8.3 Cycling of Matter and the Climate System

Key Terms
biogeochemical cycle
store
global carbon budget
nitrogen fixation

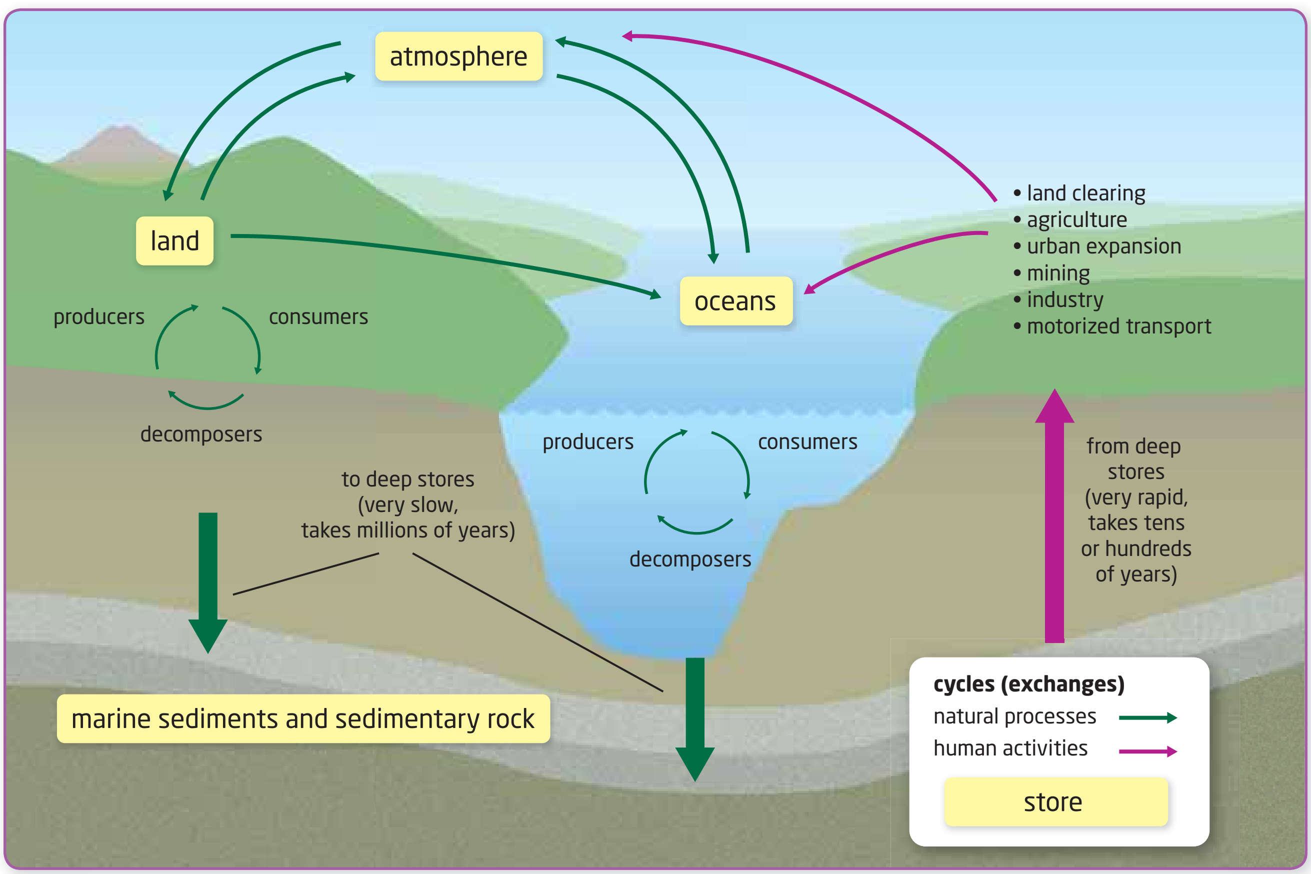
You have learned that Earth and its atmosphere behave as a closed system. This system contains a fixed amount of matter that cannot increase or decrease. However, you also know that the concentration of greenhouse gases in the atmosphere has been increasing. Where did these additional gases come from? The answer lies in natural cycles that transfer matter continuously among the atmosphere, land, water, and living things. An increase in matter in one part of the system is balanced by a decrease in matter in another part of the system. This circulation of matter is known as a **biogeochemical cycle**.

