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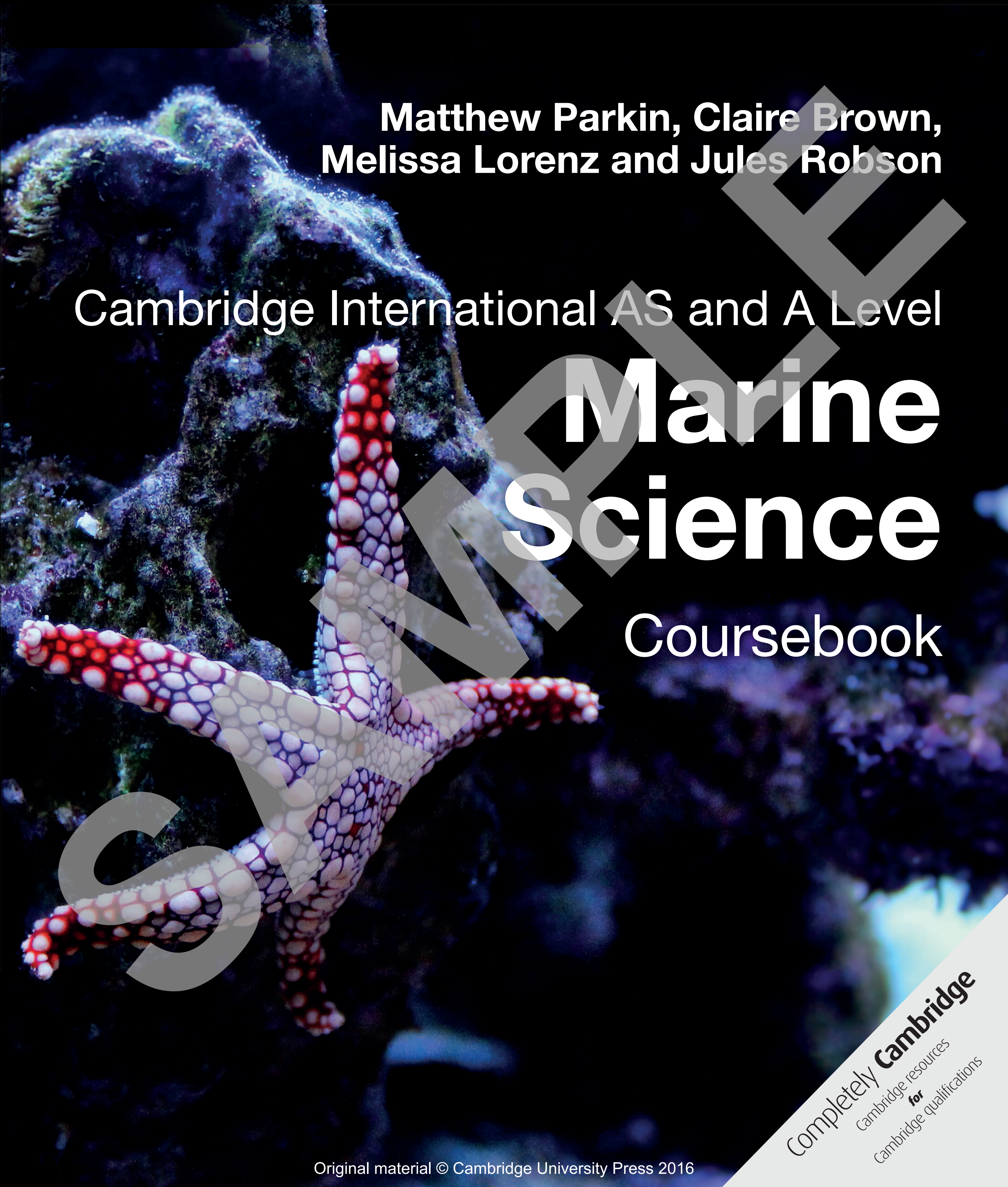
Matthew Parkin, Claire Brown, Melissa Lorenz and Jules Robson

Cambridge International AS and A Level Marine Science

Coursebook



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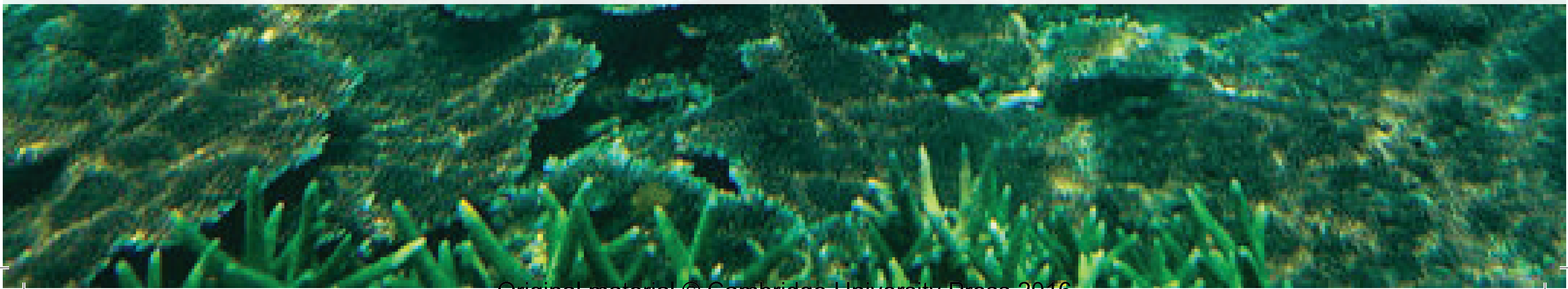
Contents

Chapter 4
Nutrient cycles in marine ecosystems

Learning outcomes

By the end of this chapter, you should be able to:

- describe the general processes that take place within a nutrient cycle
- explain what is meant by a reservoir within a nutrient cycle
- describe and explain the processes that add nutrients to the surface water of the ocean
- describe the processes that remove nutrients from the surface water of the ocean
- summarise the nitrogen, carbon, magnesium, calcium and phosphorus cycles as a simple diagram
- state the uses of each of the above nutrients in living organisms
- plot and interpret accurate graphs of experimental results
- apply what you have learnt to new, unfamiliar contexts.



Cycling of elements through the ecosystem

Nutrient cycles are some of the most important processes that occur in any ecosystem. They show the movement of **nutrients** that are essential for life, such as nitrogen, carbon and phosphorus. These nutrients are used by living organisms and are moved through the food chain by feeding. When organisms die the nutrients are recycled by **decomposers** and return to inorganic forms. The inorganic forms remain in the environment, sometimes for millions of years, before being converted back into organic forms to be used once again, thus continuing the cycle.

The ocean is an important **reservoir** for these elements, which means that they may be held there for long periods of time. Microorganisms are able to fix inorganic substances into organic molecules, which enables them to be used by other organisms. In this way the nutrients are moved from the **abiotic** part of the cycle to the **biotic**. The nutrients may then be removed temporarily from the cycle if they sink to the ocean floor as faeces, or after the organism has died. Some will be incorporated into coral reefs and others will be removed from the ocean altogether by harvesting. Inorganic molecules are returned to the ocean by various processes, including dissolving directly into the water, **run-off** from the land and **upwelling**.

Chapter 3 discussed the effect of nutrient concentration in the ocean. Up to a certain point, the more nutrients present, the more productive the environment. When there are too many nutrients the productivity can increase too fast and the ecosystem is damaged. Recently, it has been suggested that artificially altering the nutrient balance in the oceans could increase productivity and therefore increase the amount of carbon dioxide used in photosynthesis. This has been proposed as a solution to the increasing levels of carbon dioxide in the atmosphere. However, this solution may have unintended consequences, such as decreasing the pH of the water and damaging animals with shells. It could also lead to harmful algal blooms as discussed in chapters 3 and 8.

KEY TERMS

Abiotic: the environment's geological, physical and chemical features, the non-living part of an ecosystem

Assimilated: the conversion of a nutrient into a useable form that can be incorporated into the tissues of an organism

Biotic: the living parts of an ecosystem, which includes the organisms and their effects on each other

Decomposers: bacteria and fungi that break down dead organic matter and release the nutrients back into the environment

Nutrient: a chemical that provides what is needed for organisms to live and grow

Nutrient cycles: the movement and exchange of elements that are essential to life, from inorganic molecules, through fixation and then into living organisms before being decomposed back into inorganic molecules

Reservoir: part of the abiotic phase of the nutrient cycle where nutrients can remain for long periods of time

Run-off: the flow of water from land caused by precipitation

Upwelling: the movement of cold, nutrient-rich water from deep in the ocean to the surface

Nutrient cycles

Nutrient cycles are the essential movement and recycling of the elements that are necessary for organisms to live and grow. Globally the carbon and nitrogen cycles are probably the best known and most clearly understood, but there are many other elements that are important. These include phosphorus, calcium and magnesium. In this chapter you look at why each of these is necessary for life, as well as the mechanisms that add them or remove them from the oceans.

