Chapter 2.5- 2.10

The Carbon Cycle

Carbon is the key element for living things. Carbon can be found in the atmosphere and dissolved in the oceans as part of the inorganic carbon dioxide (CO_2) molecule. Each year, about 50 to 70 billion tonnes of carbon from inorganic carbon dioxide are recycled into more complex organic substances. This is done through photosynthesis.

During photosynthesis, plants use light energy to combine carbon dioxide from the atmosphere and water from the soil. Photosynthesis actually happens in a chain of reactions, but it can be summed up in the equation below:

Reactants							*Products*		
$6CO_2$	+	$6H_2O$	+	light	→	$C_6H_{12}O_6$	+	$6O_2$
carbon dioxide	+	water	+	light energy	→	sugar (glucose)	+	oxygen

Some of the organic carbon is released back to the environment through cellular respiration as carbon dioxide. Once again, this process actually requires a long chain of reactions, but can be summed up in the simplified equation below.

Reactants				*Products*		
$C_6H_{12}O_6$	+	$6O_2$	→	$6H_2O$	+	$6CO_2$
glucose	+	oxygen	→	water	+	carbon dioxide

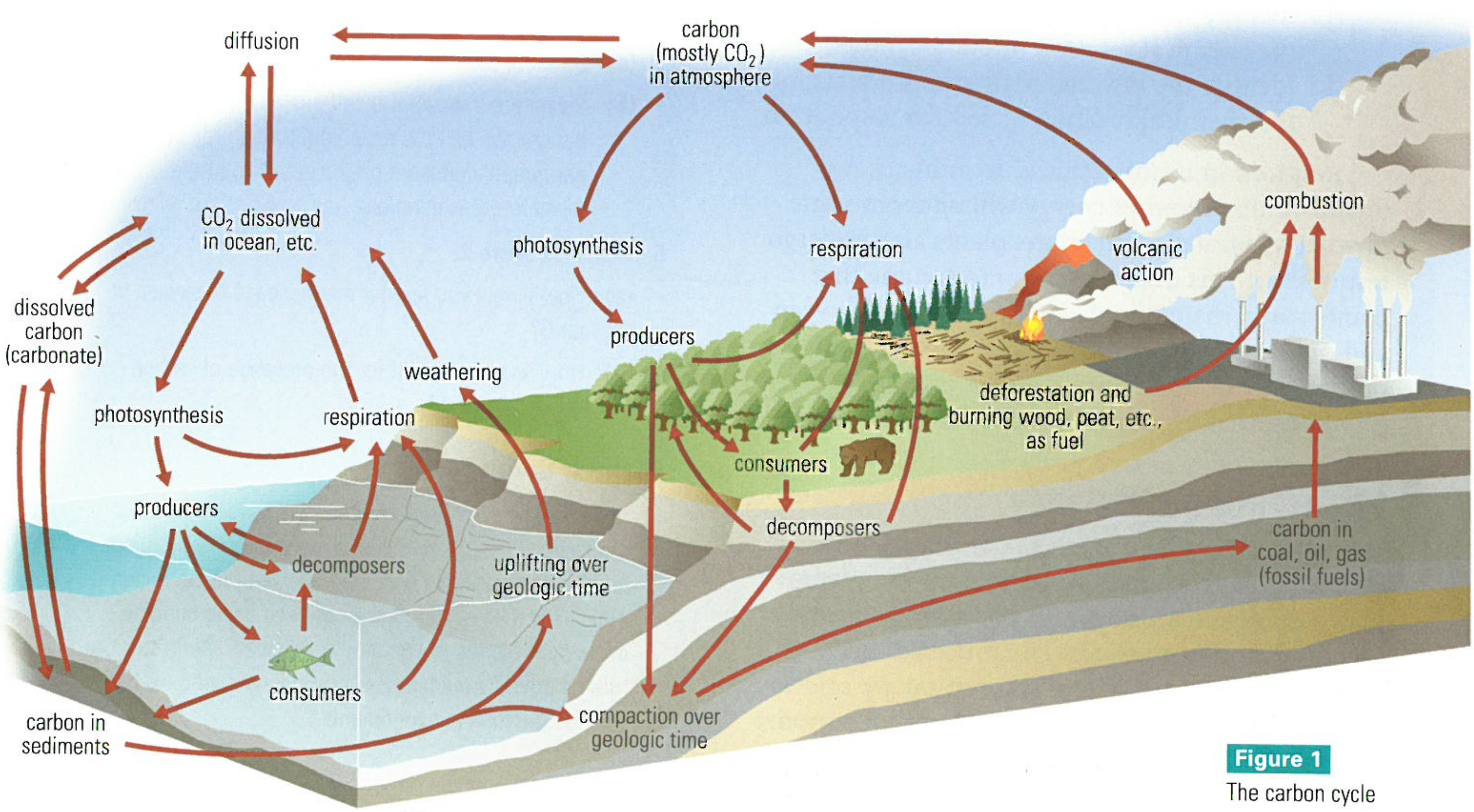


Figure 1
The carbon cycle

Because photosynthesis and cellular respiration are complementary processes, and because the carbon that they use is repeatedly cycled through both processes, this relationship is often called the **carbon cycle**. This cycle is actually much more complex than a simple exchange of carbon-as-carbon-dioxide and carbon-as-glucose (**Figure 1**). Most of the carbon that forms living organisms is returned to the atmosphere or water as carbon dioxide from body wastes and when the dead organisms decay. However, under certain conditions the decay process is delayed and the organic matter may be converted into rock or fossil fuels such as coal, petroleum, and natural gas. This carbon is then unavailable to the cycle until it is released by processes such as uplifting and weathering, or by burning as fuels. The burning process (**combustion**) releases carbon dioxide into the atmosphere.

Reservoirs for Inorganic Carbon: Delays in the Cycle

When it is not in organic form, carbon can be found in three main reservoirs (storage areas): the atmosphere, the oceans, and Earth's crust. The smallest of these reservoirs is the atmosphere. Carbon dioxide makes up a very small percentage (about 0.03%) of the gases that we breathe in. However, atmospheric carbon dioxide is easily accessed by land plants for use in photosynthesis.

A tremendous amount of inorganic carbon is held as dissolved carbon dioxide in the oceans, where it is available to algae and other water plants for photosynthesis. However, some carbon dioxide reacts with sea water to form the inorganic carbonate ion (CO_3^{2-}) and bicarbonate ion (HCO_3^-). Combined with calcium these ions become calcium carbonate ($CaCO_3$), which is used to make shells and other hard structures in living things. The carbon in carbonates can be recycled, but in the ocean much of it ends up as sediment. As layers of sediment form, the carbonates are crushed and heated and eventually become rock. Limestone is made from the discarded shells and bones of living things. And that is why by far the largest reservoir of the Earth's carbon is in sedimentary rocks. Carbon can be trapped in rock for millions of years until geological conditions bring it back to the surface. Volcanic activity can break down carbonate-containing rocks such as limestone, releasing carbon dioxide. Acid rain falling on exposed limestone will also cause the release of carbon dioxide into the atmosphere.

Figure 2 shows how long, on average, a carbon dioxide molecule will remain in each reservoir.

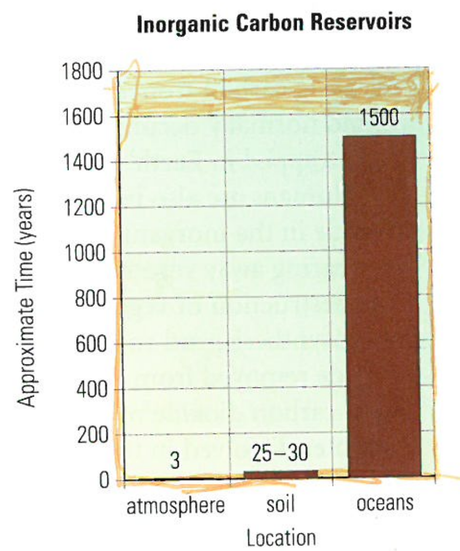


Figure 2
The average carbon atom is held in inorganic form much longer in the ocean than in the atmosphere. The time for carbon held in rocks (millions of years) would not fit well in this graph.

Reservoirs for Organic Carbon

Organic carbon is also held in reservoirs — the bodies of living things. However, all living things die, and decomposition eventually returns the carbon to the cycle in inorganic form. There is one important exception to this rule: some ecosystems, such as bogs, store huge quantities of carbon in organic form. In a bog there is very little oxygen, and under these conditions decomposition is very slow. Carbon atoms may remain locked away in dead plant matter (**peat**) for many years in a bog. Occasionally these deposits are overlain with sediment, and as more layers of sediment are piled on top, the slowly decaying organic matter can end up trapped between layers of rock. The result is the formation of a carbon-containing fossil fuel, coal (**Figure 3**).

Conditions similar to those in a bog also exist on the floors of oceans; there too organic carbon can be trapped for long periods. Oil is formed in a process similar to the formation of coal, when decaying aquatic animals and plants are trapped under sediment in a low-oxygen environment.

In the form of fossil fuels in Earth's crust, organic carbon can be held out of the carbon cycle for many millions of years.

The Human Impact on the Carbon Cycle

Humans have modified the global carbon cycle by releasing carbon from organic reservoirs faster than would normally occur, by mining and burning fossil fuels trapped in Earth's crust, and by burning forests.