In a typical biogeochemical cycle, materials remain for a short or long period of time in part of the cycle before passing on to the next part of the cycle, as shown in **Figure 8.20**. Places where matter is stored for longer periods are known as **stores**. Stores are also commonly referred to as *reservoirs*. Usually, the cycle is in balance because the amount of material flowing into a store, such as the atmosphere, is nearly the same as the amount flowing out of the store. Human activities, such as coal mining and oil drilling, alter the balance of natural cycles by rapidly releasing large amounts of materials from stores, as illustrated in **Figure 8.20**. For example, burning fossil fuels releases carbon and nitrogen from stores underground and transfers them into the atmosphere. Disruptions of the carbon cycle and the nitrogen cycle by human activities have been a significant cause of recent climate change.

biogeochemical cycle a natural process that exchanges matter and energy between the abiotic environment to the biotic environment and back

store a part of a biogeochemical cycle in which matter or energy accumulates; also called a reservoir

Figure 8.20 Human activities can disrupt natural cycles. The purple arrows indicate human activities that affect natural processes, which are illustrated by the green arrows.



The Carbon Cycle and Climate Change

Study Toolkit

Word Parts Break the word *biogeochemical* into parts. Determine what each word part means. Then combine the meanings of the word parts to infer the definition of the whole word.

You already know that carbon dioxide is added naturally to the atmosphere by respiration and is removed from the atmosphere by photosynthesis. However, this balanced exchange of carbon compounds between living things and the atmosphere forms only one small part of the planet-wide carbon cycle, as shown in **Figure 8.21**. Carbon compounds are found in several stores on Earth, as shown in **Table 8.6**. These stores differ greatly in size and in the average length of time that carbon remains in each form. As you learned in Section 8.2, the gases carbon dioxide and methane contain carbon. Some rocks, such as limestone, and sediments on the sea floor contain solid forms of carbon, as do the bodies of living things. Carbon also exists as a solid in coal and as a liquid in oil. Carbon changes form as it moves through the carbon cycle; it can be a solid, a liquid, or a gas.

Table 8.6 **Major Stores of Carbon on Earth**

Store	Estimated amount of carbon (gigatonnes)	Residence time
Marine sediments and sedimentary rock	68 000 000 to100 000 000	Carbon is trapped in these rocks for millions or billions of years.
Oceans	39 000	Much of the dissolved carbon may remain in the ocean for 500 to 1000 years as the cold, slow-moving, deep currents move along the ocean floor.
Fossil fuels (coal, oil, and gas)	3 300	Converted into fossil fuels, the carbon can not cycle back into the atmosphere or into living things for hundreds of millions of years.
Vegetation, soil, and organic matter	2 115	Studies indicate that carbon stays in living things for an average of 5 years and in soil for approximately 25 years.
Atmosphere	750	Carbon dioxide remains in the atmosphere for a long time—between 50 and 500 years. Methane has a short atmospheric lifetime of only about 12 years. Nitrous oxide remains in the atmosphere for about 115 years.

The Global Carbon Budget

global carbon budget the relative amounts of carbon in different stores; also an accounting of the exchanges (incomes and losses) of carbon between the stores of the carbon cycle

The **global carbon budget** is a way of describing the exchanges of carbon in different parts of the carbon cycle. In a balanced carbon budget, the rate at which carbon dioxide enters the atmosphere is approximately equal to the rate at which it leaves the atmosphere. As **Figure 8.21** shows, carbon moves from the atmosphere into the other stores mainly by photosynthesis and by dissolving in the ocean. Carbon is released into the atmosphere when carbon dioxide is released from vegetation, soil, and organic matter by the respiration of plants and animals, and by the decomposition of dead matter by microorganisms. Carbon dioxide is released from fossil fuels by combustion. In the ocean, carbon dioxide comes out of solution from warmer surface waters. Carbon dioxide is released from sedimentary rock when limestone breaks down. Volcanic eruptions also release carbon dioxide into the atmosphere.

The Atmosphere Carbon dioxide is released into the atmosphere from the top layers of the ocean and from the burning of fossil fuels. Carbon is stored in the atmosphere mainly as carbon dioxide, but is also present in methane and chlorofluorocarbons.

Vegetation, Soil, and Organic Matter
On land, most carbon is stored in plants and animals and in decaying matter and organisms found in soils. Carbon atoms move into living things as animals eat or as plants take carbon dioxide from the air. Carbon moves out of living things as they respire and as cells are replaced with new cells.

The Oceans Carbon dioxide from the atmosphere dissolves in the top layers of the ocean. The carbon remains dissolved in the water that sinks to form deep ocean currents.

Fossil Fuels Coal, oil, and natural gas are called fossil fuels because they formed from the remains of plants and micro-organisms that were buried by sediments millions of years ago. The carbon in these organisms became locked in rock instead of being released by decomposition.