All nutrient cycles have a biotic and an abiotic phase (Figure 4.1). A nutrient moves from the abiotic to the biotic phase when it is absorbed and **assimilated** by producers. For example carbon dioxide (an inorganic molecule and therefore part of the abiotic cycle) is fixed during photosynthesis into glucose. This can later be converted into the other molecules needed by the producer, for example starch. It has been assimilated and is now part of the biotic cycle. During the biotic phase nutrients are moved from one organism to the next by feeding. So nutrients move along the food chain from the producers to the consumers. Some will be lost from each organism by egestion and excretion and the rest will remain within organic compounds until the organism dies. After death, organisms must be broken down by decomposers, which results in nutrients returning to their inorganic form and therefore the abiotic part of the cycle. During this part of

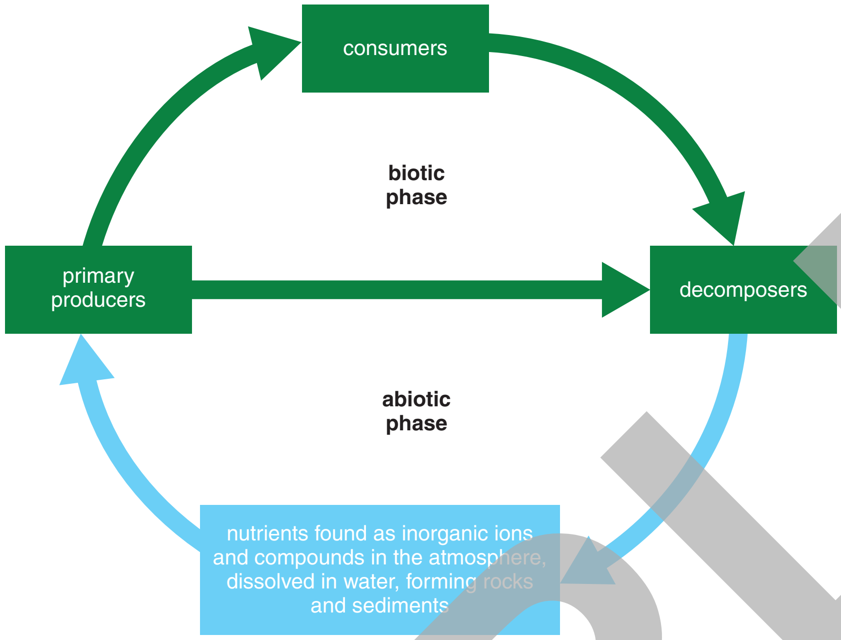


Figure 4.1. A generalised nutrient cycle showing the movement from the biotic to the abiotic phases

the cycle nutrients can be found dissolved in water, as gases in the atmosphere, or forming sediment that can later become rocks.

KEY TERMS

Assimilated: the conversion of a nutrient into a useable form that can be incorporated into the tissues of an organism

Residence time: the average time that a particle spends in a particular system

Reservoirs in nutrient cycles

A reservoir is part of the abiotic phase of the nutrient cycle where elements can remain for long periods of time. The ocean is an important reservoir for many elements. The **residence time** is the average time a particle spends in a system. Average residence times for nutrient ions in the ocean tend to be very long because some of them fall to the bottom in faeces or dead organisms. They can remain in sediment on the ocean floor for thousands or even millions of years (Table 4.1)

The time the same nutrients spend in just the surface layer of the ocean are much shorter because the nutrients are constantly being used and recycled by the organisms living there. This surface reservoir is of particular importance because it enables the high productivity of phytoplankton. Nutrient availability is often the main limiting factor after light intensity for growth of producers.

nutrient	average residence time/years
phosphate (phosphorus)*	20 000–100 000
magnesium	17 000 000
hydrogencarbonate** (carbon)*	100 000
nitrogen	2 000
calcium	1 000 000

*Where the nutrient is found as an ion, the element is given in parentheses

**Sometimes called bicarbonate

Table 4.1. Approximate residence times for different nutrients in the ocean

Phytoplankton are found in the surface layer of the ocean where there is plenty of light. It is therefore the concentration of nutrients that determines the rate of growth. The higher the rate of growth of phytoplankton, the higher the rate of photosynthesis and therefore the higher the productivity. The productivity of the phytoplankton determines how much energy can be transferred to the next trophic level (see Chapter 3). In general, the amounts of nitrogen and phosphorus limit the rate of growth because they are found in the lowest concentrations in the water. This means that there is usually slightly less than is needed by the producers. If the concentrations increase, the productivity increases. The average concentrations of ions dissolved in the water at the ocean surface are shown in Table 4.2.

ion	average concentration in seawater/ppm
chloride	19 345.00
sodium	10 752.00
sulfate	2701.00
magnesium	1295.00
calcium	416.00
hydrogencarbonate	145.00
nitrate	0.50
phosphate	0.07

Table 4.2. Average concentrations of some of the ions found dissolved in seawater

SELF-ASSESSMENT QUESTIONS

1 a Describe what is meant by the words biotic and abiotic in reference to nutrient cycles.

b Explain how nutrients move from the abiotic to the biotic part of a nutrient cycle.

2 a Describe how nutrients move within the biotic part of the cycle.

b Name two places where you would find nutrient ions within the abiotic part of a nutrient cycle.

Processes that add nutrients to the surface water

There are three main processes that add nutrients to the reservoir within the surface water. These are:

- dissolving in the water from the atmosphere
- upwelling
- run-off.

The relative importance of these processes depends on each nutrient. For nutrients present in high concentrations in the atmosphere, dissolving will add more to the reservoir than run-off, for example.

Dissolving of atmospheric gases

Nitrogen and carbon are both present in the Earth's atmosphere and are therefore both able to dissolve directly into the water. Nitrogen is present in the form of nitrogen gas, N_2, and carbon as carbon dioxide gas, CO_2. The amount of gas that can dissolve in the water depends on several factors. These include the:

- temperature of the water
- atmospheric concentration of each gas
- amount of mixing of water at the surface.

In some areas there will be more gas dissolving in the water than there is diffusing back into the atmosphere. These areas are known as **sinks**.

In other areas it will the other way around, and more gas will diffuse into the atmosphere than is dissolving into the water. These areas are called **sources**. Generally the overall concentration tends to remain at an equilibrium, with the same amount dissolving into the ocean as is removed by diffusion back into the atmosphere (Figure 4.2).

KEY TERMS

Sink: an area where there is a net loss of material (for example where more gas dissolves into the ocean than diffuses into the atmosphere)

Source: an area where there is a net gain of material (for example where more gas diffuses into the atmosphere than dissolves in the ocean)

Upwelling

Upwelling involves cold water from the deep ocean being brought to the surface. These deep waters have higher concentrations of nutrients than those at the surface because of the tendency for the remains of living things to sink. So faecal matter and dead organisms sink from the surface layers to the deeper parts of the ocean. Here they may be broken down by decomposers and the nutrient ions returned to the water. During upwelling this nutrient-rich water rises to the surface where it effectively fertilises the surface layers and increases productivity. Areas with high levels of coastal upwelling tend to be the