Humans are also increasing the amount of carbon dioxide in the inorganic reservoir of the atmosphere by clearing away vegetation, in order to build or farm. The destruction of vegetation reduces the amount of photosynthesis, and so reduces the amount of carbon dioxide removed from the atmosphere (**Figure 4**). Most carbon dioxide released into the air eventually becomes dissolved in the oceans, but the oceans can hold only so much. The amount of carbon dioxide in the atmosphere is rising.

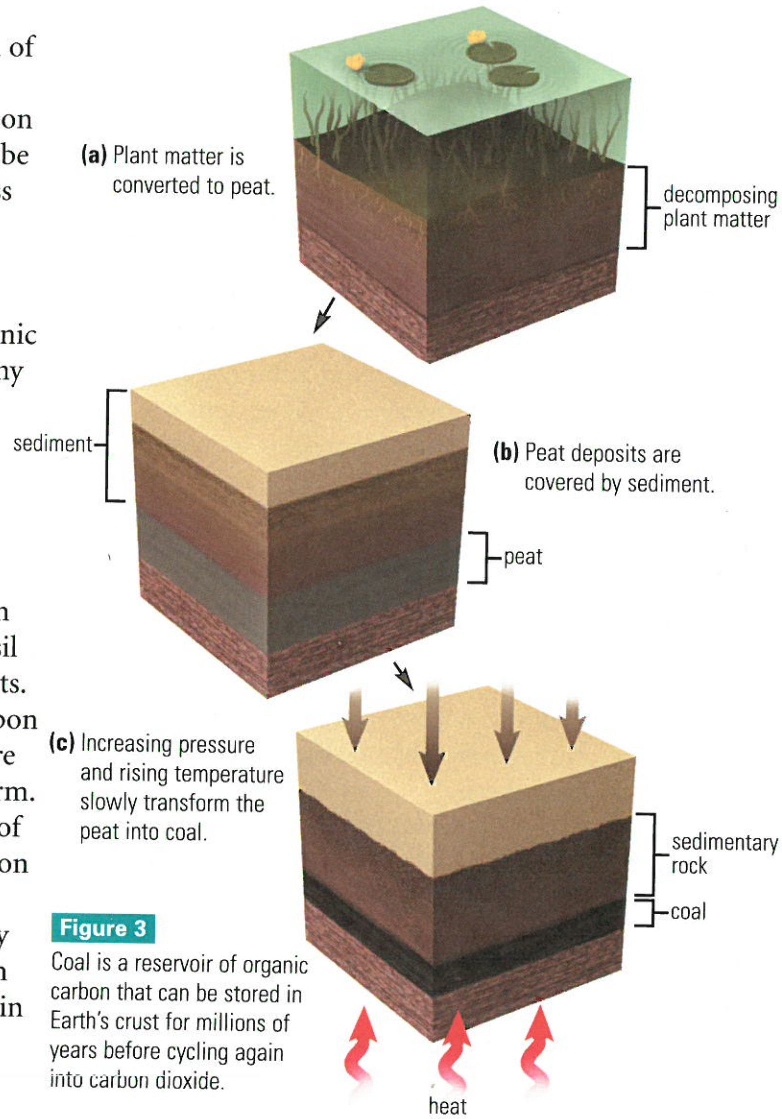


Figure 3
Coal is a reservoir of organic carbon that can be stored in Earth's crust for millions of years before cycling again into carbon dioxide.

Try This Activity: Effect of Carbon Dioxide Levels on Photosynthesis

How do carbon dioxide levels affect photosynthesis? In this modelling experiment you can examine how a plant responds to varying levels of carbon dioxide.

Materials: apron, safety goggles, similar potted plants, plastic bags, small plastic containters, soda lime (which absorbs carbon dioxide), and baking soda (which slowly releases carbon dioxide)

Always wash your hands after handling soil.

(a) Describe a way of controlling the (K4) experiment.

(b) Decide how you will measure the effects of changes in carbon dioxide levels on the plants.

- Set up each plant as shown in **Figure 5**.
- Observe the effects and record your observations.

(c) Use the results of your experiment to answer the initial question.

Figure 5

SKILLS HANDBOOK: (K4) Creating the Design

Figure 4
The burning of the rainforest disrupts the balance between photosynthesis and cellular respiration. Many human activities affect the carbon cycle.

Challenge

3 In many parts of the world, some of the most productive forests are being cleared for farmland. In constructing your board game, how will you show the importance of maintaining plant communities?

Understanding Concepts

1. In your own words, explain why photosynthesis and cellular respiration are considered to be complementary processes.
2. Explain the importance of decomposers in the carbon cycle.
3. The oceans are often described as a carbon reservoir. In what ways is carbon held within the oceans?
4. Explain how the burning of fossil fuels by humans affects the carbon cycle.
5. Carbon cycles more quickly through some ecosystems than others.
   (a) Explain why carbon is cycled more slowly in northern ecosystems than in the tropics.
   (b) Explain why carbon is cycled more rapidly in grassland communities than in peat bogs and swamps.

Making Connections

6. Scientists have expressed concerns about the burning of the rainforests to clear land for farming.
   (a) Explain how the burning of the forests could change oxygen levels in the atmosphere.
   (b) What impact would the change in oxygen levels have on living things?
7. Study **Table 1**.
   (a) Calculate the amount of carbon entering the atmosphere as carbon dioxide every year and the amount of carbon leaving the atmosphere. Is atmospheric carbon dioxide increasing or decreasing?
   (b) Draw a bar graph showing factors that increase and decrease atmospheric carbon dioxide levels.
   (c) The burning of forests contributes 2 x 10^{13} kg of carbon yearly, but its impact on creating a carbon imbalance is even greater than the carbon dioxide released from the burning plants. What other factor would be affected by burning plants?
   (d) Provide a list of suggestions that would reduce the flow of carbon dioxide into the atmosphere. How would the suggestions affect your life? Which of your suggestions do you think you could help with?

Table 1 **Carbon Cycle**

Carbon movement	Mass of carbon per year (10^{13} kg)
from atmosphere to plants	120
from atmosphere to oceans	107
to atmosphere from oceans	105
to atmosphere from soil	60
to atmosphere from plants	60
to atmosphere from burning of fossil fuels	5
to atmosphere from net burning of plants	2
to oceans from runoff	0.4

8. In 1998 the federal government of Canada proposed a "carbon tax" on gasoline. Some people believe such a tax would reduce the amount of carbon dioxide entering the atmosphere.
   (a) Would the tax reduce the amount of carbon dioxide entering the atmosphere? Give reasons for your answer.
   (b) What businesses would be affected by the tax? (C) Explain how they would be affected.
   (c) What other groups or individuals would be affected by the tax? Would it apply equally and fairly to everyone?
   (d) Based on your analysis, who would you expect to oppose the tax? Who would you expect to support the tax?

(C) Defining the Issue

2.6

The Nitrogen Cycle

Life depends on the cycling of nitrogen. Nitrogen atoms are required so that cells can make proteins. Nitrogen is also required for the synthesis of deoxyribonucleic acid or DNA, the hereditary material found in all living things. The movement of nitrogen through ecosystems, the soil, and the atmosphere is called the **nitrogen cycle.**

When you consider that nitrogen gas (N_2) composes nearly 79% of the Earth's atmosphere, you would think that access to nitrogen would not be a problem for organisms. Unfortunately, this is not the case. Nitrogen gas is a very stable molecule, and reacts only under limited conditions. To be useful to organisms nitrogen must be supplied in another form, the nitrate ion (NO_3^-).

The nitrogen cycle is exceptionally complex. The simplified description in **Figure 1** shows two ways in which atmospheric nitrogen can be converted into nitrates, in a process called **nitrogen fixation**. The first method is through lightning, and the second is through bacteria in the soil.

