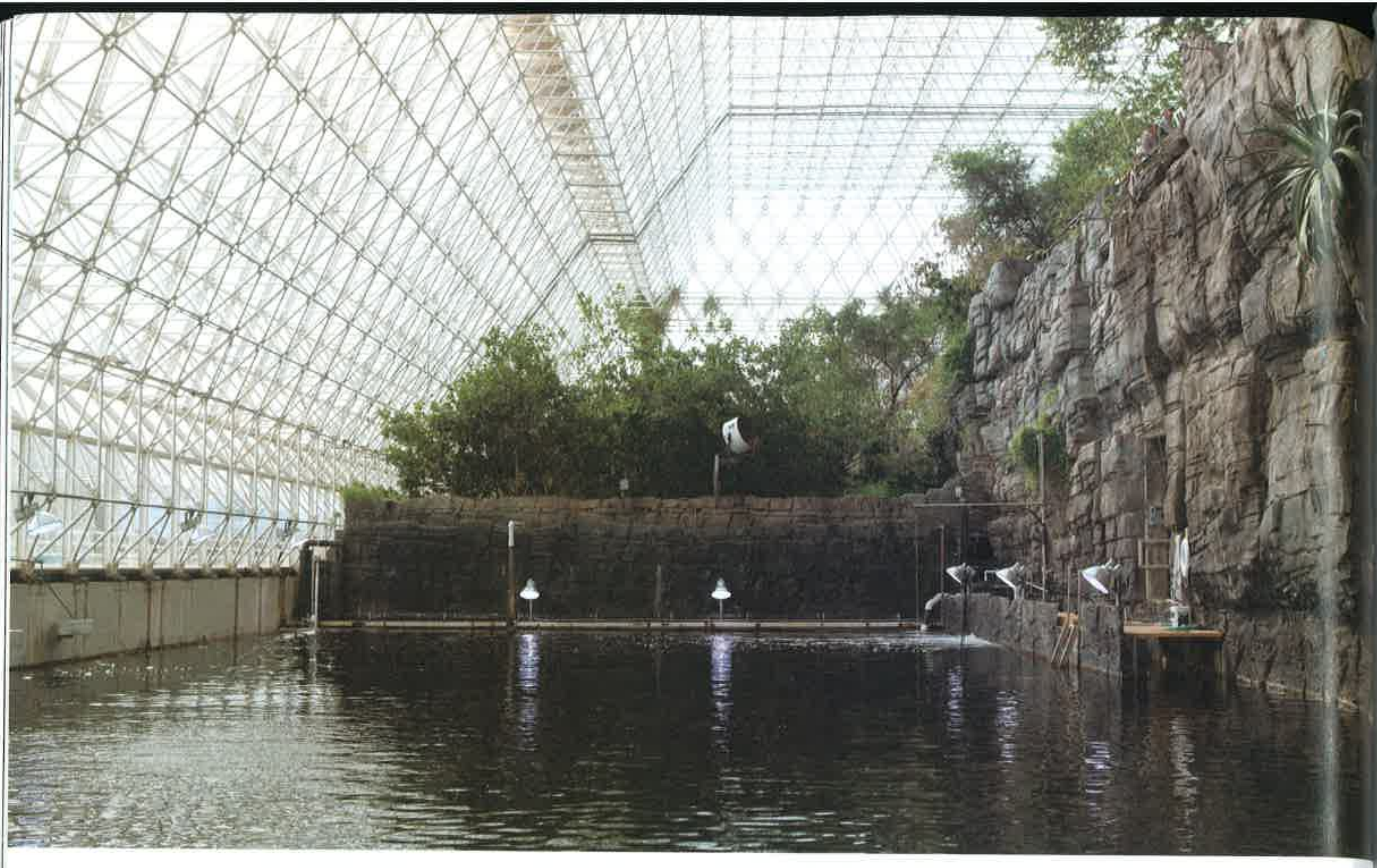
Each biome required a mind-boggling array of considerations—not only how diverse plant and animal species would interact within and across biomes, but also the nutrient requirements of each organism they planned to include. Termites, for example, would need enough dead wood at the beginning of closure to sustain them until some of the larger plants began dying off. Termites live in the soil, stirring it and allowing air to penetrate soil particles. If the termites ran out of dead wood and starved to death, organisms living in the soil would not get enough oxygen and the entire desert would be jeopardized. Hummingbirds, on the other hand, would need nectar-filled flowers. “Try figuring out how many flowers a day a hummingbird needs,” says Tony Burgess, a University of Arizona ecologist who helped design the biomes in Biosphere 2 and remained involved until 2004. “From there you need to know what the blooming season is, and then what the nectar load per flower is. And then you have to translate all of that into units of hummingbird support. Now imagine doing that sort of thing about 3,000 times.”

Biome-level planning was equally complicated. A rainforest would need consistently warm temperatures, but most desert biomes fluctuate wildly between day and night. In the summer, the grassland biome might literally starve the rainforest by gobbling up all the CO_2 needed for photosynthesis.