Marine Sediments and Sedimentary Rocks
Marine animals, such as corals, clams, oysters, and mussels, use carbon to build their shells and other hard structures. Shells, sediments, and other materials build up in layers on the seabed and eventually harden to form sedimentary rocks, such as chalk and limestone.

Figure 8.21 The carbon cycle involves the movement of carbon between the oceans, atmosphere, rock, and living things on Earth. Changes in the balance of carbon in different carbon stores can result in climate change.

Activity 8-4

Modelling Carbon Stores

Which carbon store holds the most carbon? In this activity, you will use sticky notes to represent carbon that is stored in various stores.

Materials

- 10 yellow sticky notes
- 1 pink sticky note
- 1 blue sticky note
- 5 photographs

Rules

1 blue sticky note = 50 yellow sticky notes
1 pink sticky note = 100 000 yellow sticky notes

Procedure

1. Use the list of stores in the table to identify the carbon stores represented by each photograph. Identify the form that carbon takes in each store. Record your answers on each photograph.
2. Arrange the photographs in a circle on a table.
3. Use the information in the table to identify the number of sticky notes that belong in each store. Place the proper number of sticky notes on each photograph.

Questions

1. Which store holds the most carbon? How long does carbon remain in that store?
2. What factors affect how much carbon is in the fossil-fuels store? How would you model the recent change in the rate at which carbon remains in that store?
3. How does the thermohaline circulation pattern in the ocean affect the amount of carbon in the ocean?
4. Can you see any relationship between the amount of carbon in a store and the length of time that the carbon remains in the store?

Major Stores of Carbon on Earth Relative to the Atmosphere

Store	Relative Amount in Store
Rock and sediments	91 000–130 000
Oceans	52
Fossil fuels	4
Vegetation, soil, and organic matter	3
Atmosphere	1

How Human Activities Affect the Carbon Cycle

Human activities alter the carbon cycle by changing the relative amounts of carbon in each store and the length of time that carbon remains in each store. For example, carbon compounds are stored as fossil fuels for hundreds of millions of years. When humans burn fossil fuels, these carbon compounds are released into the atmosphere in much larger amounts and in a much shorter time period than they would be naturally. As a result, carbon compounds build up in the atmosphere, which leads to global warming.

When the amount of carbon dioxide in the atmosphere increases, the oceans begin to absorb additional carbon dioxide from the atmosphere. This process is part of a natural negative feedback loop that acts to maintain the amount of carbon dioxide in the atmosphere and, thus, the global average temperature. However, this absorption of carbon dioxide by the oceans causes the oceans to become warmer and more acidic, and their ability to absorb carbon dioxide is reduced. This imbalance could result in a positive feedback loop that accelerates the rate of global warming.

Learning Check

1. What is the relationship between the terms *biogeochemical cycle* and *store*?
2. Identify the five carbon stores described in **Figure 8.21**.
3. Draw a time line that illustrates the relative amounts of time that a single carbon atom would spend in each reservoir if it were traced through the entire carbon cycle.
4. How does driving to school upset the global carbon budget?

The Nitrogen Cycle and Climate Change

Eighty percent of the atmosphere consists of nitrogen gas (N_2). In this form, nitrogen is very stable and non-reactive. However, nitrogen is used by living things in many physical processes. Before nitrogen can enter other parts of its cycle and be used by living things, it must be converted into a chemically reactive form such as ammonium (NH_4^+) or nitrate (NO_3^-). In these forms, and in gases such as nitrous oxide (N_2O), nitrogen plays a significant role in climate change.

Nitrogen Fixation

Because nitrogen gas is very stable, it takes large amounts of energy to split apart each molecule. The process that converts nitrogen gas into compounds that contain nitrate or ammonium is called **nitrogen fixation**. This process transfers nitrogen from the atmosphere to the land, water, and organisms. Three routes are responsible for most nitrogen fixation on the planet. The first two are natural and are shown in **Figure 8.22**. The third is exclusively a result of human activity.

nitrogen fixation the process by which atmospheric nitrogen is changed into forms that can be used by plants and other organisms

In the early 20th century, a new industrial method called the Haber–Bosch process created a revolution in agriculture and had a major impact on the nitrogen cycle. The process uses high temperatures and pressures to combine nitrogen from the atmosphere with hydrogen to make ammonia (NH_3). The ammonia is used to manufacture nitrate fertilizers.