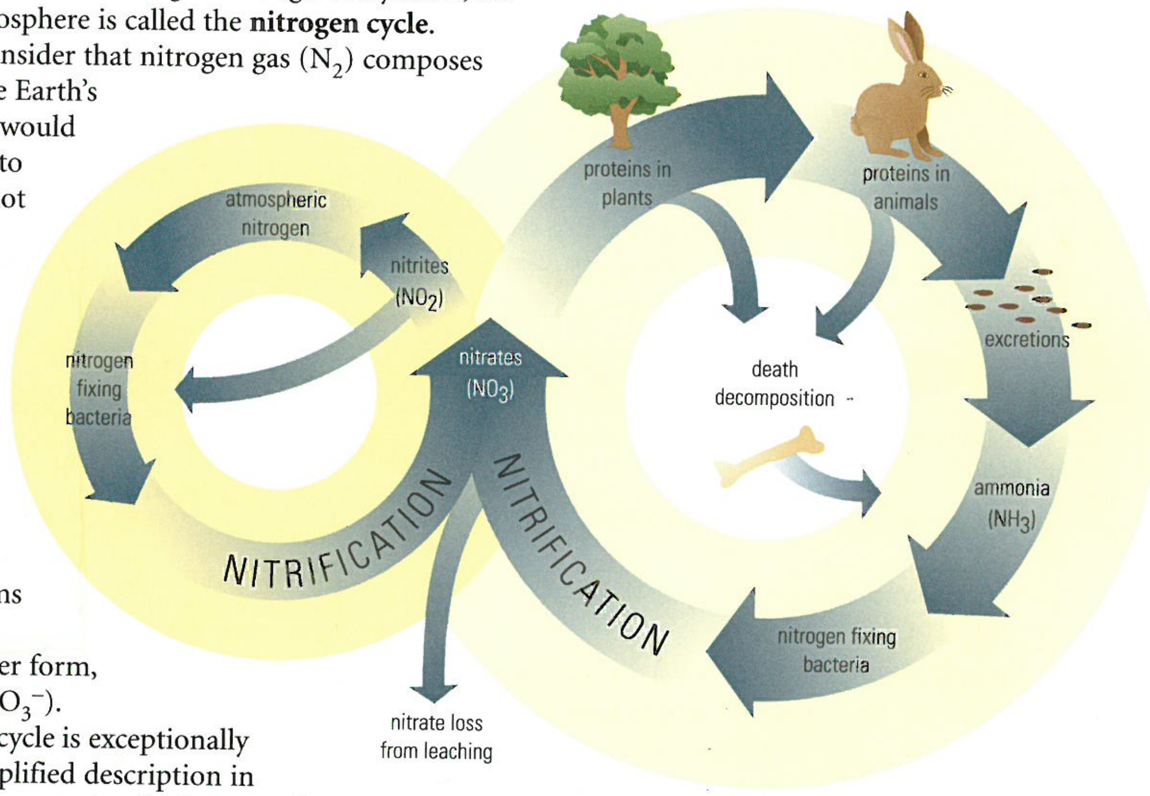


Figure 1
Like carbon, nitrogen moves in a cycle through ecosystems, passing through food chains and from living things to their environment and back again.

Nitrogen Fixation by Lightning

A small amount of nitrogen is fixed into nitrates by lightning. The energy from the lightning causes nitrogen gas to react with oxygen in the air, producing nitrates. The nitrates dissolve in rain or surface water, enter the soil, and then move into plants through their roots. Plant cells can use nitrates to make DNA, and they can convert nitrates into amino acids, which they then string together to make proteins. When a plant is consumed by animals, the animal breaks down the plant proteins into amino acids and then can use the amino acids to make the proteins it needs.

Nitrogen Fixation by Bacteria

Some bacteria are capable of fixing nitrogen. These bacteria provide the vast majority of nitrates found in ecosystems. They are found mostly in soil. Nitrogen-fixing bacteria can also be found in small lumps called nodules on the roots of legumes such as clover, soybeans, peas, and alfalfa (**Figure 2**). The bacteria provide the plant with a built-in supply of usable nitrogen, while the plant supplies the nitrogen-fixing bacteria with the sugar they need to make the nitrates. This plant-bacteria combination usually makes much more nitrate than the plant or bacteria need. The excess moves into the soil, providing a source of nitrogen for other plants.

The traditional agricultural practices of including legumes in crop rotation and mixed planting capitalize on bacterial nitrogen fixation.

Figure 2
A clover root. You can see the swollen nodules where the nitrogen-fixing bacteria do their work.

Nitrogen and Decomposers

All organisms produce wastes and eventually die. When they do, a series of decomposers break down the nitrogen-containing chemicals in the waste or body into simpler chemicals such as ammonia (NH_3). Other bacteria convert ammonia into nitrites, and still others convert the nitrites into nitrates. These bacteria all require oxygen to function. The nitrates then continue the cycle when they are absorbed by plant roots and converted into cell proteins and DNA.

Farmers and gardeners who use manure and other decaying matter take advantage of the nitrogen cycle. Soil bacteria convert the decomposing protein in the manure into nitrates. Eventually, the nitrates are absorbed by plants.

Figure 3
Plants that grow in nitrogen-poor soils can form only a limited amount of chlorophyll. The yellowness of this plant's leaves indicates that the plant is starving for nitrogen.

Denitrification

At various stages in the decay process, denitrifying bacteria can break down nitrates into nitrites, and then nitrites into nitrogen gas. Eventually, the nitrogen gas is released back into the atmosphere. This process, called **denitrification**, is carried out by bacteria that do not require oxygen. Denitrification ensures the balance among soil nitrates, nitrites, and atmospheric nitrogen, and completes the nitrogen cycle.

Older lawns often have many denitrifying bacteria. The fact that denitrifying bacteria grow best where there is no oxygen may help to explain why gardeners often aerate their lawns in early spring. By exposing the denitrifying bacteria to oxygen, the breakdown of nitrates into nitrogen gas is reduced. Nitrates will then remain in the soil, where they can be drawn in by grass roots and used to make proteins.

This information may also help you understand why the leaves of some plants may not be a rich green colour. Chlorophyll is a protein, and plants require nitrates to make it. The colour of a plant's leaves may tell you the nitrate content of the soil (**Figure 3**).

The denitrification process speeds up when the soil is very acid or water-logged (oxygen content is low). Bogs, for example, are well known for their lack of useful nitrogen. They can support only a few types of plants — those able to live with low levels of nitrogen. Insect-eating plants, such as sundews and pitcher plants (**Figure 4**), are commonly found in bogs. In an interesting reversal of roles, these plants obtain their nitrogen by digesting trapped animals.

Figure 4
Insect-eating plants like this pitcher plant, a native of Ontario, can grow in nitrogen-poor soil.

The Phosphorus Cycle

Phosphorus is a key element in cell membranes, in molecules that help release chemical energy, in the making of the long molecules of DNA, and in the calcium phosphate of bones. Phosphorus tends to cycle in two ways: a long-term cycle involving the rocks of the Earth's crust, and a short-term cycle involving living organisms (**Figure 5**).

Living things divert phosphates from the normal (long) rock cycle. Phosphorus is found in bedrock in the form of phosphate ions (PO_4^{3-}), combined with a variety of elements. Phosphates are soluble in water and so can be dissolved out of rock. While dissolved, phosphates can be absorbed by photosynthetic organisms and so pass into food chains.

Phosphates eroded from rock are also carried by water from the land to rivers, and then to the oceans. In the ocean, phosphates are absorbed by algae and other plants, where they can enter food chains. Animals use phosphates to make bones and shells. When they die, these hard remains form deposits on the ocean floor. Covered with sediment, the deposits eventually become rock, ready to be brought to the surface again. The cycle can take millions of years to complete.

In the short cycle, wastes from living things are recycled by decomposers, which break down wastes and dead tissue and release the phosphates. The short cycle is much more rapid.

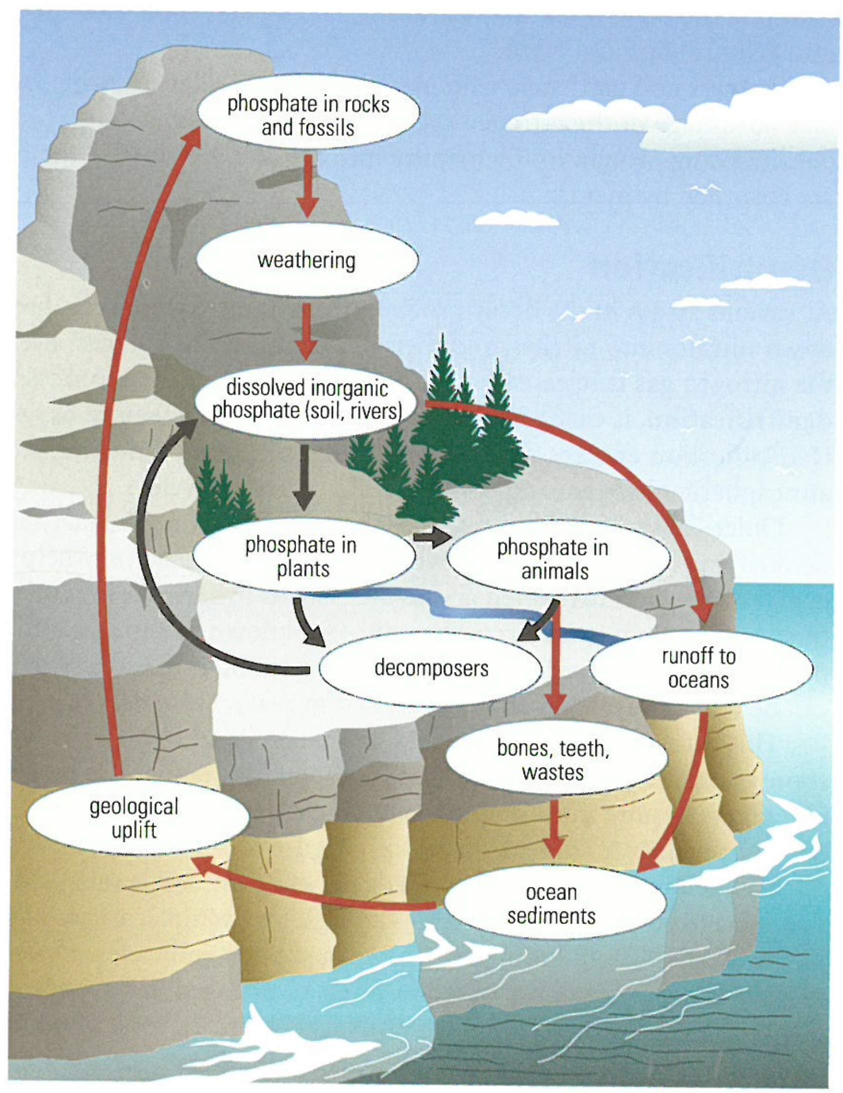


Figure 5
Phosphates cycle in both long and short cycles

Variations in Nutrient Cycling

Nitrates and phosphates are both nutrients. **Nutrients** are chemicals that are essential to living things. The rate with which nutrients cycle through an ecosystem is linked to the rate of decomposition. Organic matter decomposes relatively quickly in the tropical rain forests. Warmth, moist soil, and the vast number of diverse and specialized decomposers permit a cycle to be complete in as little as a few months. Cycling in cooler forests takes an average of between four and six years. In the even cooler tundra, nutrient cycling takes up to 50 years. In the oxygen-poor environment of most lakes, cycling may take even longer. Temperature and oxygen levels are the two most important abiotic factors regulating decomposition. Other factors, such as soil chemistry and the frequency of fire, also affect decomposition and cycling.