In this context, dead wood, flowers, and CO_2 are all examples of **limiting factors**—resources so critical that their availability controls the distribution of species and thus of biomes. The principle of limiting factors states that the critical resource in least supply is what determines the survival, growth, and reproduction of a given species in a given biome. Living things can only survive and reproduce within a certain range (between an upper and lower limit that they can tolerate) for a given critical resource or environmental condition, referred to as their **range of tolerance**. [INFOGRAPHIC 7.6]

limiting factor The critical resource whose supply determines the population size of a given species in a given biome.

range of tolerance The range, within upper and lower limits, of a limiting factor that allows a species to survive and reproduce.



↑ The Biosphere 2 ocean, shown here, is still used for marine research on the effect of increasing CO_2 levels on coral.

Ecologists routinely monitor a variety of limiting factors as a way of assessing ecosystem health, but anticipating what each individual organism would need to survive before the fact proved daunting.

An all-star team of scientists—oceanographers, forest ecologists, and plant physiologists—spent 2 years sorting through these challenges. Drawing on their combined expertise, they set about choosing the combination of soils, plants, and animals that seemed most capable of working together to recreate the delicate balances that had made Biosphere 1 such a spectacular success. A summer-dormant desert, like the ones found in Baja California, was chosen because it would reduce the desert's CO_2 demands when the savanna's productivity was at its highest. The ocean was situated between the desert and rainforest so that it could serve as a temperature buffer between the two. And each biome was created from a carefully selected array of species: The marsh biome was composed of intact chunks of swampland harvested from the Florida Everglades, and the savanna was composed of grasses from Australia, South America, and Africa. Well water mixed with aquarium salt filled the ocean, as did coral reefs culled from the Caribbean.

But it wasn't long before the rigor and pragmatism of good science began to clash with the idealism of Biosphere 2 financiers. And when that happened, critics say, science lost out.

Some scientists worried that the ocean wouldn't get enough sunlight to support plant and animal life. Others opposed the use of soil high in organic matter; soil microbes decompose the soil's organic carbon and release it into the air as CO_2. Although this organic soil might eliminate the need for chemical fertilizers, there were concerns that it would provide too much fuel for the soil microbes, and would thus send atmospheric CO_2 concentrations through the roof. Despite these concerns, scientific advisors to the project were overruled.

The first few months of Mission 1 went smoothly enough, but eventually, plants and animals started dying. Humans grew hungry and mysteriously sleepy. And before long, they turned on each other.

Like Earth, Biosphere 2 was designed as a materially closed and energetically open system: Plants would conduct photosynthesis with sunlight that streamed through the glass, but no biomass would enter or leave. Temperature, wind, rain, and ocean waves would be controlled mechanically. "But the facility would have to be self-sustaining," says Burgess. "Everything would die, unless the biota met its most fundamental purpose—using energy flow for biomass production." Humans would have to survive exclusively on what they could grow or catch under the dome. The system as a whole would have to continuously recycle every last bit of nutrient that was in the soil on day one.

At first, the carefully constructed agricultural biome seemed well suited to the challenge. Carrots, broccoli, peanuts, kale, lettuce, and sweet potatoes were grown on broad half-acre terraces that sat adjacent to the sprawling six-story human habitat; a bevy of domestic animals also provided sustenance—goats for milk, chickens for eggs, and pigs for pork. Indeed, eating only what they could grow made the biospherians healthier. Everyone lost weight. Bad cholesterol and blood pressure went down; so did white blood cell counts. And slowly, the biospherians say, their relationship to food changed. "Inside, I knew exactly where my food came from, and I totally understood my place in the biosphere and how it impacted the food I ate," says Jayne Poynter, the biospherian responsible for tending the farm. "When I breathed out, my CO_2 fed the sweet potatoes that I was growing. When I first got out, I lost sense of that. I would stand for hours in the aisles of shops, reading all the names on all the food things and think 'where does this stuff come from?' People must have thought I was nuts."

But the glazed glass of the dome admitted less sunlight than had been anticipated. Less sunlight meant less biomass production. And that meant less food. Mites and disease also cut crop production. Biosphere 2's size precluded the use of pesticides and herbicides: In that small an atmosphere, the toxins would build up rapidly and could have had a deleterious impact on air quality and human health.

Now, a few months in, food was starting to run out. And that wasn't the only problem.