Figure 8.22 **A** The extreme temperature at the edge of a lightning bolt allows nitrogen gas to bond with oxygen to form nitrates that living plants can use. **B** Bacteria in the roots of a pea plant convert nitrogen from the soil into a form of nitrogen that the plant can use.

How Humans Affect the Nitrogen Cycle

As shown in **Figure 8.23**, human activities have an impact on the functioning of the nitrogen cycle. In general, these human activities can be classified into three categories: addition of nitrogen to the land, addition of nitrogen to water, and addition of nitrogen to the atmosphere.

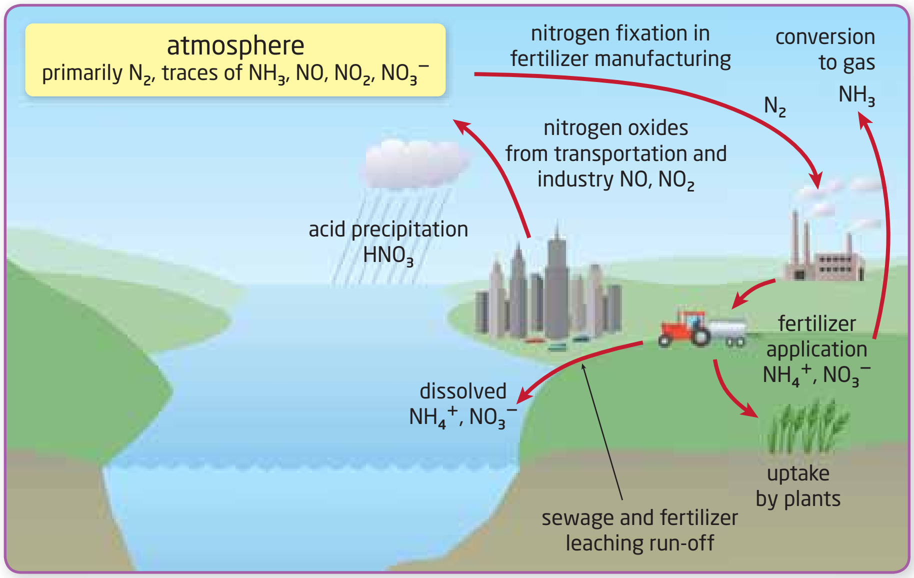


Figure 8.23 Human activities, such as industry and agriculture, alter the nitrogen cycle.

The Effect of Agriculture on the Nitrogen Cycle

Experts estimate that agricultural activities now account for as much as one half of all nitrogen fixation on Earth. Modern agriculture involves the use of manufactured fertilizers over a large area. Industrial processes manufacture over 100 million tonnes of nitrogen fertilizer per year. This fertilizer helps to grow crops that sustain about one third of Earth's population. But while artificial fertilizer helps to reduce starvation in some parts of the world, its overuse contributes to many environmental problems, including climate change.

Water Pollution and the Nitrogen Cycle

When farmers add more fertilizer to fields than their crops can take up, the excess nitrogen builds up in the soil. Rain and melting snow wash the nitrogen from the soil and carry it to nearby waterways. In streams and lakes, the nitrates cause rapid growth of algae and other water plants. Algal blooms clog waterways and deprive other aquatic organisms of oxygen. Nitrates in both surface water and ground water can also cause harm to human health, because nitrates in drinking water may lead to cancer.

At the mouths of rivers, massive quantities of fertilizers, sewage, and livestock waste pour into the ocean, creating *dead zones*. In these areas, algal blooms have created huge masses of dead algae. As the algae decompose, oxygen in the water is used up, making these areas unfit for all organisms that require oxygen. About 150 dead zones currently exist in the world's oceans, covering hundreds of thousands of square kilometres. In Canada, this problem is most noticeable in Québec and in Lake Winnipeg in Manitoba.

How Air Pollution Affects the Nitrogen Cycle

If you have ever been downwind of a large livestock farm, you may have caught a whiff of ammonia (NH_3) in the air. Ammonia reacts with other compounds in the air to form *smog*. Agriculture is also a source of the greehouse gas nitrous oxide (N_2O).

Millions of tonnes of nitrogen are added to the atmosphere every year from the combustion of fossil fuels in power plants and vehicles. Nitric oxide (NO) from vehicle exhaust is a common ingredient in smog and ground-level ozone. Reactive forms of nitrogen from these sources dissolve in moisture in the atmosphere to form nitric acid (HNO_3). This compound returns to Earth's surface in acid rain, which damages lakes, soil, vegetation, bridges, and buildings.