Understanding Concepts

1. Explain why nitrogen is important to organisms.
2. If nearly 79% of the atmosphere is nitrogen, how could there be a shortage of nitrogen in some soils?
3. How do animals obtain usable nitrogen?
4. Nitrogen-fixing bacteria are found in the roots of bean plants. Explain how the bacteria benefit the plant and how the plant benefits the bacteria.
5. Draw a diagram of the nitrogen cycle for a farm or garden where manure is used.
6. Explain why it is a good practice to aerate lawns.
7. Explain why phosphorus is important to living things.
8. Some farmers alternate crops that require rich supplies of nitrogen, such as corn, with alfalfa. Alfalfa is usually less valuable in the marketplace than corn. Why would farmers plant a crop that provides less economic value?
9. Explain why bogs and swamps are usually low in nitrogen.
10. Speculate about why clover would begin to grow in an older lawn. How would the presence of clover benefit the lawn?
11. Nitrate levels were analyzed from living material and soil samples in three different ecosystems (grassland, temperate rain forest, and tropical rain forest) in the same month. To determine the mass of nitrates in living things, all living plant matter was collected in a study area and the levels of nitrates were determined. The same analysis was conducted for the top layer of soil. The results are listed in **Table 1**, where each ecosystem is identified by a number.

Table 1 **Nitrate Content of Three Ecosystems**

Study area	Soil nitrates (kg/ha)	Biomass nitrates (kg/ha)	Soil temperature (°C)
1	30	90	25
2	10	175	19
3	2	270	30
tundra	?	?	?

   (a) In which community does nitrogen cycle most rapidly? Explain your conclusion.
   (b) Which ecosystem (grassland, temperate rain forest, and tropical rain forest) is study area 1, 2, and 3? Give reasons for your answers.
   (c) Speculate about the data that might be collected from a tundra ecosystem (**Figure 6**). Explain your prediction.

12. The phosphorus cycle has been described as having two components — a long cycle and a short cycle. The carbon cycle can be described the same way. Draw a diagram that splits the carbon cycle into "short" and "long"components.

Making Connections

13. With each grain harvest, nitrogen is removed from the field. Farmers have traditionally rotated the crops they plant in each field. A wheat crop was often followed by a legume crop. Because legumes support nitrogen-fixing bacteria, soil nitrogen levels are replenished. The use of nitrogen-rich fertilizers has allowed farmers to abandon crop rotation.
   (a) What advantages are gained from planting wheat year after year?
   (b) New strains of crops have been especially bred to take up high levels of nitrogen. These strains produce more grain. Speculate about some possible long-term disadvantages that these crops might present for ecosystems.

Reflecting

14. Crop rotation is an effective way of restoring nitrogen to the soil; however, the planting of legumes is not always popular with farmers. Legume crops may provide less income, because they are more difficult to tend, more costly to plant, difficult to harvest, or worth less in the marketplace. Farmers must continually balance short-term gains and long-term results in this way. Provide some examples of how you balance short-term gains with long-term results in decisions that you make.

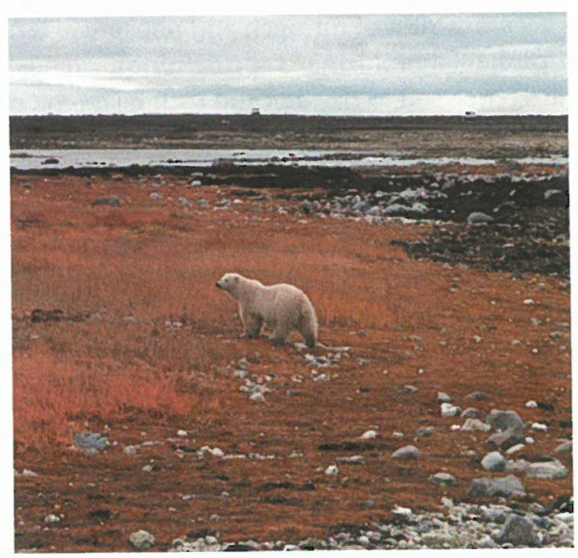


Figure 6

Agriculture and Nutrient Cycles

The seeds, leaves, flowers, and fruits of plants all contain valuable nutrients, which is why we eat them. However, as crops are harvested, the valuable nitrogen and phosphorus in these plants are removed and do not return to the field or orchard. This diversion of nitrates and phosphate from the local cycles would soon deplete the soil unless the farmer replaced the missing nutrients. **Fertilizers** are materials used to restore nutrients and increase production from land. Some estimates suggest that fertilizers containing nitrogen and phosphates can as much as double yields of cereal crops such as wheat and barley. However, fertilizers must be used responsibly. More is not necessarily better.

Soil bacteria convert the nitrogen content of fertilizers into nitrates, but the presence of high levels of nitrates may result in an increase in the amount of nitric acids in the soil. Changes in the levels of acidity can affect all organisms living in the soil, including decomposer bacteria.

Depending on the soil and the other chemicals in the fertilizer, a typical annual application of between 6 and 9 kg/ha of nitrogen fertilizer can in 10 years produce a soil that is 10 times more acidic. (An increase of 10 times means a drop in pH of 1, see **Figure 1**.) This can have devastating effects on food production. Most grassland soils in Canada's prairies have a pH near 7 (neutral). If the pH of the soil drops to 6, some sensitive crops like alfalfa and barley don't grow as well. The effect on agricultural land near the Great Lakes is even greater, as the local soils are more vulnerable to acids. A drop to a pH of 5 will affect almost all commercial crops. Acid rain and snow only add to the problem.

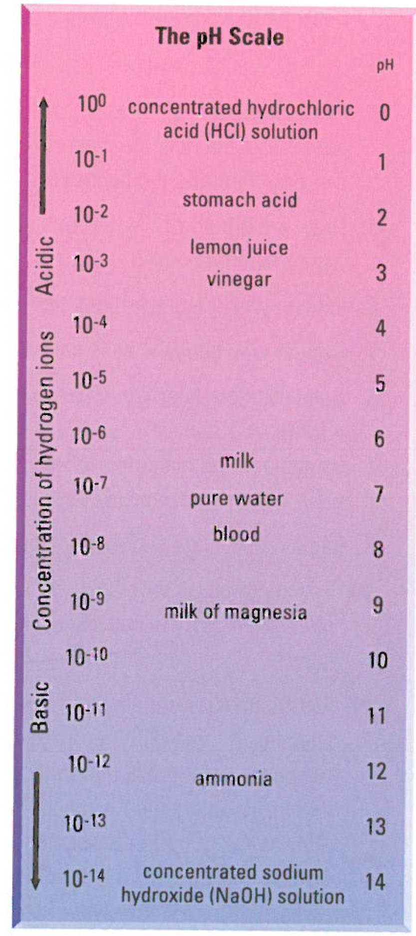


Figure 1
A drop in pH from 7 to 6 is a tenfold increase in acidity. A drop in pH from 7 to 5 represents a hundredfold increase in acidity.

Fertilizer and Ecosystems

The accumulation of nitrogen and phosphate fertilizers produces an environmental problem. As spring runoff carries decaying plant matter and fertilizer-rich soil to streams and then lakes, the nutrients allow algae in the water to grow more rapidly (**Figure 2**) in what is called an algal bloom. When the algae die, bacteria use oxygen from the water to decompose them. Because decomposers flourish in an environment with such an abundant food source, oxygen levels in lakes drop quickly, so fish and other animals may begin to die. Dying animals only make the problem worse, as decomposers begin to recycle the matter from the dead fish, allowing the populations of bacteria to grow even larger, and use still more oxygen.

Nitrates present another problem. As you have seen, there are bacteria that convert nitrates into nitrites. But nitrites are dangerous to animals that have hemoglobin in their blood, such as humans and other mammals, fish, reptiles, and amphibians. Nitrites can attach to the hemoglobin in blood, reducing its ability to carry oxygen to body tissues.

The problem of nitrates in water is especially serious for young animals, including human infants. Humans and other animals usually have bacteria that convert nitrates into nitrites in their large intestines. For adults, the presence of these bacteria in the digestive system is not

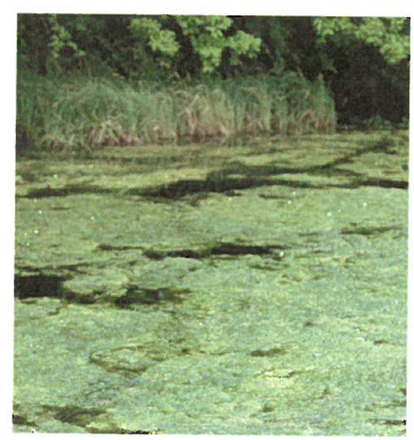


Figure 2
Spring runoff of nitrogen and phosphorus fertilizers promotes the growth of algae.