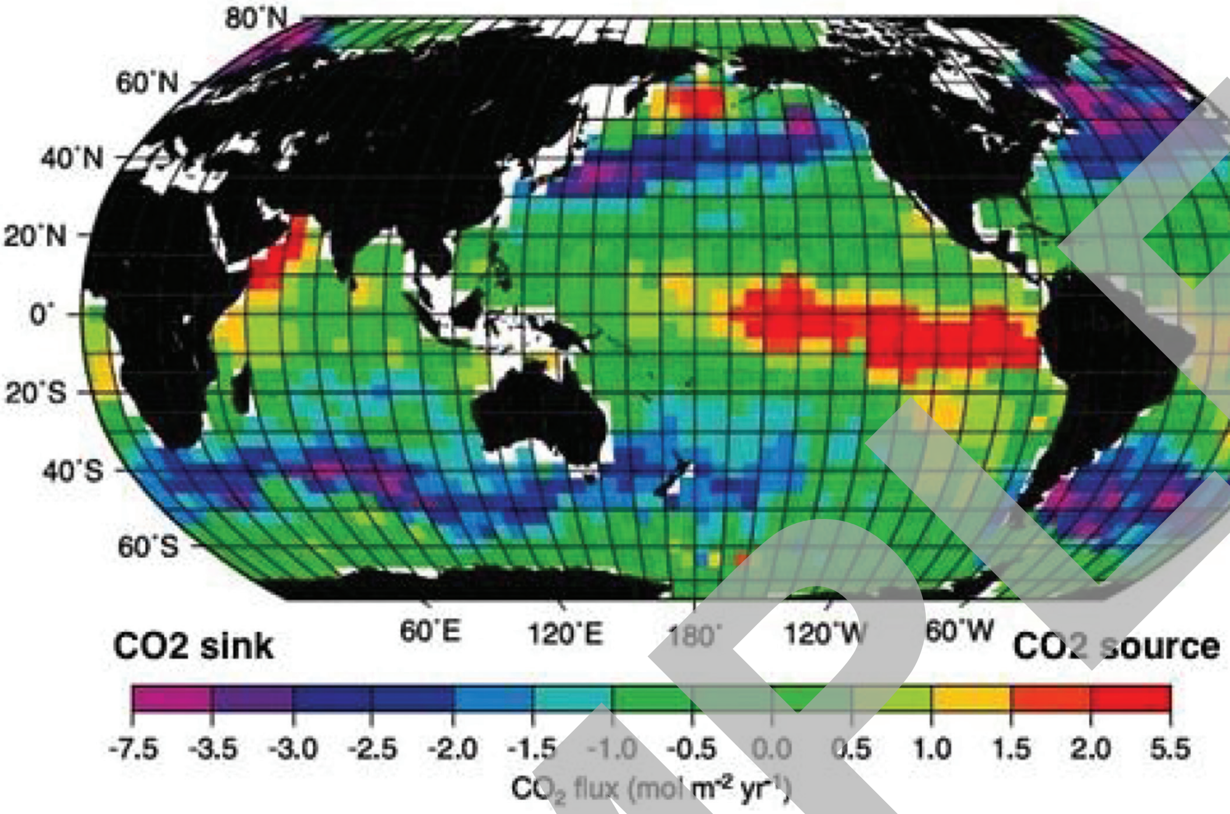


Figure 4.2. Movement (flux) of carbon dioxide into and out of the ocean over the course of a year. Purple and blue areas are carbon sinks; yellow and red areas are carbon sources; green areas are at an equilibrium, with the same amount of carbon dioxide dissolving as being released

most productive and have high catches of commercially important fish. It has been estimated that 25% of fish are caught from just 5% of the ocean where there are high levels of upwelling.

Coastal upwelling is caused when winds blow parallel to the shore (Figure 4.3). This displaces the warm surface water, which moves further offshore and has to be replaced by water from deeper in the ocean. Other mechanisms of upwelling are discussed in Chapter 7. If the wind is moving in the opposite direction and drives the water towards the coastline, it is also possible for downwelling to occur. This of course removes nutrients from the surface layers of the ocean.

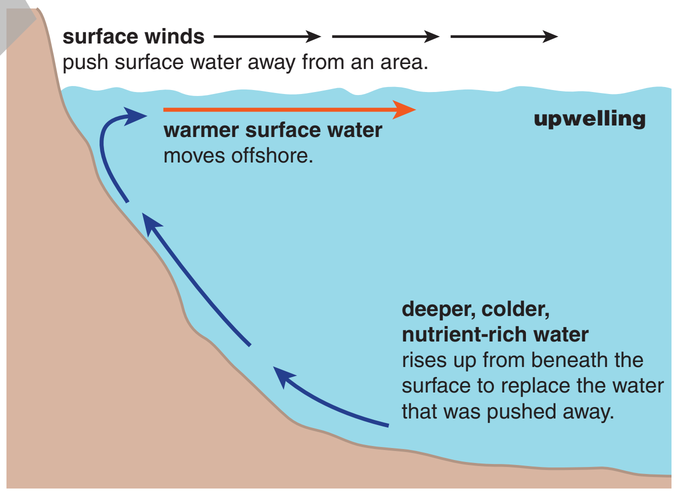


Figure 4.3. Coastal upwelling caused by surface winds

Run-off

Run-off is part of the water cycle in which water flows into streams and rivers and from there to the ocean. During the water cycle, water evaporates from rivers, lakes, oceans and streams. It condenses into clouds in the atmosphere and from there falls on the land as precipitation (Figure 4.4). Some of the precipitation enters the soil in a process called **infiltration**. The rate of infiltration is affected by the characteristics of the soil. Sandy soil, which

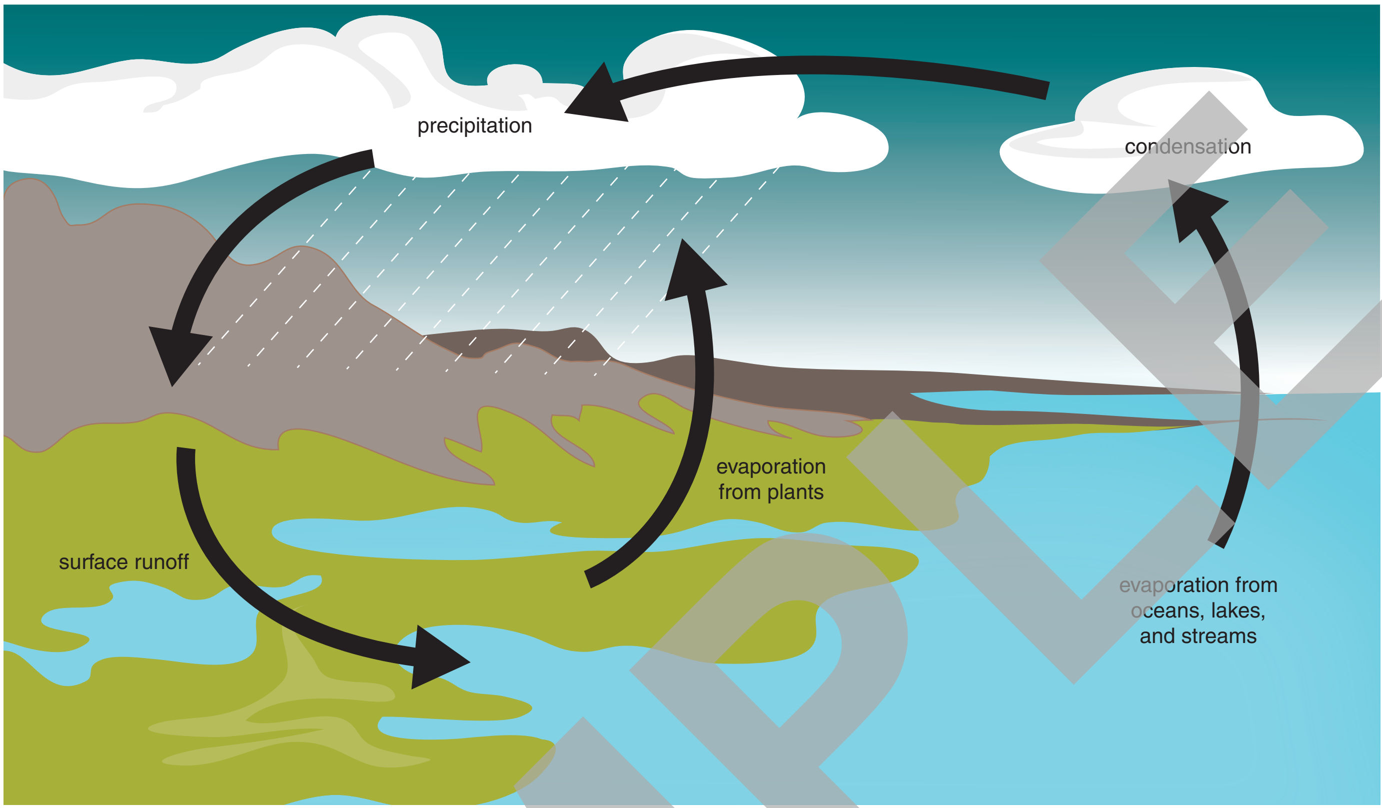


Figure 4.4. Summary of the water cycle

is formed from large particles with relatively large gaps between them, has a high infiltration rate, compared with clay soil, which has a low infiltration rate. The higher the infiltration rate, the lower the rate of surface run-off. In other words, the more impermeable the ground, the more surface run-off there is.