Reducing the Effect of Nitrogen on Climate Change

By reducing the amount of excess nitrogen produced and used by farms and other industries, climate scientists hope to reduce the amount of greenhouse gases that enter the atmosphere. Scientists have proposed several ways to reduce the amount of nitrogen-containing compounds in the air. These actions are outlined in **Table 8.7**. For example, in the midwestern United States, researchers have introduced a program to educate farmers about fertilizer use. The program encourages farmers to use the least amount of fertilizer possible. Participating farmers apply substantially less fertilizer to most of their land than they did previously. This decrease in fertilizer use decreases the excess nitrogen available for fixation. Because water that runs off the land and through rivers eventually reaches the oceans, this practice helps to reduce the size of dead zones in the area.

In Canada, the increased use of precision-farming techniques promises to reduce the amount of nitrogen-based fertilizers used by Canadian farmers in the future. In precision farming, farmers use satellites and geographic information systems to determine exact locations of areas that require fertilizers. Thus, the farmers can apply an appropriate amount of fertilizer to only the specific part of a field that requires fertilizer. This technique will reduce the amount of excess fertilizer that enters rivers, lakes, and oceans.

Study Toolkit

Synthesizing Use the flowchart on page 310 to explain how the use of nitrogen-rich fertilizers may lead to sea-level rise.

Table 8.7 **Methods of Reducing Nitrogen Emissions**

Course of Action	Estimated Maximum Reduction in Reactive Nitrogen Emissions
Controlling nitrogen oxide emissions from the burning of fossil fuels	25 billion kg/year
Increasing the efficiency of fertilizing crops	15 billion kg/year
Improving management of livestock	15 billion kg/year
Providing sewage treatment for half the world's urban population	5 billion kg/year

Section 8.3 Review

Section Summary

- Carbon and nitrogen cycle through living organisms quickly, but also have cycles that can store them in rocks for millions or billions of years.
- Carbon has five main stores: living things, oceans, rocks, fossil fuels, and the atmosphere.
- Human activities, such as the burning of fossil fuels, releases carbon dioxide into the atmosphere, which may result in climate change.
- Nitrogen fixation is the process by which atmospheric nitrogen is changed into forms that can be used by plants and other organisms. It can be done by lightning, by bacteria, or by industry.
- Human activities, especially the use of fertilizers for agriculture, have increased the amount of nitrogen in rivers, lakes, and oceans. This nitrogen causes algal blooms that result in dead zones in lakes and oceans.

Review Questions

K/U **1.** Name the sinks in the carbon cycle.

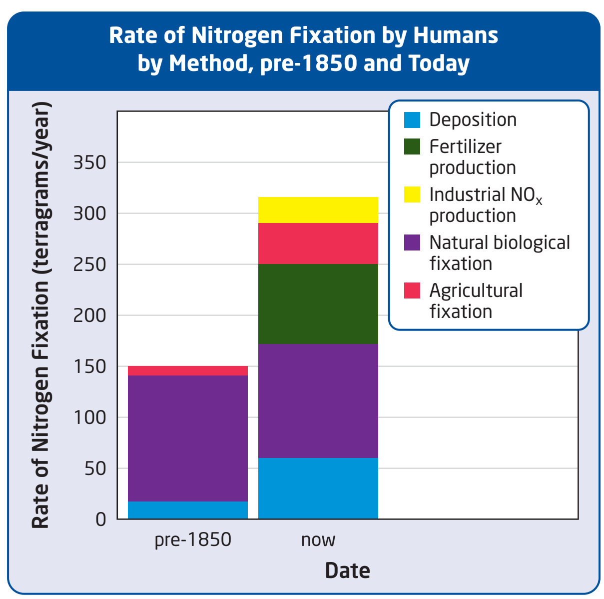
K/U **2.** Use **Table 8.6** and **Figure 8.21** to create a flowchart that shows how carbon compounds move between the different stores in the carbon cycle.

A **3.** One proposal for dealing with carbon dioxide levels is to plant more trees. Why would this action be a good short-term solution but not necessarily a good long-term sink for carbon?

K/U **4.** How are humans affecting the carbon cycle?

K/U **5.** In what three ways is nitrogen gas changed into nitrogen molecules usable by living things?

T/I **6.** The graph on the right shows the rates at which nitrogen fixation occurred as a result of human activities before 1850 and today. What is the total human-induced increase in nitrogen fixation in terragrams per year since 1850? What percentage increase in total nitrogen fixation has occurred since 1850?



T/I **7.** Why might ponds near golf courses have more algae growing in them than pristine mountain ponds do?

C **8.** Draw a diagram that illustrates how the carbon cycle and nitrogen cycle are linked.