SKILLS HANDBOOK: (K) Planning an Investigation

harmful, because the stomach of an adult is so acidic that the bacteria cannot survive. But the stomach of an infant is much less acidic, so the bacteria can move up into the stomach, where they will convert nitrates into nitrites. The nitrites can then pass into the blood of the infant.

The question of how much nitrate should be allowed in drinking water and food is important, but we also need to know more about the nitrogen cycle in order to properly evaluate the environmental impact of nitrates.

Try This **Activity**

Effects of Nitrogen on Algal Growth

Spring runoff of nitrogen fertilizers causes algae to grow rapidly in neighbouring lakes. In some lakes, a film of algae coats the entire surface of the water. This makes the lake a lot less appealing to swim in, but more importantly the resulting lack of oxygen places other organisms in the ecosystem in peril.

By passing pond water through a filter and then allowing the filter and algae to dry, you can measure the mass of algae collected.

(a) Using this technique, design a controlled (K) investigation to measure how a fertilizer affects growth of algae.

- Have your design, safety precautions, materials, and written procedure approved by your teacher before beginning the (M) procedure. Conduct your investigation and collect your results.

(b) Report on the results of your investigation. (O2) Include an evaluation of your design, including suggestions for improvement.

Work the Web

Ploughing fields actually reduces the population of earthworms. Earthworms help decomposition and improve soil quality. Research the role of earthworms by visiting www.science.nelson.com and following the Science 10, 2.7 links. What recommendations would you make to farmers based on your research?

(M) Observing and Recording (O2) Evaluating the Evidence

Challenge

1,2,3 How will you address the problem of nitrogen fertilizers in your Challenge? What problems are created as excess nitrogen is carried from the land into aquatic ecosystems? How could you measure the problems?

Understanding Concepts

1. Why do the levels of nitrogen and phosphorus in fields decline when crops are harvested?
2. Explain how excess fertilizers might affect decomposing organisms.
3. (a) Why do algal blooms usually occur in spring?
   (b) Explain how algal blooms affect other organisms in freshwater ecosystems.
4. What dangers do high levels of nitrates in the drinking water present for infants?
5. Explain why not planting a crop and then ploughing in the fall might help a farmer restore nitrogen and phosphorus levels in the soil.

Making Connections

6. Human waste contains nitrates and nitrites. Before the arrival of municipal sewers, the backyard outhouse was standard for collection of human waste. Outhouses can still be found at some cottages. Outhouses consist of a small building over a hole in the ground. Explain why outhouses pose a risk to neighbouring lakes, using information that you have gained about the nitrogen cycle.
7. To decrease the amount of carbon dioxide in the atmosphere a group of scientists has proposed adding nitrogen and phosphorus fertilizer to the oceans.
   (a) How would dumping fertilizers in the ocean help reduce carbon dioxide levels?
   (b) What environmental problems could be caused by the approach?
   (c) Suggest how an environmental modelling experiment could help determine the impact of adding fertilizers to the ocean.

Reflecting

8. Fertilizers have been with us for a long time. Explain why we must begin changing our views on the use of fertilizers so the ecosystems we live in will be sustainable. Why is it so difficult to change practices?

Effects of Deforestation on Cycling

Measurements have shown that matter cycles continuously within closed ecosystems. Based on those experiments, ecologists speculated about the impact that human activities had on the cycling of matter in the biosphere, but because they couldn't do controlled experiments, they could not demonstrate whether their speculations were accurate. Important questions, such as "How does deforestation affect nutrient cycling?" (**Figure 1**) could be answered only through environmental simulations, so the results were unreliable. In this case study you will examine a large-scale attempt at a controlled experiment in a natural ecosystem.

Figure 1
It is difficult to carry out a controlled experiment on the effects of logging on matter cycles.

(a) Imagine that you were going to carry out an experiment on how nutrient cycles in a forest are affected by logging. What would you want to measure? (K4)

Trying the Experiment

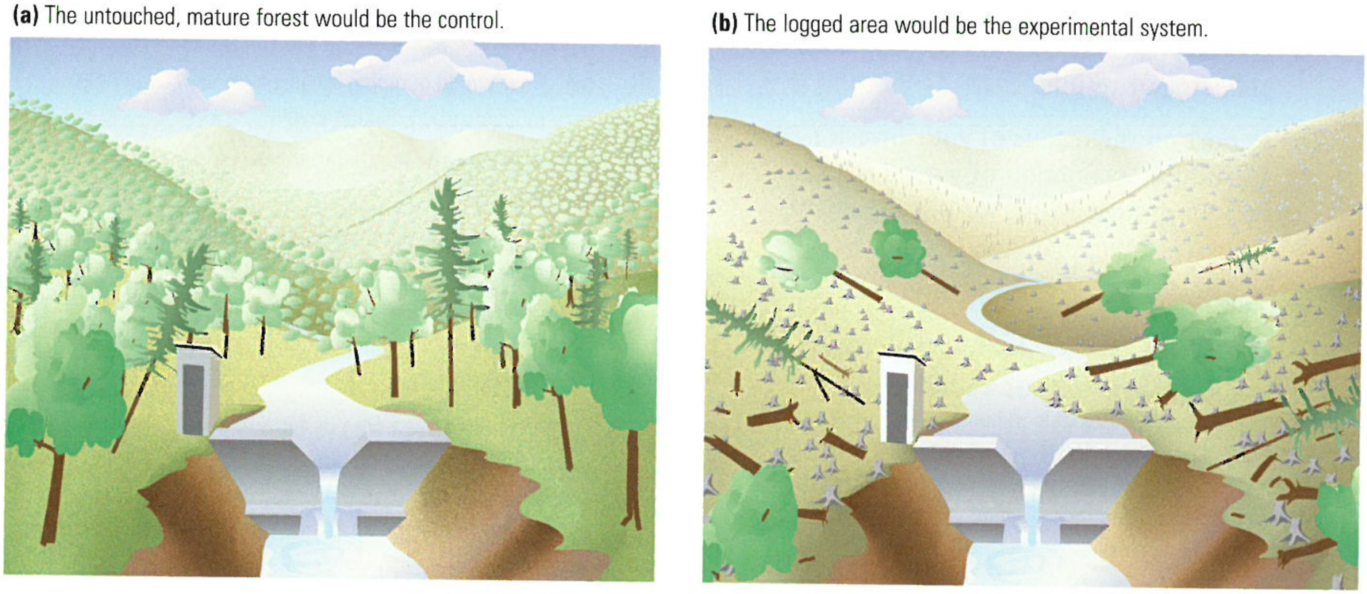
As part of a series of experiments that are still continuing, in the 1960s, Yale and Cornell universities conducted a large-scale study at Hubbard Brook Experimental Forest in New Hampshire. Researchers designed a controlled experiment to compare the flow of water and nutrients from a mature forest with the flow from one that would be logged (**Figure 2**) during the study. The mature forest would serve as a control, while the cut forest would serve as the experimental system. Concrete dams were constructed across creeks flowing out of the forests. Because the dams were anchored to bedrock, no water could slip by, and water volumes and dissolved nutrients could be measured.

(b) What advantages would be gained by conducting the experiment on a natural ecosystem, as opposed to a computer simulation?

Figure 2
The Hubbard Brook controlled experiment

(a) The untouched, mature forest would be the control.

(b) The logged area would be the experimental system.



SKILLS HANDBOOK: K4 Creating the Design

Setting Up

In the first part of the experiment, before cutting any trees, researchers measured the amount of water and nutrients that entered and left the forests. For several years, precipitation gauges measured water flow into the forest ecosystems. Water inflow samples were also collected to determine the amount of nutrients that entered the forests in each of the valleys. Finally, the amount of water leaving the two forest ecosystems was measured, and the water analyzed for nutrients. The nutrient inflow was found to be equal to the nutrient outflow in the two forests. In addition, scientists found that the amount of nutrients that flowed in and out was very small compared to the quantity of nutrients being cycled in the forest ecosystems.

(c) What conclusions can you draw from the initial measurements?

Experimental Logging

In the next part of the experiment, researchers disturbed the experimental ecosystem by systematically cutting down trees. The trees and shrubs were left on the ground and the soil was not disturbed any more than necessary. The cut area was then sprayed with herbicides to prevent further growth. Researchers continued to monitor water and nutrient inflow and outflow for both forests.

(d) Predict what would happen to the volume of water outflow after the trees and shrubs were cut. Explain your prediction.

(e) How would the change in runoff in the logged area affect the amount of nutrients flowing out of the forest ecosystem?

Measuring Changes

Overall, the flow of nutrients from the cut forest was four to six times greater than from the unlogged forest, but the flow of nitrates was much greater (**Figure 3**).

(f) Study the concentration of nitrates flowing from the forested system. Explain the annual peaks in the flow.

(g) Compare nitrate outflow from the mature forest and logged area from 1965 to 1971. Speculate about the reasons for the changes.