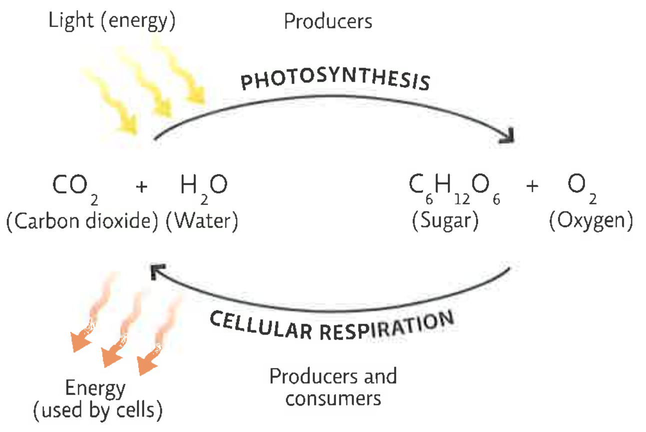
The humans were so tired they couldn't work. Nobody knew why, but scientists on the outside suspected it had something to do with nutrient cycles.

Nutrients such as carbon cycle through ecosystems.

On Earth, nutrients cycle through both **biotic** and **abiotic** components of an ecosystem—organisms, air, land, and water. They are stored in abiotic or biotic parts of the environment called **reservoirs**, or sinks, and linger in each for various lengths of time, known as *residence times.* Organisms acquire nutrients from the reservoir, the chemical cycles through the food chain, and eventually the chemical is returned to the reservoir. For carbon, the atmosphere—where carbon is stored as CO_2—is the most important reservoir. (Oceans and soil are also abiotic reservoirs for carbon. Oceans absorb CO_2 directly from the atmosphere and soils accumulate it during decomposition.) Plants and other photosynthesizers use carbon molecules from atmospheric CO_2 to build sugar, releasing oxygen in the process. Because they "produce" sugar, an organic molecule, from inorganic atmospheric CO_2, they are called **producers**.

This sugar molecule represents stored chemical energy that the producer can use. A **consumer**, the organism that eats the plant (or that eats the organism that eats the plant), also uses the chemical energy of sugar. This energy is released to the cell via the process of **cellular respiration**. [INFOGRAPHIC 7.7] All organisms—producers and consumers—perform cellular respiration. (For

Infographic **7.7** | **CARBON CYCLES VIA PHOTOSYNTHESIS AND CELLULAR RESPIRATION**



↑ In photosynthesis, producers use solar energy to combine CO_2 and H_2O to make sugar, releasing O_2 in the process. When producers (or any consumer who eats another organism) need energy, they break apart the sugar via the reverse reaction, cellular respiration. Oxygen is required for this reaction (which is why it is called "respiration").

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biotic The living (organic) components of an ecosystem, such as the plants and animals and their waste (dead leaves, feces).

abiotic The nonliving components of an ecosystem, such as rainfall and mineral composition of the soil.

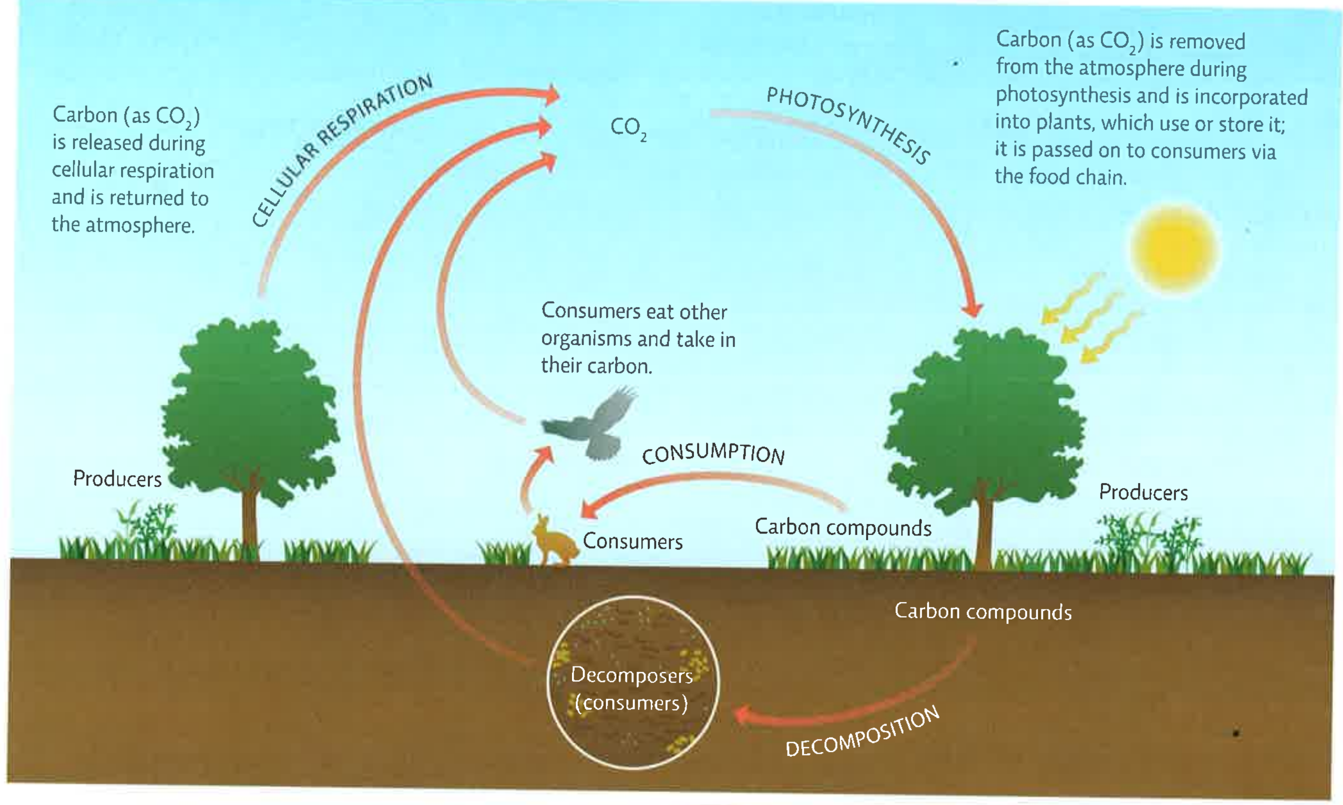
reservoirs (or sinks) Abiotic or biotic component of the environment that serves as a storage place for cycling nutrients.