As the water flows towards the sea it **leaches** nutrients from the soil. This means that water-soluble nutrient ions dissolve in the water. Run-off can also collect other substances as it flows, such as oil, heavy metals, pesticides and sewage. These all end up in the ocean. Excess nutrients in run-off can lead to marine dead zones (Chapter 3) and harmful algal blooms (Chapter 3, and discussed in more detail in Chapter 8).

KEY TERMS

Infiltration: part of the water cycle where water soaks into the soil from ground level and moves underground

Leaching: a process during which water-soluble nutrients are removed from the soil and dissolve in water that is flowing to the sea (run-off)

SELF-ASSESSMENT QUESTIONS

3 What effect do you think upwelling would have on a food web?

4 Explain why nitrogen and carbon dioxide dissolve in the water from the atmosphere, but not phosphate.

Processes that remove nutrients from the surface layer

The main way in which nutrients are removed from the surface layer is through uptake and assimilation by producers. They fix the inorganic ions into useable organic compounds that are fed on by consumers. In this way the nutrients are able to move through the food chain. For example, phytoplankton take up nitrate ions and use them to produce amino acids. These are then built up into proteins that form part of the phytoplankton structure. Zooplankton eat the phytoplankton and digest these proteins, using the amino acids released in digestion to produce their own proteins. Small fish then eat the zooplankton and the process continues. Once the nutrients have entered the food chain there are different paths they can take. Some sink to the floor as **marine snow**, some are incorporated into coral reefs, and some are removed by harvesting.

KEY TERM

Marine snow: particles of organic material that fall from surface waters to the deeper ocean

Marine snow

Marine snow is the name given to the particles of organic matter that fall from the surface of the ocean to the deeper water. It is made up of faeces from the organisms living in the surface layers, as well as dead animals, phytoplankton and zooplankton. It is called marine snow because that is what it looks like, small white particles floating in the water (Figure 4.5).

Figure 4.5. Marine snow in the water

This continuous fall of organic matter provides food for many organisms that live deeper in the ocean. Some of it is fed on by zooplankton and fish as it falls, some is eaten by filter feeders much deeper down. Much of it is not eaten at all and forms part of the sediment at the bottom of the ocean. Some of the nutrients in the sediment are released into the water by processes such as erosion and dissolving, others remain in the sediment for many years.

SELF-ASSESSMENT QUESTIONS

5 Describe the process that removes nutrients from the water and allows them to enter the food chain.

6 Describe what forms marine snow and explain where the majority of it ends up.

Incorporation into coral reefs

Coral polyps secrete a hard shell made from calcium carbonate to protect themselves and the zooxanthellae that live within them. Figure 4.6 shows some of the structures produced by coral. Coral eat tiny zooplankton and digest them to gain the nutrients they need. The zooplankton have previously gained their nutrients from phytoplankton. Any type of nutrient can be incorporated into the living parts of the reef and the other organisms that live there. But the hard shells last even after the living part has died. Coral reefs are very large and can last for a very long time, so the nutrients contained in them are removed from the cycling process for a long time. Most established coral reefs are between 5000 and 10 000 years old. Reef formation is discussed in Chapter 5.

Figure 4.6. Structures produced by coral polyps

Harvesting

Harvesting refers to the removal of marine species by humans. In 2016 it was estimated that the global fish catch in 2010 had been 109 million metric tonnes. This is 30% higher than had been previously thought. Other species are also harvested, including crustaceans such as crabs and lobsters, molluscs such as mussels and squid, and macro-algae such as seaweeds. All the nutrients present in these species are removed when they are harvested from the ocean. However, many of the nutrients eventually find their way back to the ocean through the normal cycling of nutrients. For example, fish may be eaten and digested by humans and some of the nitrogen-containing compounds are then lost in urine, which ends up in sewage. In many areas, sewage is released into rivers and oceans after only being partially treated. In some areas, raw sewage is released. In this way, the nitrogen-containing compounds present in the original fish return to the ocean.

SELF-ASSESSMENT QUESTIONS

7 What are the two important nutrients used by corals to produce their hard shells?

8 Explain why harvesting is important in marine nutrient cycles and explain whether you think it is beneficial or harmful.

Examples of marine nutrient cycles

The processes discussed so far that take place in marine nutrient cycles can all be summarised in the same diagram (Figure 4.7).

Nutrients enter the reservoir of dissolved nutrients in the surface layer by dissolving, run-off and upwelling, and are removed by uptake by producers. Once in the food chain nutrients can sink, become incorporated into coral reefs or be harvested. Each nutrient is needed for a different purpose within organisms, and each nutrient cycle is slightly different.

KEY TERM

Dissociation (dissociates): a reversible chemical change where the molecules of a single compound separate into two or more other substances

The carbon cycle

Carbon is needed by living things because it is the basis of all organic materials. Carbohydrates such as glucose and starch, lipids, proteins, and nucleic acids such as DNA are all based on chains of carbon molecules. Carbon enters the biotic phase of the cycle through the fixation of carbon dioxide in photosynthesis. Carbon dioxide is then released through respiration by all living things.

The main way carbon enters the ocean is by dissolving of carbon dioxide gas from the atmosphere. Carbon dioxide dissolves in water to form carbonic acid (H_2CO_3). This then **dissociates** into hydrogencarbonate ions (HCO_3^-) and hydrogen ions (H^+) in a reversible reaction. Hydrogencarbonate dissociates further into carbonate ions (CO_3^{2-}) and hydrogen ions (H^+). So in solution there is a dynamic equilibrium between carbon dioxide, hydrogencarbonate and carbonic acid. In seawater 89% of the dissolved inorganic carbon is found as hydrogencarbonate, 10% is carbonate and 1% is dissolved carbon dioxide.

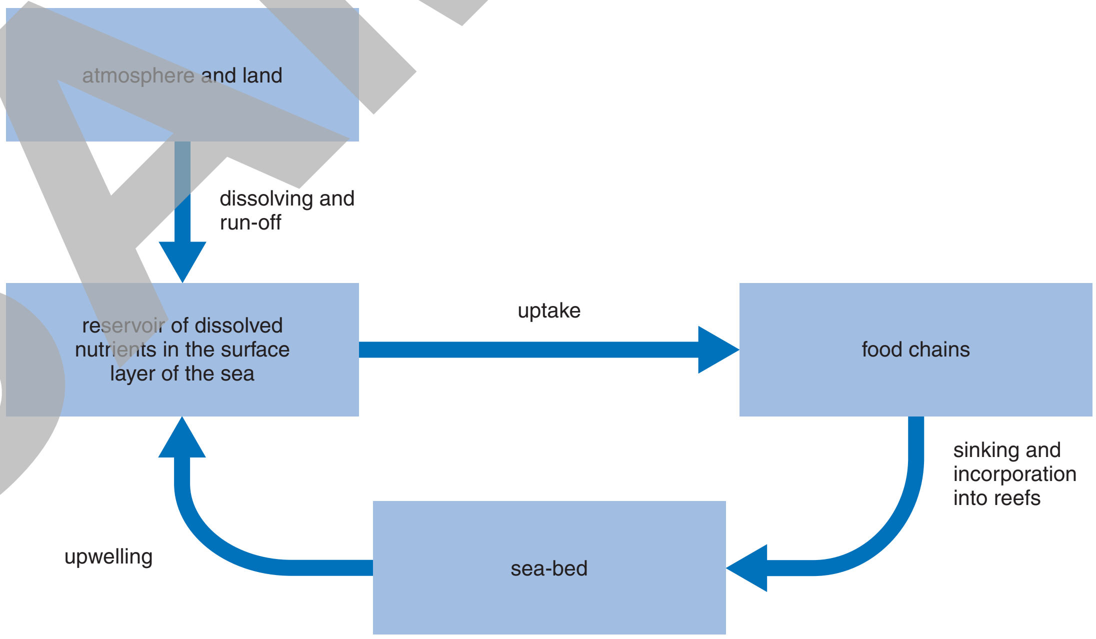


Figure 4.7. A summary of marine nutrient cycles

The reactions in this equilibrium are:

carbon dioxide + water ⇌ carbonic acid

$$CO_2 + H_2O \rightleftharpoons H_2CO_3$$

carbonic acid ⇌ hydrogencarbonate ion + hydrogen ion

$$H_2CO_3 \rightleftharpoons HCO_3^- + H^+$$

hydrogencarbonate ion ⇌ carbonate ion + hydrogen ion

$$HCO_3^- \rightleftharpoons CO_3^{2-} + H^+$$

The algae and photosynthetic bacteria that make up the phytoplankton are able to take in dissolved forms of carbon dioxide and use it in photosynthesis. It is fixed into glucose, which can then be used to form other compounds needed by the phytoplankton. When the phytoplankton are eaten by zooplankton, the carbon-containing compounds are broken down during digestion. The zooplankton then assimilate them into their own biomass. This process is repeated when the zooplankton are eaten by other consumers.