Understanding Concepts

1. Algal growth increases in valleys that have been logged. Explain why.
2. Assume that all the dead trees in the logged sites dry out. At some point, lightning strikes the area and the logs burn. How would the fire affect the flow of nutrients from the logged area?
3. Critique the experimental design used by the Hubbard Brook researchers. Identify problems for the design that were created by:
   - **(a)** using herbicides to prevent growth of plants following the logging of the area.
   - **(b)** leaving the trees and the shrubs that were cut on the ground in the experimental forest.

Making Connections

4. In much of Central and South America, farmers cut and burn rain forests to open land for the growing of crops.
   - **(a)** Use a series of diagrams to show the effects of this practice on nutrient flow.
   - **(b)** What could the farmers do instead to increase output from their current land? What effects would you expect your recommendations to have on local ecosystems?

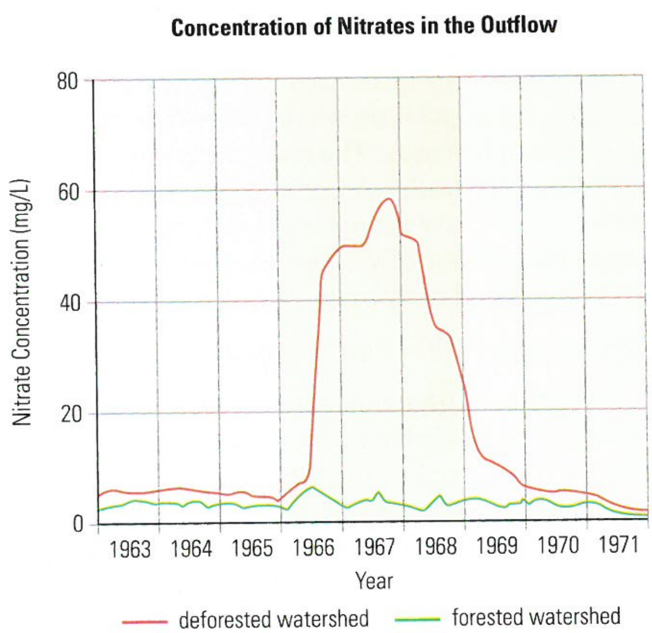


Figure 3
Flow of nitrates from both forests

2.9

Monitoring Changes in Populations

The population of humans on the planet remained remarkably stable for thousands of years before the invention of agriculture. When a significant number of human societies switched from hunting and gathering to agriculture, the population of humans began to grow. Societies that harvest and store food for use during the winter months or during periods of drought have an advantage over those that must seek their food every day. During the centuries that followed the switch to agriculture, there was a steady rise in the human population, but no real explosion. It was not until the mid-1600s that the global human population reached about 500 million.

During the last three centuries, the global population has risen at an exponential rate (**Figure 1**). The population increased from 500 million in 1650 to 1 billion in 1850. That doubling took 200 years. The next doubling, to 2 billion people, took 80 years. From 1930 to 1975 (45 years) the population doubled again, to 4 billion. At the current annual growth rate of 1.55%, which adds about 80 million people per year, the next doubling to 8 billion will be complete by 2013, only 39 years.

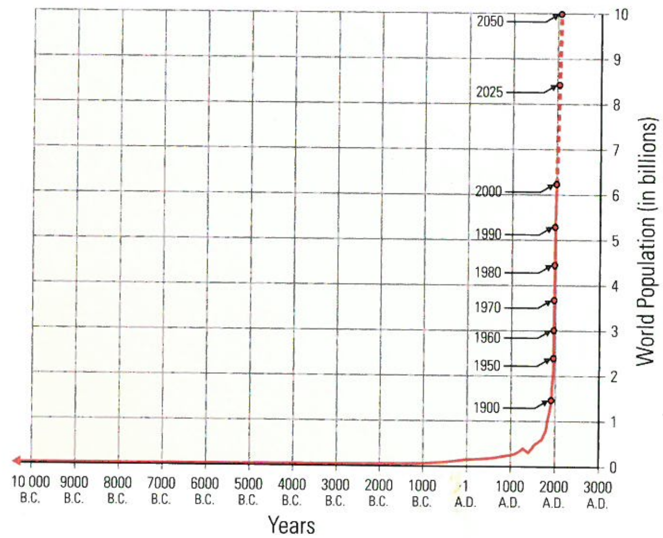


Figure 1
The global human population is growing rapidly.

Population Growth Patterns

Changes in population size in a community occur when individuals are added to or removed from a population (**Table 1**).

If **natality** (the birth rate) increases while other factors remain constant, the population will increase. The same holds true if immigration increases. The reverse effect occurs if there is an increase in **mortality** (the death rate) or emigration. In populations in natural ecosystems, all four factors interact, with natality and mortality generally having the greatest effect. The four factors involved in population growth can be expressed mathematically by the formula

Population growth = (births + immigration) – (deaths + emigration)

In mature ecosystems, where resources tend to be constant or available in predictable patterns, populations remain relatively stable over the long term (population growth = 0). Increases in natality are balanced by increases in mortality or increased emigration. This balance is referred to as dynamic equilibrium, or a steady state.

Table 1 **Factors That Affect Population Size**

Factor	Description
natality (births)	the number of offspring of a species born in one year.
mortality (deaths)	the number of individuals of a species that die in one year.
immigration	the number of individuals of a species moving into an existing population.
emigration	the number of individuals of a species moving out of an existing population.

Open and Closed Populations

Ecologists classify populations as either open or closed. In most natural ecosystems all four factors (natality, mortality, immigration, and emigration) are acting on the population of each organism. These populations are said to be **open populations**. However, immigration and emigration do not happen in laboratory settings and in some game reserves, so populations of organisms in these situations are considered **closed populations** — only natality and mortality affect their population size.

The global population of humans or any other type of organism is also considered a closed population. People do not emigrate to other planets, and as far as we know none are immigrating either. Changes in the size of a global population result only from natality and mortality.

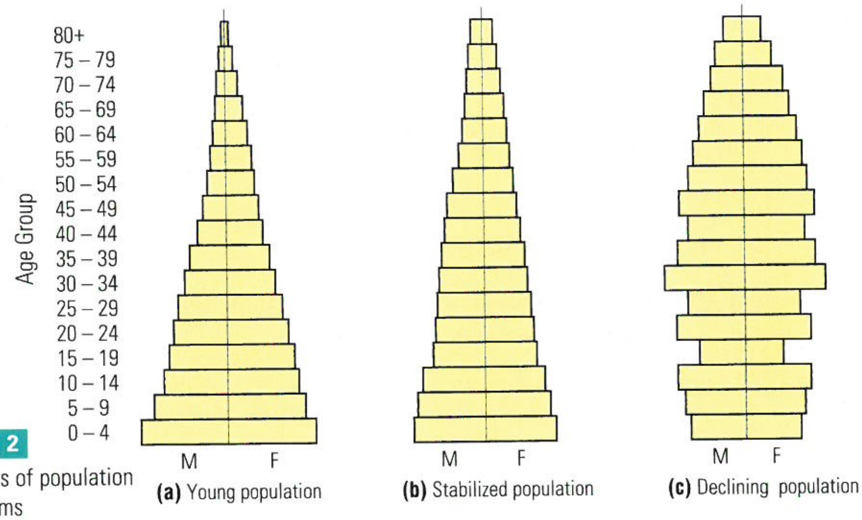


Figure 2

Examples of population histograms

The current growth rate of the global human population is about 2.7 times as many births as deaths, which means that in 1996 Earth's population of 5.8 billion increased by 89.9 million people, or by 246 200 people each day. The human population is not in dynamic equilibrium.

Population Histograms

Population histograms (**Figure 2**) are useful when studying populations of long-lived organisms, such as humans. Double histograms are often used to provide a profile of age groups by sex. These histograms allow you to examine the population of an organism in terms of its age structure and the proportions of males and females at a specific instant in time.

The shape of the pyramid allows you to predict changes in the population. A pyramid with a wide base, as shown by histogram **(a)** in **Figure 2**, is characteristic of a rapidly growing population. It means that the number of births has been high recently. Another indicator of future growth is the number of individuals capable of reproduction. If this number is high, it means that a large number of births can be expected in coming years. In a human population, individuals of reproductive age would be found at the centre of the pyramid.

In contrast, histogram **(b)** in **Figure 2** represents a fairly stable population. There have been fewer births than in the A population. In addition, with infant mortality higher than the mortality of most other age groups, the population is growing very slowly. This population is approaching what is often described as zero population growth.

When the base of the pyramid is narrower than the middle section, as shown in histogram **(c)**, fewer offspring are being produced. If the trend continues, this population will decline. **Figure 3** shows population histograms for three countries.