producer An organism that converts solar energy to chemical energy via photosynthesis.

consumer An organism that obtains energy and nutrients by feeding on another organism.

cellular respiration The process in which all organisms break down sugar to release its energy, using oxygen and giving off CO_2 as a waste product.

Infographic **7.8** | **THE CARBON CYCLE**



Carbon (as CO$_2$) is released during cellular respiration and is returned to the atmosphere.

Carbon (as CO$_2$) is removed from the atmosphere during photosynthesis and is incorporated into plants, which use or store it; it is passed on to consumers via the food chain.

Consumers eat other organisms and take in their carbon.

↑ Carbon cycles in and out of living things during photosynthesis and cellular respiration. As consumers (including decomposers) eat other organisms, carbon is transferred. Some carbon is stored in the bodies of organisms and in soil, but over the long term, the carbon cycle is balanced between photosynthesis and respiration.

Humans unbalance the carbon cycle via activities that increase the amount of CO$_2$ in the atmosphere.

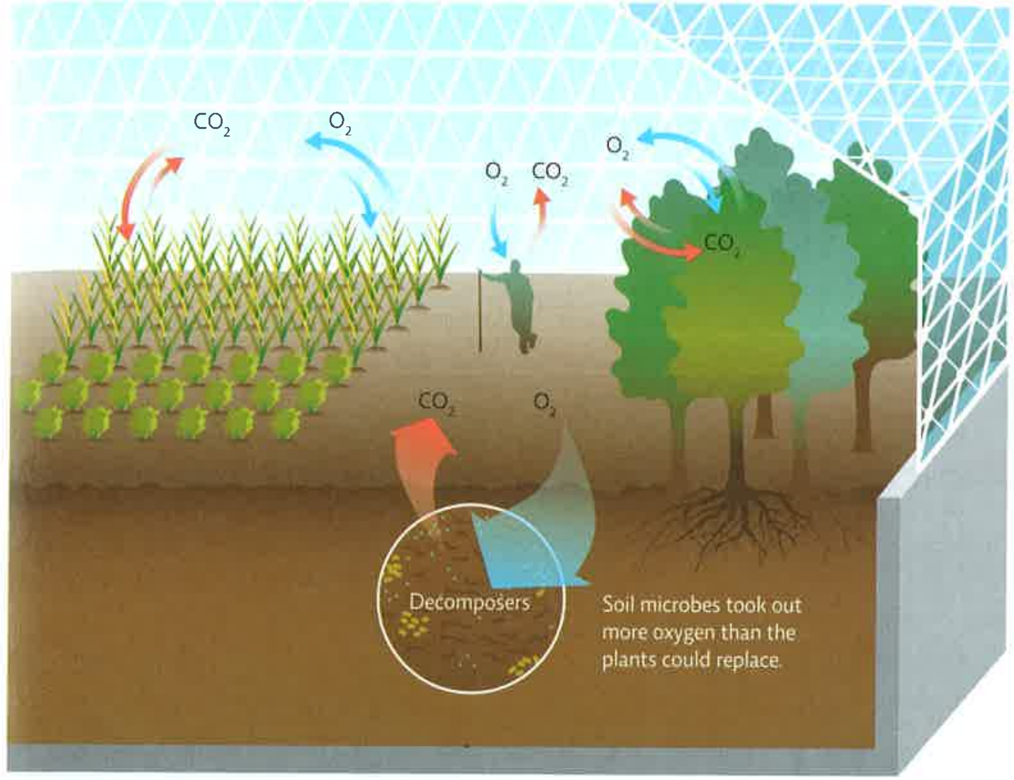
more information on producers, consumers, and the food chain, see Chapter 9.)