At each stage, the organisms are respiring so they release carbon dioxide back into the water. From here it can diffuse back into the atmosphere. When the organisms die, some of the organic matter is broken down by decomposing bacteria and returns to the water as dissolved inorganic carbon. Some of the organic matter falls to the ocean floor as marine snow, where it may remain for long periods of time (Figure 4.8)

The flux of carbon between the ocean and the atmosphere is around 90 gigatons year[1]. In other words, the same amount of carbon dioxide dissolves into the ocean as diffuses back into the atmosphere. However, there are also approximately 2 gigatons of carbon each year added to the ocean through human activities such as burning fossil fuels. This makes the oceans a very important carbon sink in terms of reducing atmospheric carbon dioxide. But the risk is that the ocean will become more acidic because of the extra carbonic acid formed. It has been estimated that since the 18th century, the pH of the ocean has decreased by 30%. This can have negative effects on the ecosystem. For example, a low pH triggers chemical reactions that decrease the concentration of carbonate ions; this makes it more difficult for corals to produce their calcium carbonate skeleton. This can also affect other species with calcified shells, including oysters and clams. If the water becomes even more acidic, it can dissolve the coral skeletons and the shells of other organisms, making them weaker and more vulnerable to damage.

Some scientists have suggested that artificially fertilising the ocean with iron would increase the productivity of the phytoplankton and mean that more carbon dioxide could be absorbed. This has been put forward as a possible way to reduce the amount of carbon dioxide in the atmosphere. The theory is that, since iron is often a limiting factor for phytoplankton growth, adding more will cause increased growth rates and thus increased use of carbon

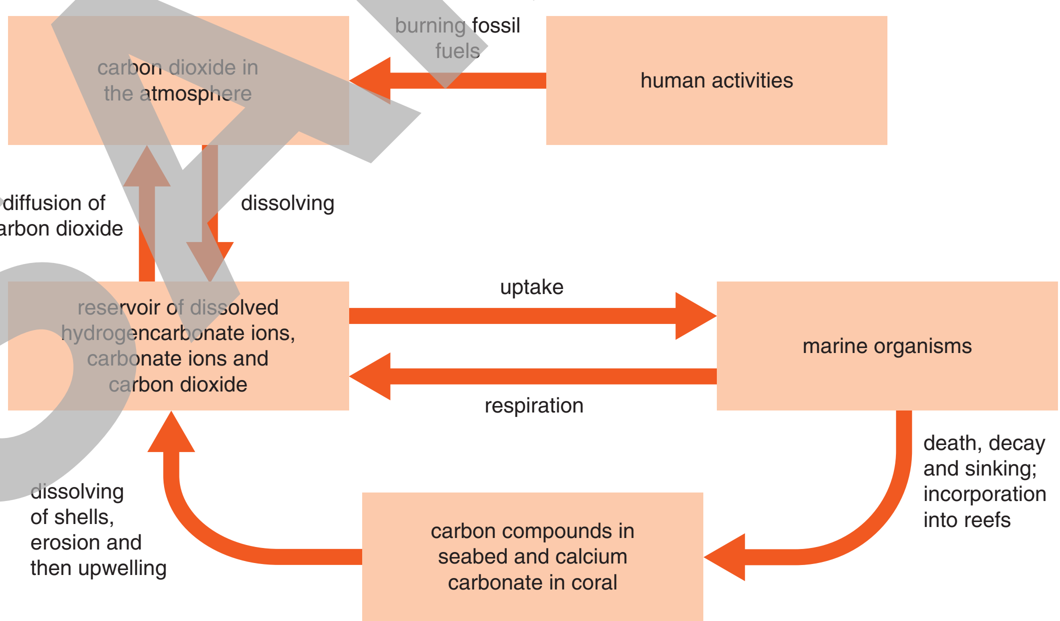


Figure 4.8. Summary of the main processes in the marine carbon cycle

dioxide. This process is known as ocean seeding or iron fertilisation. Trials have shown that ocean seeding does increase the growth of phytoplankton but there are risks to this procedure. If the productivity increases too much, a harmful algal bloom could take place. The long-term effects of altering the ecosystem in this way are not clearly understood. If more carbon dioxide is absorbed, the pH of the water could decrease further, causing harm to many different species.

PRACTICAL ACTIVITY 1

Simple investigations into the exchange of carbon dioxide between the atmosphere and the ocean

Introduction

High concentrations of carbon dioxide dissolve into seawater from the atmosphere. When carbon dioxide dissolves in water it forms carbonic acid. As levels of carbon dioxide in the atmosphere increase, more is dissolving in the ocean, which decreases the pH. This can cause problems for marine organisms with hard shells, as the shells can start to dissolve. In these simple investigations you will use an egg to represent a marine organism with a shell. Like with marine organisms, eggs have shells made from calcium carbonate. You will also add carbon dioxide to samples of water and record how long it takes the water to become acidic.

Apparatus

- Raw chicken eggs
- Acetic acid or white vinegar
- 3 × 250 cm^3 beakers
- 100 cm^3 beaker
- Goggles
- Universal indicator solution
- Seawater (if real seawater is unavailable, a substitute can be made by dissolving approximately 30 g of sodium chloride in 1 dm^3 of water
- Tap water (fresh water)
- Drinking straws
- Stopwatch
- Marker pen for labelling beakers or sticky labels

Method

- Examine a raw egg and record your observations in a copy of Table 4.3.
- Carefully place a raw egg into a 250 cm^3 beaker and cover with the acetic acid or white vinegar.
- Fill the 100 cm^3 beaker with water and place it on top of the egg to keep it submerged.
- Leave for 24 h.
- Carefully remove the smaller beaker and pour the acid away.
- Remove the raw egg, rinse it with tap water, and record your observations.
- Place 100 cm^3 of seawater into a 250 cm^3 beaker and label it.
- Place 100 cm^3 of tap water into another 250 cm^3 beaker and label it.
- Add a few drops of universal indicator to each beaker.
- Blow gently through the drinking straws into each water sample and time how long it takes for the colour of the indicator to change to yellow, which shows that an acid has been produced.
- Record your results in a copy of Table 4.4.

Risk assessment

Goggles should be worn to protect the eyes from acid and universal indicator. Hands should be washed after handling raw eggs or coming into contact with acid or indicator, both of which are irritants.

Results

observations before the experiment	observations after leaving egg in acid

Table 4.3. Egg experiment results

type of water	time taken to become acidic/s
seawater	
fresh water	

Table 4.4. Exchange of carbon dioxide between the atmosphere and water

Conclusions

1 What was the main difference in the egg after it was placed in acid?

2 What implications does this have for coral and other marine organisms with hard shells as the ocean becomes more acidic?

3 Why does the universal indicator turn yellow when you blow into the water?

4 Which type of water is able to absorb more carbon dioxide without becoming acidic?

5 What does this suggest about the relative importance of seawater and fresh water as carbon sinks?

6 Why do large bodies of water in nature not become acidic this quickly?

7 Suggest ways in which you could extend the exchange of carbon dioxide investigation.

The nitrogen cycle

Nitrogen is needed to form amino acids, which are built into proteins. It is also a component of nucleic acids like DNA. The nitrogen cycle is more complex than the carbon cycle because most producers are unable to take in nitrogen gas from the atmosphere. The organisms that are able to take in molecular nitrogen (N_2) must convert it into useable forms. In the marine environment this takes place through the action of **diazotrophs** (Figure 4.9). Diazotrophs are bacteria and archaea that can convert molecular nitrogen to substances such as ammonia (NH_3).

KEY TERM

Diazotroph: an organism that is able to grow without external sources of fixed nitrogen because it is able to fix nitrogen gas into substances like ammonia

Figure 4.9. *Trichodesmium*, a genus of marine diazotroph showing its filaments of cells, which are able to fix molecular nitrogen

Nitrogen fixation requires a nitrogenase enzyme, which needs low levels of oxygen to function. Species that carry out nitrogen fixation therefore need specialised cells with lower than normal oxygen concentrations. *Trichodesmium* have cells that are specialised for nitrogen-fixing rather than carbon-fixing (through photosynthesis). Lack of photosynthesis means the cells have lower oxygen levels.