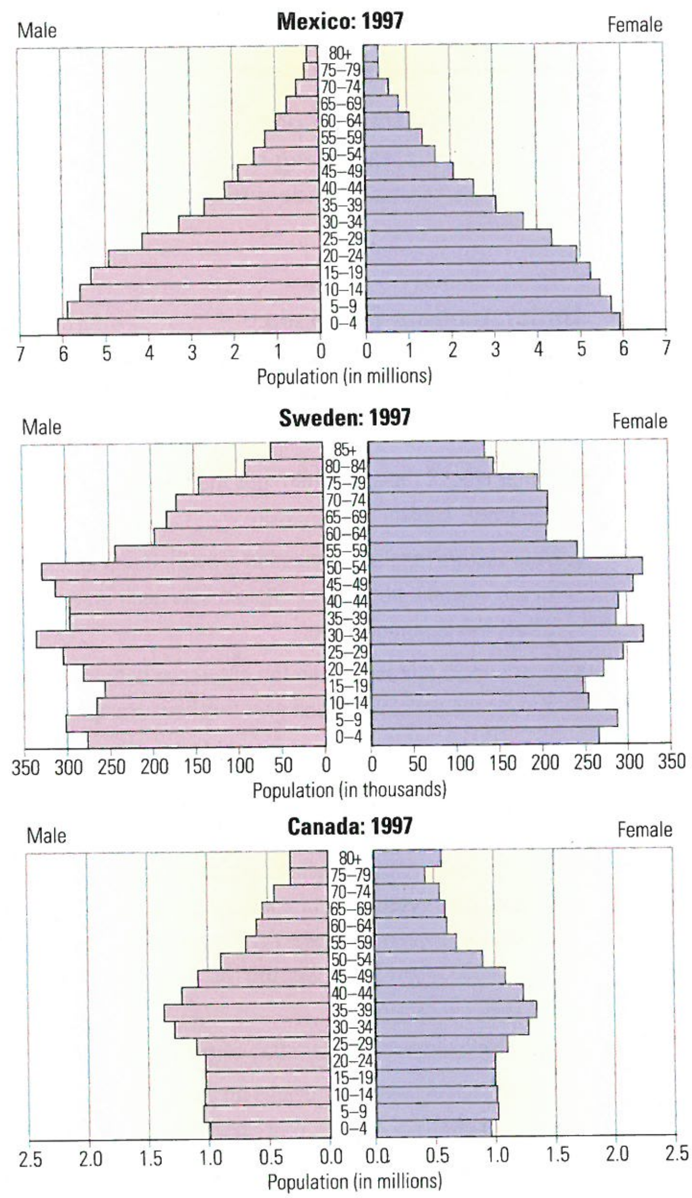


Figure 3

Mexico has a rapidly growing population, while the population in Sweden will soon start to decline. Based on the histogram, what do you predict for the future of the Canadian population?

Try This Activity Making a Histogram

To draw a histogram, you must start with population data (Table 2).

Table 2 Age Distribution of Humans in a Shopping Mall (Wednesday at 5 p.m.)

Ages	Female	Male
0–4	8	7
5–9	6	4
10–14	8	2
15–19	5	1
20–24	3	5
25–29	9	3

- Begin by drawing population size values along the *x*-axis, extending to both the right and left of the *y*-axis. Decide which half of the graph will represent the female population and which half will represent the male population.
- For the first category (0 to 4 years old), draw a bar for the number of females (8) on one side and a bar representing the number of males (7) on the other. Make sure to label the age distribution.
- Add a bar for each of the age categories.

(a) Complete the histogram showing age distribution from a shopping mall. What conclusion can you draw from interpreting the histogram?

(b) How might the results of the histogram differ if readings were taken at 10:00 a.m. on a Monday or 10:00 a.m. on a Saturday?

Understanding Concepts

1. In your own words, explain the difference between populations with linear and exponential growth rates. Provide examples in your answer.

2. What type of growth pattern has the human population followed? Explain your answer.

3. Four factors regulate population growth. Using an example of a nonhuman population, explain how each factor would affect the population size.

4. In your own words, explain the difference between open and closed populations and give two new examples of each.

5. Draw a population histogram that represents a population with a declining growth rate. Explain why the population you have represented will decline.

6. A single-cell organism called *paramecium* is found in pond ecosystems. In this type of ecosystem *paramecia* feed almost exclusively on algae. As the pond slowly warms, more algae grow. To answer the following questions, use the graph in **Figure 4**.

(a) Explain why the population of *paramecia* is increasing.

(b) Which population provides an example of a linear growth rate? Explain your answer.

(c) Predict what might happen to the population of algae and *paramecia* after point B.

(d) Sketch ecological pyramids of numbers for points A and B.

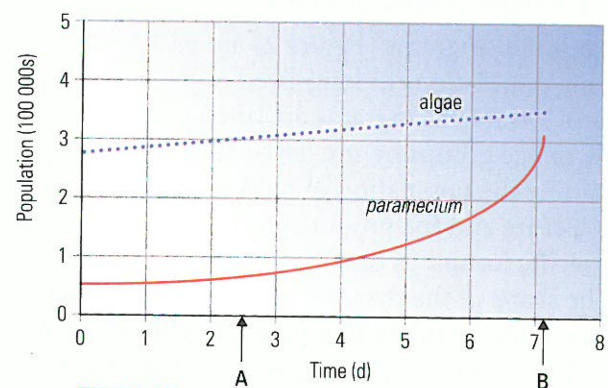


Figure 4

7. In January, 1999, the population of varying hares in a mixed woodland ecosystem was 60. During 1999, the following data on the hare population were obtained:

births = 20 deaths = 25
immigration = 3 emigration = 7

(a) Calculate the population of hares in January, 2000.

(b) Calculate the population growth as a percentage of the original population.

Work the Web

Visit www.science.nelson.com and follow the links from Science 10, 2.9. Select population data that could be represented by a histogram. Present the data first in table format and then in a histogram. Based on your histogram, make a prediction about the growth of the population.

2.10

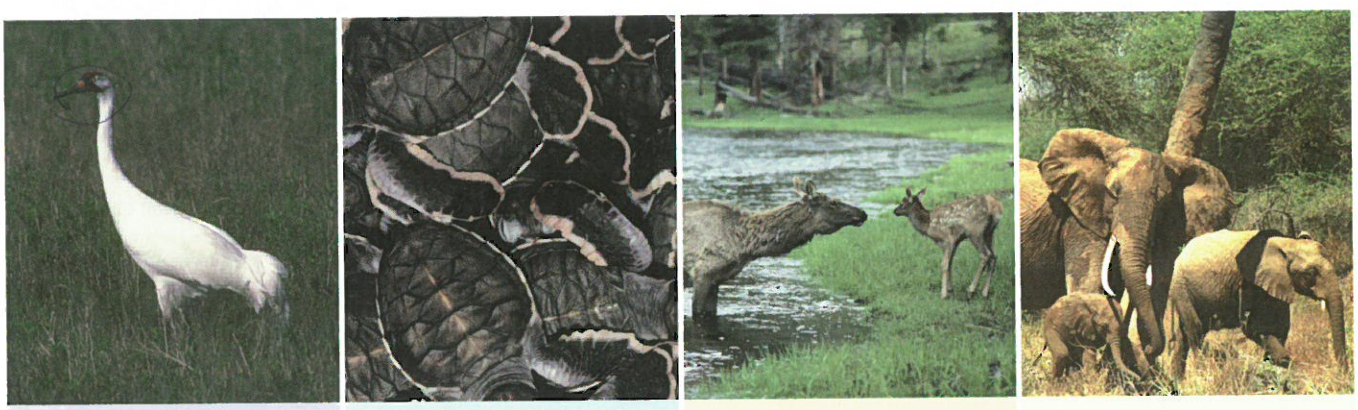
Limits on Populations

Field mice may have litters with six or more pups, and they can reproduce every six weeks. It takes only six weeks for a mouse to become sexually mature. In 6 months, a population of 20 mice could become a population of 5120 mice. Mice have been around for millions of years, so why is it that when you look out the window you see grass and trees, birds and squirrels, and not a vast carpet of millions and millions of mice?

The reason is that there are limits on all populations, including those of the prolific mouse.

Biotic Potential

One of those limits on population is imposed by the species on itself. Species vary in their capacity to reproduce. **Biotic potential** is the maximum number of offspring that a species could produce, if resources were unlimited. You have seen how quickly field mice reproduce, but many animals have a much lower biotic potential. For example, mature female black bears give birth to one or two cubs after a gestation period of 7.5 months. Generally, bears take at least two years to mature, during which time their mother will not give birth again. Biotic potential is regulated by four important factors, shown in **Figure 1**.



Factor: birth potential

Description: The maximum number of offspring per birth.

Whooping crane females lay two eggs per year, and only one chick survives.

Factor: capacity for survival

Description: The number of offspring that reach reproductive age.

The female sea turtle lays many eggs, but only a few of her offspring even reach the sea, and fewer still reach maturity.

Factor: procreation

Description: The number of times that a species reproduces each year.

Elk mate only once per year, during the fall.

Factor: length of reproductive life

Description: The age of sexual maturity and the number of years the individual can reproduce.

African elephants reach sexual maturity at about 15 years of age, but may reproduce until they are 90.

Figure 1
Factors that determine biotic potential

Limiting Factors

The environment provides factors that prevent populations from attaining their biotic potential. Any resource that is in short supply is a limiting factor on a population. Food, water, territory, and the presence of pollutants and other toxic chemicals are all limiting factors, as shown in **Table 1**.

Table 1 **Factors That Limit Populations**

	Factors that cause a population to increase	Factors that cause a population to decrease
Abiotic	favourable light favourable temperature favourable chemical environment	too much or too little light too cold or too warm unfavourable chemical environment
Biotic	sufficient food low number or low effectiveness of predators few or weak diseases and parasites ability to compete for resources	insufficient food high number or high effectiveness of predators many or strong diseases and parasites inability to successfully compete for resources

For example, a fern plant produces more than 50 000 spores in a single year (**Figure 2**). If all fern spores germinated, fern plants would cover all of North America within two generations of the first plant. This doesn't happen because of the limiting biotic and abiotic factors. If the weather is wetter than usual, the soil is moist, and many fern spores will germinate, so the fern population will increase. A return to drier weather will not only prevent spores from germinating, but will also kill plants in exposed areas, so the population declines. The presence of many grazing animals will reduce the population of ferns, and if there are few grazers the population will grow (**Figure 2**). Fluctuations like these, caused by one factor, can occur in natural ecosystems; however, most populations are affected by more than one factor at a time.