From its initial incorporation into living tissue via photosynthesis, to its ultimate return to the atmosphere through respiration or through the burning of carbon-based fuels, carbon cycles in and out of various molecular forms and in and out of living things as it moves through the **carbon cycle**. [INFOGRAPHIC 7.8] Even though a single carbon atom might cycle in a few weeks or years, decades can pass before changes in a Brazilian rainforest impact a farm in Iowa. Inside Biosphere 2, the same cycle took approximately 3 days, which meant that changes in one biome could be felt in another biome much more quickly than on Earth.

Still, Biosphere 2's carbon cycle was not that different from Earth's—carbon moved from living tissue to the atmosphere and back in the same predictable manner. Or at least it should have. As the biospherians' energy waned, it became clear that something had gone terribly wrong.

It turned out that oxygen levels had fallen steadily—from 21% down to 14%; at such low concentrations, the biospherians were unable to convert the food they consumed into usable energy. "We were just dragging ourselves around the place," Poynter says. "And we had sleep apnea at night. So we'd wake up gasping for air because our blood chemistry had changed."

Infographic **7.9** | **OXYGEN DEPLETION IN BIOSPHERE 2**



Soil microbes took out more oxygen than the plants could replace.

← The plants in Biosphere 2 were producing oxygen, but the excessive growth of soil microbes used oxygen faster than the plants could replace it via photosynthesis. This caused the oxygen levels in the air of Biosphere 2 to fall from 21% to 14%, causing health problems for the biospherians.

In just a few months, some 7 tons of oxygen—enough to keep six people breathing for 6 months—had gone missing. As scientists from Columbia University later discovered, soil microbes were gobbling up all that O$_2$ and converting it into CO$_2$ as they decomposed the organic matter in the soil. [INFOGRAPHIC 7.9]

The biospherians responded by filling all unused planting areas with morning glory vines, a pretty and fast-growing (but as it turned out, invasive) species they hoped would maximize the amount of CO$_2$ converted back into O$_2$ by photosynthesis. But even with an abundance of plants and enough CO$_2$, photosynthesis was still limited by the availability of sunlight; not even morning glories could keep up with the soil microbes in their warm, well-watered, highly organic soil.

Biosphere 2 is not alone with regard to a disrupted carbon cycle. Human activity has greatly altered carbon amounts in Earth's atmosphere. Many of our actions (such as burning fossil fuels) increase the amount of carbon normally released into the atmosphere or degrade natural ecosystems so that less carbon is removed from the atmosphere (as in the case of deforestation). Just like with Biosphere 2, this extra carbon causes problems such as global climate change, acidification of oceans, and alterations of communities worldwide.

Adding to the confusion, concrete used to build parts of Biosphere 2 was absorbing some of the CO$_2$ and converting it into calcium carbonate, trapping some of the carbon and oxygen in this unexpected sink.

Besides carbon, two other chemicals essential for life—nitrogen and phosphorus—cycle through ecosystems. Nitrogen, the most abundant element in Earth's atmosphere, is needed to make proteins and nucleic acids, but plants cannot utilize nitrogen in its atmospheric form (N$_2$). All plant life, and ultimately all animal life too, depends on microbes (bacteria) to convert atmospheric nitrogen into usable forms as part of the **nitrogen cycle**.