When the ammonia produced from nitrogen fixation dissolves in water, it forms ammonium ions (NH_4^+), which the phytoplankton are able to take in and convert to protein. Phytoplankton can also take in nitrite ions (NO_2^-) and nitrate ions (NO_3^-) but the oxygen must first be removed, which requires energy. However, because nitrite and nitrate are present in the water in higher concentrations than ammonia, many phytoplankton species do take in most of their nitrogen in these forms.

The proteins made by phytoplankton will be passed to consumers where they are digested by the consumers into amino acids and used to build the consumers' proteins. When consumers and producers die, the proteins are broken back down into amino acids by **saprophytic** bacteria and fungi. The amino acids are converted back into ammonia by ammonifying bacteria. Ammonia can then be oxidised into first nitrites and then nitrates in a process known as nitrification.

KEY TERM

Saprophytic (saprophyte): decomposers that feed on dead organic matter ('death eater')

The conversion of ammonia to nitrites is carried out by species of bacteria from the genus *Nitrosomonas* and from nitrites to nitrates by bacteria from the genus *Nitrobacter*. These species are chemoautotrophic (like the bacteria found at hydrothermal vents) and gain energy from the reaction. The final type of bacteria involved in the nitrogen cycle is the denitrifying bacteria, which convert ammonia and nitrates back into nitrogen gas (N_2). This reduces the amount of nitrogen available for phytoplankton to use and, because nitrogen is normally a limiting factor for growth, reduces productivity.

Nitrates are also added to the oceans by upwelling and run-off, particularly of nitrogen-based fertilisers (Figure 4.10).

SELF-ASSESSMENT QUESTIONS

9 Give one positive and one negative effect of increased levels of carbon dioxide dissolving in the ocean.

10 Copy and complete Table 4.5 to show the types of bacteria involved in the nitrogen cycle and their functions.

type of microorganism	function in the nitrogen cycle
diazotrophs	
saprophytic bacteria	
ammonifying bacteria	
nitrifying bacteria	
denitrifying bacteria	

Table 4.5. Bacteria and the nitrogen cycle

The magnesium cycle

Magnesium is needed by producers to synthesise the photosynthetic pigment chlorophyll. Magnesium is found in rocks such as dolomite (calcium magnesium carbonate) and enters water through erosion and weathering. It is also used in many chemical industries and is found in fertiliser. The main way in which it enters the ocean is therefore through run-off after being leached from the soil. Once the magnesium is taken in by phytoplankton it is used to form chlorophyll, which is essential for photosynthesis. Chlorophyll is a large and complex molecule with a magnesium ion at its centre.

The main way in which magnesium ions are removed from the water is by deposition in the sediment at the bottom of the ocean (Figure 4.11). Because magnesium is present in every living cell, it is also removed by harvesting living organisms from the ocean, and incorporation into the organisms in coral reefs.

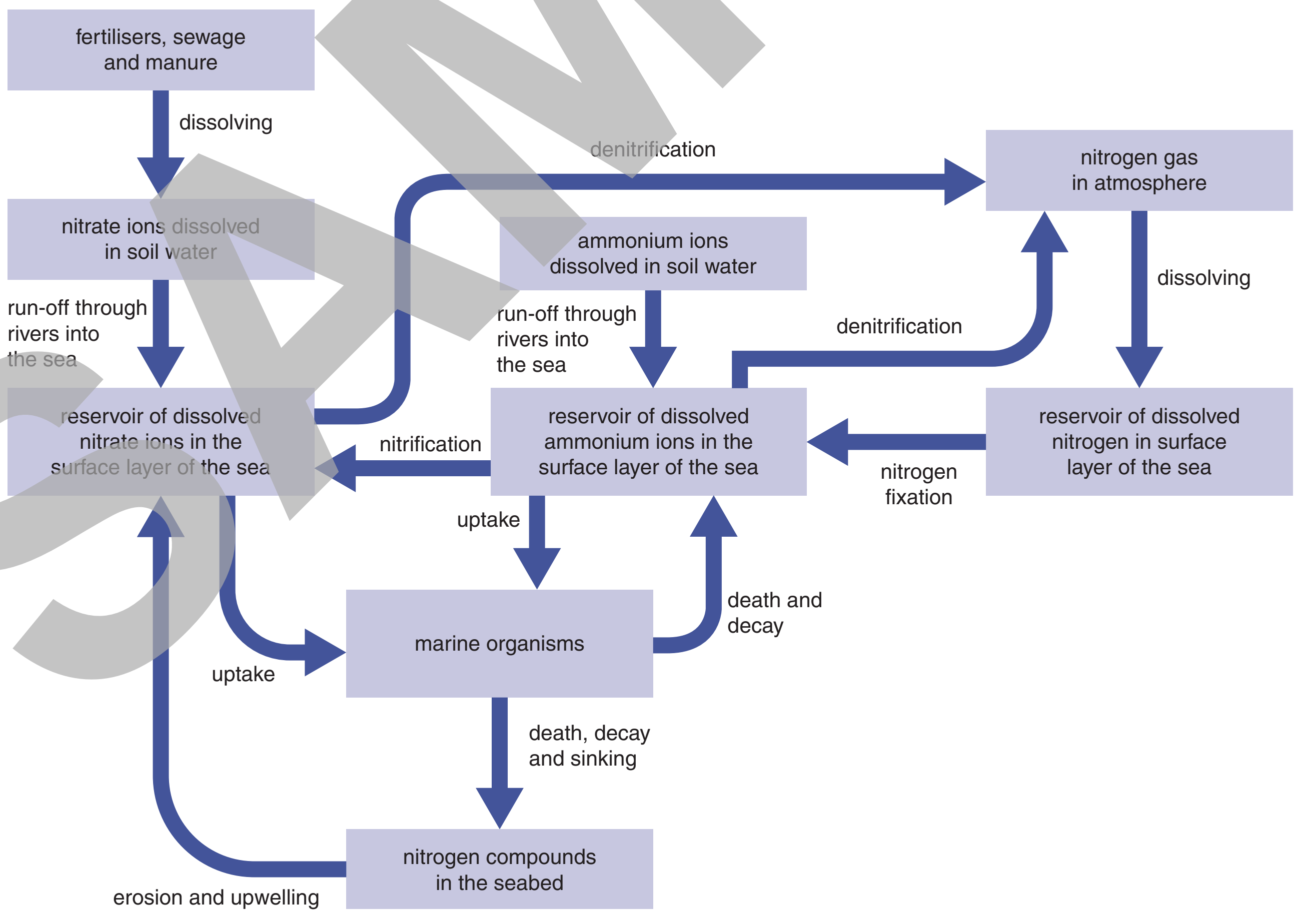


Figure 4.10. Summary of the main processes in the marine nitrogen cycle

PRACTICAL ACTIVITY 2

Investigating the nitrogen cycle in a fish tank

The nitrogen cycle is an important nutrient cycle both on land and in the sea. Most fish excrete their nitrogenous waste in the form of ammonia. This can cause them problems in an enclosed environment such as a fish tank. If the levels of ammonia increase too much, their gills and skin will be damaged. In an established aquarium this is less of a problem as levels of bacteria build up and start to cycle the nitrogen. Some species convert ammonia to nitrite and some convert the nitrite to nitrate. In this experiment you will use a fish tank without any fish and monitor the cycling of ammonia into nitrite and nitrate. All the equipment can be purchased easily from pet stores and aquatic shops. The test strips can be bought from the same suppliers as well as cheaply online. You can use an aquarium that you already own but you must use new gravel as old gravel will already have colonies of bacteria. This is a long-term investigation that will take a few minutes every week for several weeks.

Apparatus

- Fish tank with air pump (approximately 1 gallon capacity)
- Gravel (2.5 kg bag)
- Two live aquarium plants
- Test strips for ammonia, nitrite and nitrate
- Small pieces of raw fish or prawns
- The foot of a pair of tights
- Elastic band

Method

- Rinse the gravel and place it in the bottom of the tank to a depth of 2–4 cm
- Set up the air pump according to the instructions and add the live plants.
- Use the test strips to test for the levels of ammonia, nitrite and nitrate and record the results in a copy of Table 4.6.
- Place the raw fish or prawns into the bottom of a sock or pair of tights and close with an elastic band.
- Place this into the fish tank.
- Test the water approximately every 3 days for at least 3 weeks, longer if you can.
- Record the results in a copy of Table 4.6, making sure that you include enough space for all the readings you are planning to take. The units you use will depend on the test kit you purchase and will need to be added to the heading of your table.

Risk assessment

Hands should be washed after handling raw fish and prawns and after testing the water.

date	ammonia concentration	nitrite concentration	nitrate concentration

Table 4.6. Results

Analysis

Plot a graph to show the concentration of each nutrient against time in days. You can plot three lines on the same graph if you include a key, or you can draw three separate graphs.