Figure 2
Abiotic and biotic factors limit the number of ferns in an ecosystem.

Carrying Capacity

Populations fluctuate regularly due to an interaction of the many biotic and abiotic limiting factors. However, communities do tend toward stability. Stability is achieved when an ecosystem is in equilibrium, when none of the populations exceeds the carrying capacity of the ecosystem. The **carrying capacity** is the maximum number of individuals of a species that can be supported indefinitely by an ecosystem. The carrying capacity for any species is determined by the availability of resources, such as food and water.

A population can exceed the carrying capacity of the ecosystem, but not for long. Consider the field mouse again. Imagine that the population of predators is lower than usual. Suddenly, the mouse population can grow. However, the extra mice will eat all the available food. Hungry rodents soon become sickly — making them easy prey for the hawks, owls, and foxes that are present. The mouse population will decline again, to or below the carrying capacity. Ecosystems soon re-establish equilibrium.

Did You Know?

The "lemming mass suicides" you may have seen or read about don't really happen. When Arctic lemming populations grow larger than the local carrying capacity, many of the lemmings migrate to neighbouring territories. They always try to arrive alive when they migrate.

Limits of Tolerance

You have seen that the survival and reproduction of an organism depend on the presence of nutrients and the ability of the organism to withstand the abiotic factors in the environment. This understanding has developed over many years.

In the mid-1800s, Justus von Liebig noted that certain substances must be present if plants are to grow. If any one of these substances is present in low amounts, the growth of the plant is reduced, regardless of how much of the other substances is present. This observation became known as the **law of the minimum:** the nutrient in least supply is the one that limits growth.

In 1913, Victor Shelford added to von Liebig's work by noting that too much of a factor can harm an organism. This principle is often called Shelford's **law of tolerance:** an organism can survive within (tolerate) a certain range of an abiotic factor; above and below the limit it cannot survive. The greater this range of tolerance, the greater the organism's ability to survive.

As seen in **Figure 3**, maximum population size is possible when the abiotic factor is at an optimum level within the range of tolerance. However, many abiotic factors act on a species at any given time. Most species have a broad range of tolerance for some factors, and a narrow range for others.

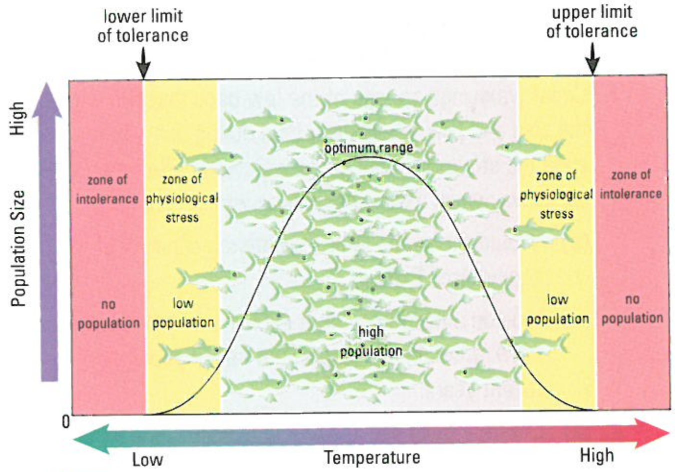


Figure 3

The population of a fish species is likely to increase as the water temperature gets closer to the optimum. None of the fish can survive if the water gets too hot or too cold.

Table 2 Factors that Cause Changes in Populations

Density-independent factors	Density-dependent factors
• flood • fire • spraying with pesticides • change in climate or temperature • destruction of habitat • drought	• food shortage • competition for mates, breeding areas (habitat) • disease caused by a microorganism or parasite • introduction of an exotic species • increased predation • competition for water and other resources

Density Dependent and Independent Factors

The number of organisms in an ecosystem is important when considering the effects of some abiotic and biotic factors. A population is said to be dense when there is a large number of organisms in a small area.

Density-independent factors affect members of a population regardless of population density. Fire and flood are two naturally occurring events that are density-independent. They will affect a population regardless of its size.

When the density of a population increases, other factors may limit further growth or reduce population numbers. **Density-dependent factors** affect a population *because* of the density of the population. Food supply, water quality, sunlight, disease, and territory are density-dependent factors. For example, when a tree in a dense forest becomes infected with a fungal blight, the infection will spread more quickly than it would in a forest where trees are separated by larger distances.

Similarly, individuals in more densely populated areas are more prone to starvation, as food is in lower supply. Competition for food may leave animals weak and more susceptible to predation. The density-dependent factors in **Table 2** will cause higher mortality rates, lowering the population density. When the population density is reduced, the effects of the density-dependent factors are also reduced.

Challenge

1,2 Changes in populations of different species are often used to assess environmental impact. Species can either be counted or be measured by mass. How will you monitor changes in populations to determine environmental impact for your Challenge?

3 There are more resources in a tropical rain forest than in a tundra ecosystem, so the forest is able to support many more animals and many more different species. In designing your board game, how will you teach players how carrying capacity limits the number and type of organisms in an ecosystem?

Understanding Concepts

1. Cedar waxwings are one of the few birds that can withstand the cold and lack of available food during our winters. To ease the strains of winter, bird watchers in Barrie provide cedar waxwings with seeds during winter months.
   - **(a)** Would the seeds alter the carrying capacity of the ecosystem? Explain.
   - **(b)** Provide a hypothesis that explains why bird watchers have noted an increase in the falcon population in recent years.
2. **(a)** Create a table like **Table 3** and classify the following information within it.
   - Larger mammals generally live longer than smaller ones.
   - Pregnant female elephants carry their young for nearly 18 months.
   - Elephants reach sexual maturity at 15 years.
   - Elephants usually produce one offspring each birth.
   - Most elephants wait more than 5 years between births.
   - Female elephants care for their young for more than 10 years.
   - Mice often produce litters of 6 or more.
   - After about 6 weeks, mice reach sexual maturity.
   - In a natural setting, few mice are older than 2 years.
   - A pregnant female mouse will carry her young for 22 days.
   - Mice will breed every 6 weeks or less.

Table 3

Biotic potential	Elephant	Mouse
offspring per birth		
capacity for survival		
procreation		
maturity		

   (b) Refer to your table and write a paragraph comparing the biotic potentials of elephants and mice.
3. A scientist studying wolves near Kirkland Lake notices a steady decline in the population of wolves for four consecutive years.
   - **(a)** Make a prediction about how the population of wolves will affect the population of moose. Give your reasons.
   - **(b)** Assuming that humans are not the cause of the wolf population decline, would it be reasonable to conclude that the wolf population will continue to decline until there are no more wolves left in the area? Give your reasons.
   - **(c)** What might cause the wolf population to begin increasing again?
   - **(d)** Using a flow chart, explain how changes in the wolf population would affect the plant community surrounding Kirkland Lake.

Making Connections

4. In an attempt to increase the local food supply for people, humans introduced 26 reindeer (24 females and 2 males) to an island off the coast of Alaska in 1910. **Figure 4** shows how the reindeer population changed after the introduction.

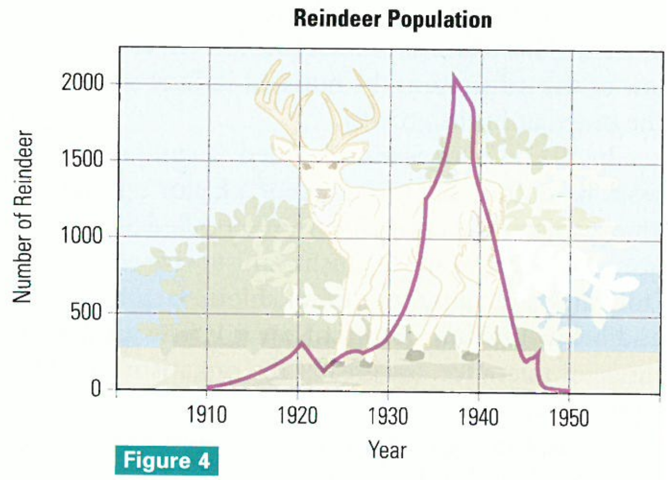


Figure 4

   - **(a)** Speculate as to why more females were introduced than males.
   - **(b)** By 1937 the reindeer population had soared to 2000. What evidence supports the hypothesis that the carrying capacity for reindeer had been exceeded?
   - **(c)** Reindeer feed on slow-growing lichens and moss. Would you expect to find more food for reindeer on the island in 1931, 1935, or 1950? Explain your answer.
   - **(d)** The introduction of a new species can cause major changes in an ecosystem. Should the reindeer have been put on the island? Explain your position.
5. Technological advances in agriculture have changed the carrying capacity for humans of most ecosystems.
   - **(a)** Give some examples of agricultural advances and how they have affected carrying capacity.
   - **(b)** Has the planetary carrying capacity for humans been reached, or can the human population grow larger without reaching capacity? In an essay, explain your position.