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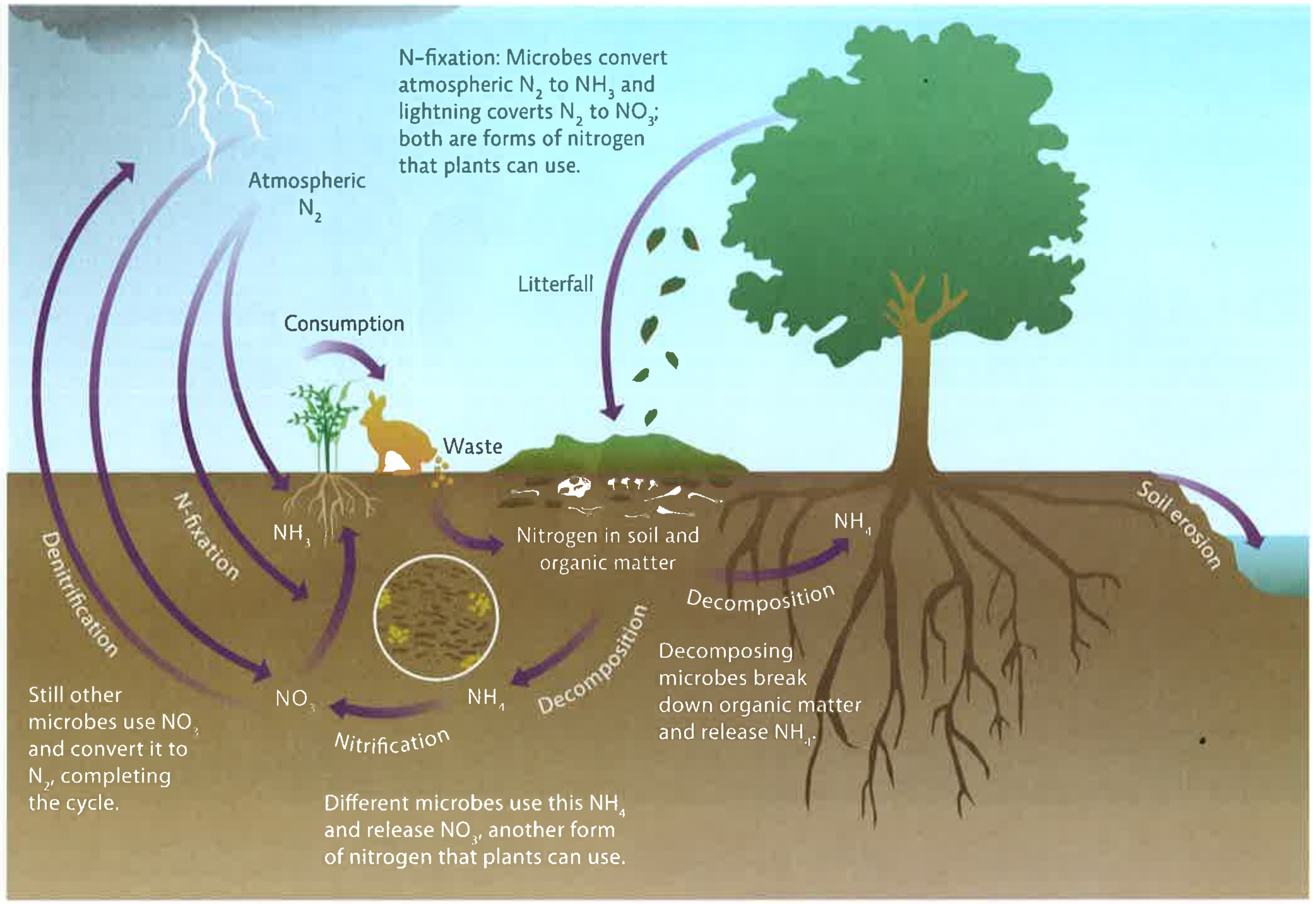
carbon cycle Movement of carbon through biotic and abiotic parts of an ecosystem. Carbon cycles via photosynthesis and cellular respiration as well as in and out of other reservoirs such as the oceans and soil. It is also released by human actions such as fossil fuel burning.

nitrogen cycle Continuous series of natural processes by which nitrogen passes from the air to the soil, to organisms, and then returns back to the air or soil through decomposition or denitrification.

Infographic 7.10 | THE NITROGEN CYCLE



N-fixation: Microbes convert atmospheric N_2 to NH_3 and lightning coverts N_2 to NO_3; both are forms of nitrogen that plants can use.

Decomposing microbes break down organic matter and release NH_4.

Still other microbes use NO_3 and convert it to N_2, completing the cycle.

Different microbes use this NH_4 and release NO_3, another form of nitrogen that plants can use.

↑ Nitrogen, needed by all living things to make biological molecules like protein and DNA, continuously moves in and out of organisms and the atmosphere in a cycle absolutely dependent on soil bacteria.

Nitrogen fertilizers promote plant growth but this depletes other soil nutrients; they can also leach out of soils and pollute aquatic ecosystems.