Conclusions

1. Describe the shape of your graphs.
2. Explain the shape of your graphs.
3. Why did you put fish or prawns into the tank?
4. Where did the bacteria come from to convert the nutrients from one form to another?
5. Did you have any anomalous or unexpected results?
6. Suggest an explanation for your answer to question 5.
7. Using your results, explain how long you think aquariums should be set up for before fish are introduced.

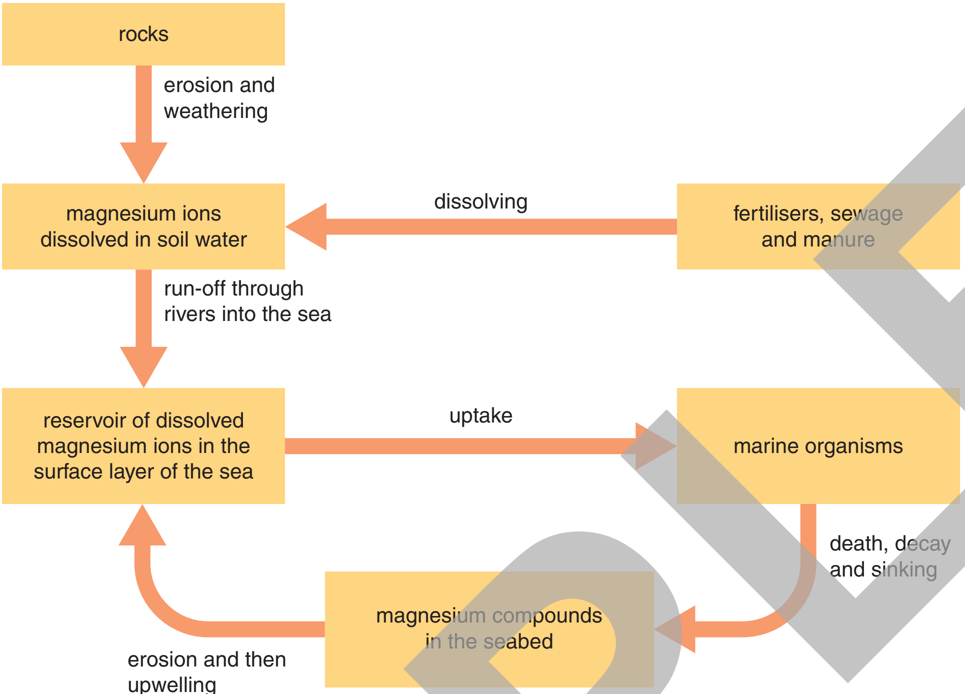


Figure 4.11. Summary of the main processes in the marine magnesium cycle

The calcium cycle

Calcium is necessary to build healthy bones, coral and teeth and so is needed by many marine animals. Rainwater reacts with carbon dioxide gas in the atmosphere to form carbonic acid. This extracts calcium from calcium-rich rocks such as limestone, marble and dolomite and forms calcium hydrogencarbonate. This dissolves in the water and enters the ocean through surface run-off. Phytoplankton such as coccolithophores use the calcium to produce scales called coccoliths from calcium carbonate (Figure 4.12) The scales are transparent and so do not disrupt photosynthesis. It has been suggested that the scales protect the cells from predators or from osmotic changes within the cells. The production of the scales also increases the rate of photosynthesis. as carbon dioxide is produced as a byproduct of the precipitation of the calcium carbonate.

Coccolithophores are eaten by zooplankton, passing the calcium to the animals. After they die, they fall to the ocean floor and become part of the sediment (Figure 4.13). Chalk is formed from coccolithophores that were deposited millions of years ago. As the seabed subsided, the sediment was subjected to heat and pressure, which formed it into rocks. The white cliffs of

Figure 4.12. Magnified picture of a coccolithophore

Dover in England are a famous example of chalk produced in this way from coccolithophores (Figure 4.14).

The phosphorus cycle

Phosphorus is necessary for all living things to form nucleic acids such as DNA. It is also essential for bones in vertebrates. The major environmental source of

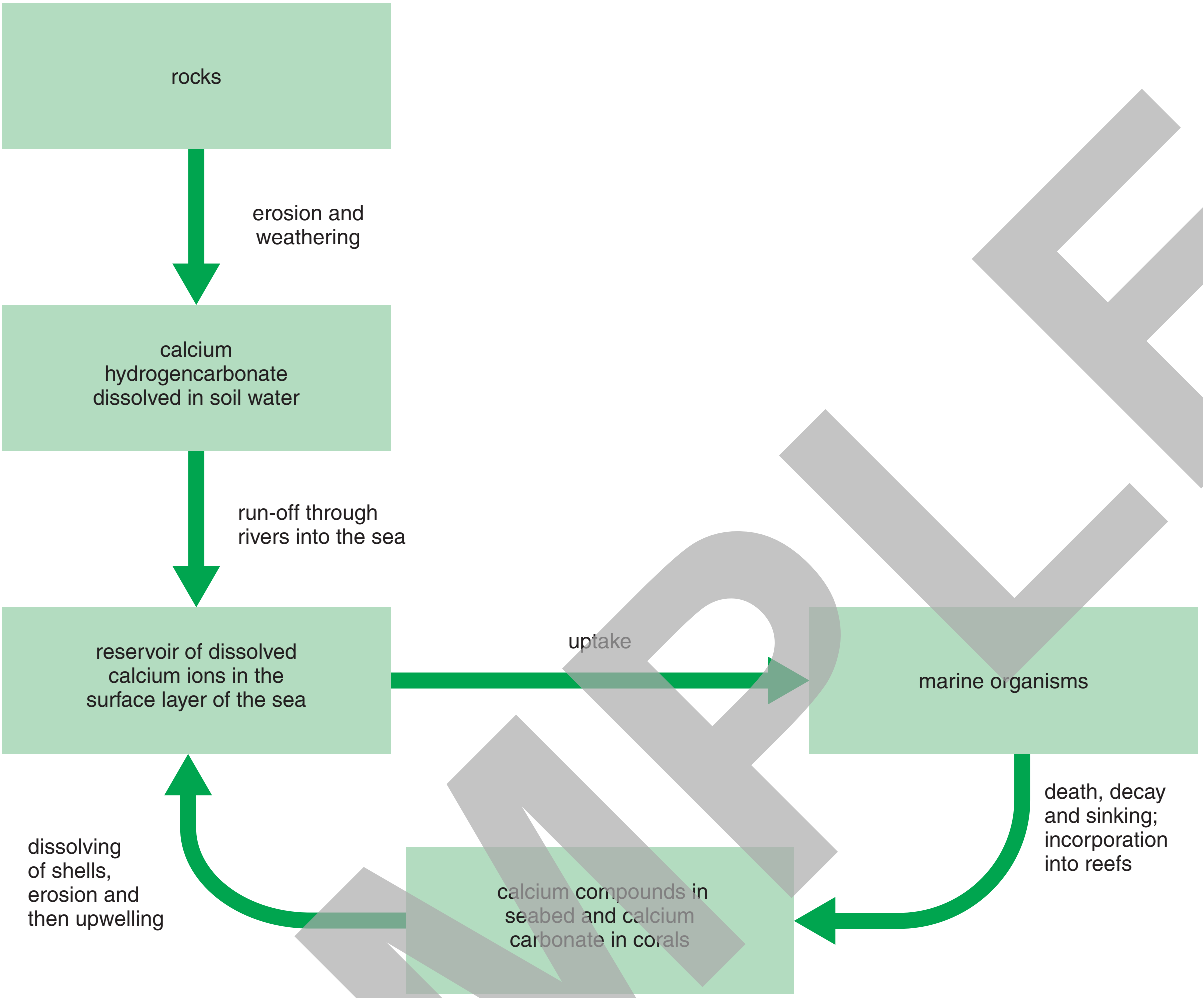


Figure 4.13. Summary of the main processes in the marine calcium cycle

Figure 4.14. The white cliffs of Dover in England

phosphorus is rocks such as apatite. Phosphorus attaches to soil particles and is therefore added to the water through soil erosion rather than being in solution. Phosphates are also found in fertilisers, manure and sewage, which also contribute to run-off.