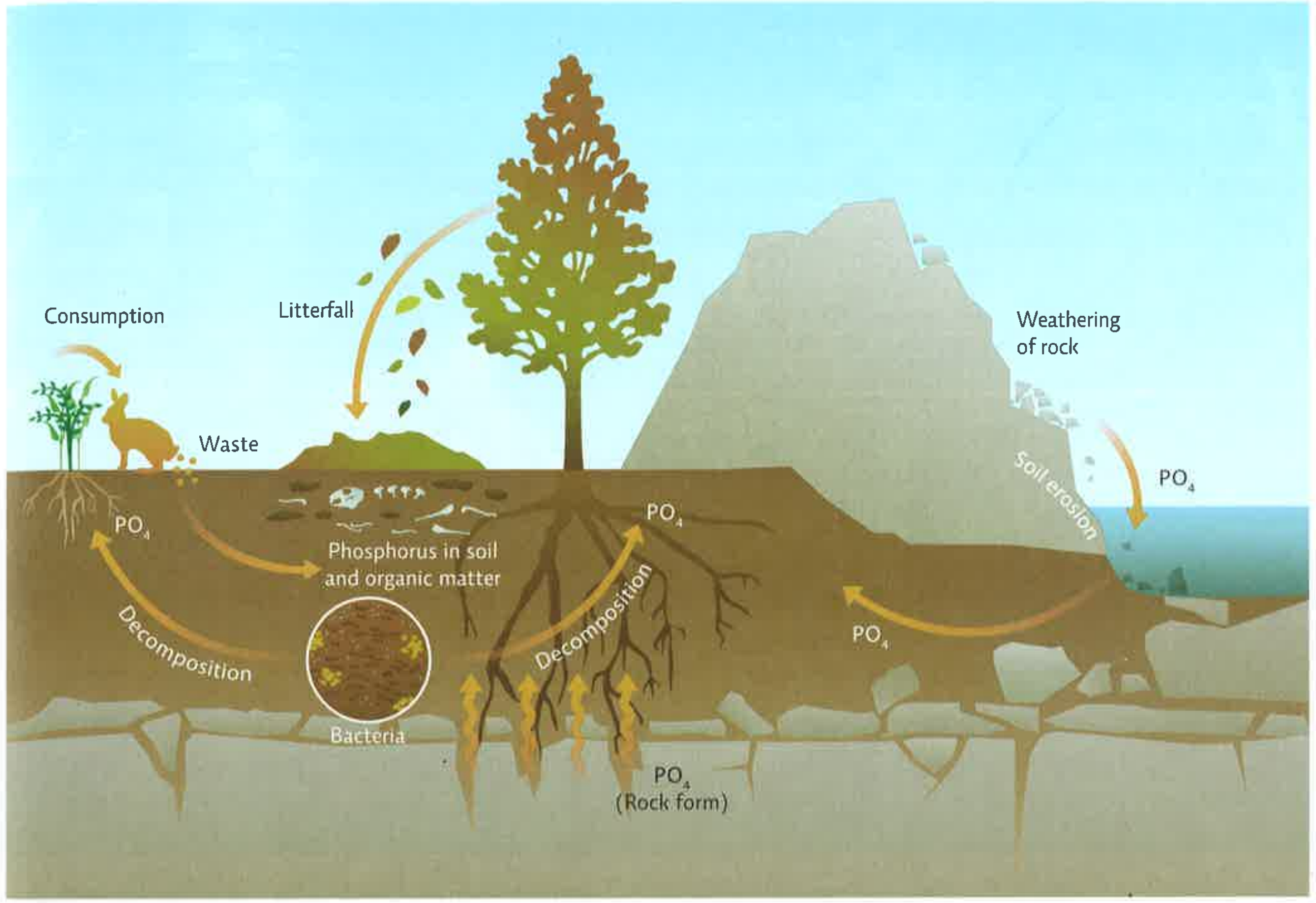
Burning fossil fuels contributes to nitrogen pollution such as smog and acid rain.

In a process called **nitrogen fixation**, atmospheric nitrogen (N_2) is converted by bacteria into ammonia (NH_3) which plants take up through their roots; consumers take in nitrogen via their diet. A small amount of N_2 is fixed by lightning, producing nitrate (NO_3). In other steps of the nitrogen cycle (decomposition, nitrification, and denitrification) various types of bacteria feed on nitrogen compounds in organic matter or the soil, eventually returning it as N_2 to the atmosphere. [INFOGRAPHIC 7.10] The nitrous oxide (N_2O), or laughing gas, that gave the biospherians trouble is a by-product of denitrification that normally exists in trace amounts in Earth's atmosphere (it is also becoming a dangerous greenhouse gas, as it is produced in ever-higher concentrations by some human activities).

Unlike nitrogen and carbon, phosphorus—which is needed to make DNA and RNA—is found only in solid or liquid form on Earth, so the **phosphorus cycle** does not move through the atmosphere, but passes from inorganic to organic form through a series of interactions with water and organisms. [INFOGRAPHIC 7.11]

In Biosphere 2, the nitrogen and phosphorus cycles were disrupted. Thanks to an overabundance of soil microbes, nitrous oxide reached levels high enough to interfere with

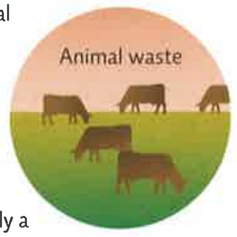
Infographic 7.11 | THE PHOSPHORUS CYCLE



↑ Phosphorus, needed by all organisms to make DNA, cycles very slowly. It has no atmospheric component but instead depends on the weathering of rock to release new supplies of phosphate (PO_4) into bodies of water or the soil, where it dissolves in water and can be taken up by organisms. Microbes also play a role when they break down organic material and release the phosphate to the soil.

Dust released through mining or in eroded areas can introduce phosphorus into the environment much more quickly than it would normally enter.

Fertilizers and animal waste (including sewage) can alter plant growth and nutrient cycling, especially in aquatic ecosystems where phosphorus is usually a limiting nutrient.



the metabolism of vitamin B12, which is ess[redacted] brain and nervous system.

Phosphorus got trapped in the water system, polluting aquatic habitats. The underwater and terrestrial plants of Biosphere 2 were dying off too quickly to complete this

herians removed excess nutrients from their pply by passing the water over algal mats that would absorb the nutrients and could then be harvested, dried, and stored.

As food reserves dwindled, the eight biospherians split into two factions. One group felt that scientific research was the top priority, and wanted to import food so that they would have enough energy to continue with their experiments. The other group felt that maintaining a truly closed system—one where no biomass was allowed to enter or leave—was the project's most important goal;

nitrogen fixation Conversion of atmospheric nitrogen into a biologically usable form, carried out by bacteria found in soil or via lightning.

phosphorus cycle Series of natural processes by which the nutrient phosphorus moves from rock to soil or water, to living organisms, and back to the soil.

↑ Justin Peterson, a Biosphere 2 undergraduate intern who assists PhD candidate Henry Adams with his Pinon Pine Tree Drought Experiment. The experiment's goal is to predict the effects of climate shifts on the trees.

proving that humans could survive exclusively on what the dome provided would be essential to one day colonizing the Moon or Mars. To them, importing food would amount to a mission failure. "It was a heartbreaking split," Poynter says. "Just 6 months into the mission, and two people on the other side of the divide had been my closest friends going in." Eventually, Poynter snuck food in. That wasn't the only breech. To solve the various nutrient cycle conundrums, the project's engineers had installed a CO_2 scrubber, and pumped in 600,000 cubic feet of oxygen.

Biosphere officials hid these actions from all but a few key people. When one reporter finally broke the story, the public was outraged. Spectators of every ilk—seasoned scientists, skeptical reporters, and casual observers alike—became convinced that other data was also being fudged. "Secrets are like kryptonite to the scientific process," says Griffin. "Once you find out something has been deliberately overhyped or downplayed, or just plain lied about, all the data from that research becomes suspect. And data that can't be trusted has no scientific value."

Three years after the first mission was completed, the editors of the respected journal *Science* deemed the entire project a failure. "Isolating small pieces of large biomes and juxtaposing them in an artificial enclosure changed their functioning and interactions, rather than creating a small working earth as originally intended," they wrote. For the $200 million dome to survive as a scientific enterprise, they concluded, it would need dramatic retooling.

Ecosystems are complicated, but learning how they function will help us restore degraded ones.

Biosphere 2 taught scientists that Earth is far too complex, that ecosystem components intertwine in far too many complicated ways, for humans to recreate. Each is governed by a countless array of interacting factors and a change in one can set off a whole chain of events that degrade the system's capacity to sustain life.

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From a scientific point of view, the fact that Biosphere 2 was not able to sustain life as hoped does not mean the project was of no value. Negative results can be just as informative as positive ones—in some cases even more so because they uncover gaps in our knowledge and help us decide how to move forward. In fact, Biosphere 2's greatest liability—its skyrocketing CO_2 levels—proved to be its most valuable asset. "Now it's like a time machine," says Griffin who points out that it is allowing us a look at the consequences of elevated atmospheric CO_2 levels, the main contributor to climate change today. Recent research by Griffin has uncovered some of the complexities of carbon cycling. His group saw unexpected fluctuations in carbon release at various levels in the tree canopy, telling him there is much we still don't know about how carbon cycles—data that could only be gathered in an enclosed forest such as that found in Biosphere 2. Today, scientists from all over the world still use the facility to study the effects of an atmosphere loaded with carbon dioxide. Ultimately, though, the most valuable lesson Biosphere 2 has provided is how irreplaceable Biosphere 1 is.◉

Research articles referenced in this chapter:
Cohen, J.E., and Tilman, D. 1996. *Science*, 274: 1150–1151.
Griffin, K.L., *et al*. 2002. *New Phytologist*, 154: 609–619.

BRING IT HOME

➲ PERSONAL CHOICES THAT HELP

Nutrient cycling is critical for maintaining Earth's ecosystems, but we interfere with nutrient cycles through our daily activities. Driving a car interferes with the carbon cycle by releasing carbon from fossil fuel reservoirs. Applying synthetic chemical fertilizers to food crops interferes with the nitrogen cycle by adding soluble nitrogen compounds to aquatic ecosystems through runoff. The challenge is to figure out ways to work with nutrient cycles rather than against them—in other words, to return nutrients to the reservoirs from which they come. How might this be done in our daily lives and in our own communities?

Individual Steps

→ Reduce your fossil fuel use to curtail carbon, nitrogen, and sulfur emissions. Take public transportation, walk, ride a bike, and drive a fuel-efficient vehicle.

→ Compost food and yard waste. Then use this material to fertilize flowerbeds, trees, and garden plots. Composting will reduce or eliminate the need for inorganic fertilizers in your yard.

Group Action

→ Participate in or organize an event to plant trees or native grasses. By doing so, you can help recapture the carbon put into the atmosphere by driving a car.

→ Many urban areas welcome individuals who are willing to "adopt a median" and plant and maintain flowerbeds and trees in small plots along roadways.

Policy Change

→ Public policy currently prevents large-scale composting of municipal wastes in most areas. Working to change these policies will extend the life of our landfills and make use of valuable nutrient-rich materials.

→ Support legislation to increase fuel efficiency of vehicles and subsidies for clean, renewable energy. More-efficient cars and cleaner energy sources will reduce our carbon outputs from fossil fuel use.