Along with nitrogen, phosphorus is an important limiting factor for growth of phytoplankton and therefore photosynthesis and productivity. Once phytoplankton take in the phosphorus, it is assimilated into DNA and also phospholipids in the cell membranes. There is now evidence that many species of phytoplankton are able to alter the composition of their cell membranes depending on the amount of phosphorus in the water. This enables them to survive even when phosphorus levels are low. Animals eat the phytoplankton and incorporate the phosphorus into their own membranes and DNA. When the phytoplankton and animals die, they are either broken down by decomposers, which releases the phosphorus back into the water, or they fall to the bottom of the ocean and become part of the sediment (Figure 4.15).

SELF-ASSESSMENT QUESTIONS

11 Copy and complete Table 4.7 to show the uses of the main nutrients

nutrient	biological use
nitrogen	
carbon	
magnesium	
calcium	
phosphorus	

Table 4.7. Uses of the main nutrients

12 Suggest what type of weather conditions could lead to an increase in the amount of phosphorus in surface run-off.

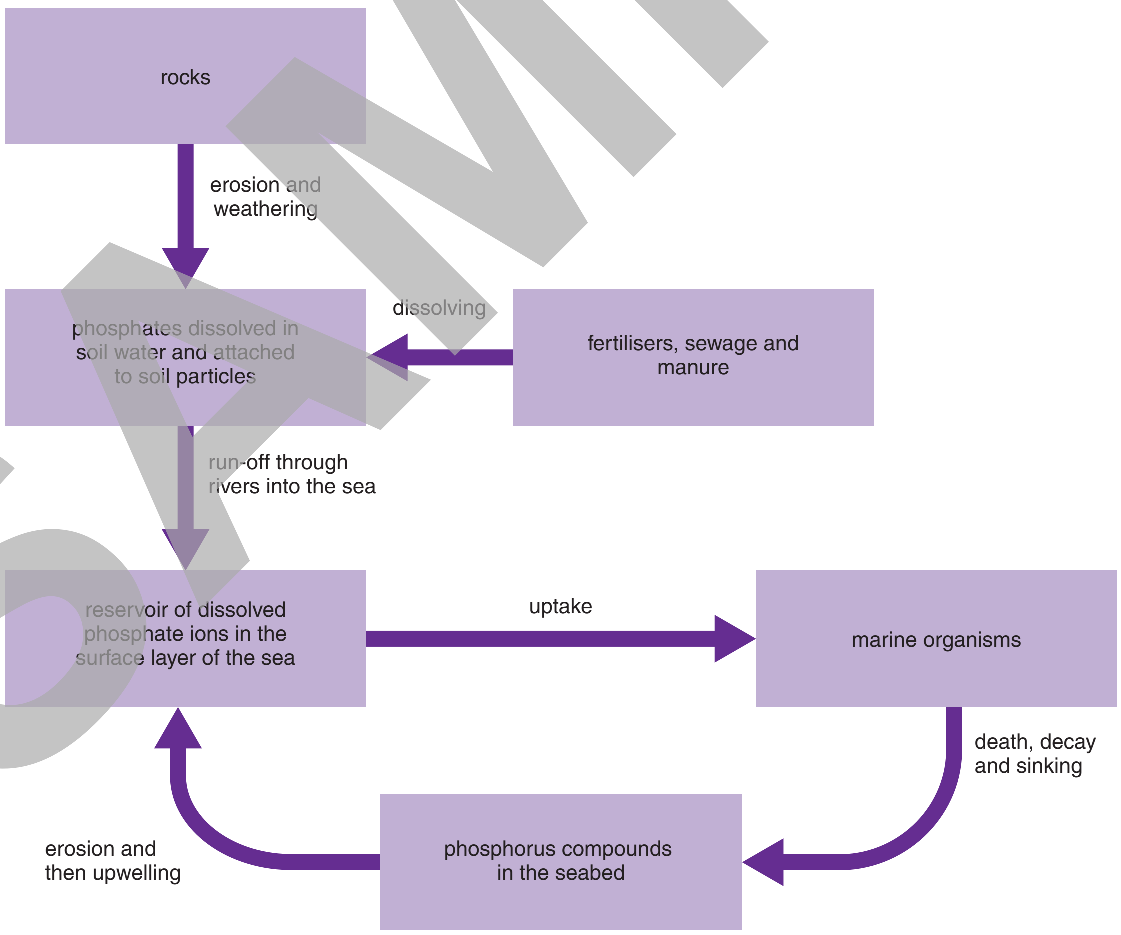


Figure 4.15. Summary of the main processes in the marine phosphorus cycle

CASE STUDY

The Redfield ratio

In the 1930s, Alfred Redfield reported that he had taken samples from various depths in the Pacific, Atlantic and Indian oceans and measured the concentrations of dissolved nutrient ions (Figure 4.16). He also compared many samples taken by other people. He discovered that the ratio of nitrate to phosphate in most of his samples was consistently around 20:1. Later this ratio was refined to 16:1 and expanded to include carbon, which occurs at a ratio of 106:16:1 with nitrate and phosphate. The same ratio was found inside the phytoplankton that lived in the water. In other words, the composition of the water and the phytoplankton appeared to be not only the same but consistent across many different areas and depths. Redfield suggested that the reason for the stability of the ratio could be the cycling of nitrogen from abiotic to biotic sources. This helped scientists understand how the run-off of nutrients from coastal areas leads to algal blooms. The Redfield ratio is still in use today because it helps our understanding of all the major nutrient cycles in the ocean. Deviations from the ratio can be caused by increased run-off of nutrients into the water and by changes in nitrogen fixation and denitrification. Aquarium owners can also use the ratio to monitor the nutrients present in the water and thus control the levels of algae.

More recently it has been discovered that, although the average ratio of carbon to nitrogen to phosphorus in phytoplankton conforms to the Redfield ratio of 106:16:1, it actually varies within individual species. Species that are adapted to living in low nutrient levels tend to have a higher nitrogen to phosphate ratio. Species that are adapted for exponential growth and that form the basis of algal blooms have a lower nitrogen to phosphate ratio. This could be because the proteins and chlorophyll necessary for photosynthesis are high in nitrogen and low in phosphates. DNA and RNA, which are necessary for growth, contain more equal amounts of nitrogen and phosphate. So the ratio within an organism depends on the strategy it has adopted for survival and the adaptations within its cells. It may be that the average Redfield ratio found in phytoplankton reflects the balance between the two different survival strategies. This would mean that alterations in global nutrient cycles would also alter the proportions of different phytoplankton species, which could have implications for the rest of the food chain.

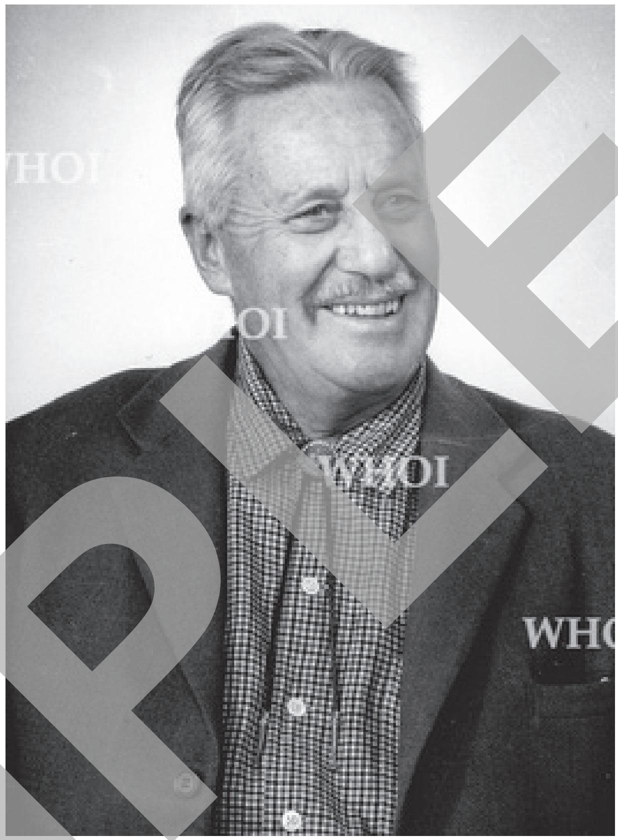


Figure 4.16. Alfred Redfield

Questions

1 Describe what will happen to the Redfield ratio if excess nitrates enter the water through the run-off of fertilisers.

2 What effect would this have on the types of phytoplankton that grow and their ratio of nitrate to phosphate?

3 Explain why you think that scientists continue to monitor the Redfield ratio in seawater.

Maths skills

Plotting and interpreting graphs

Plotting graphs is an important skill because graphs help us to visualise and better understand data. The data on a line or scatter graph should be plotted with the independent variable (the one that has been changed) on the *x*-axis. The dependent variable (the one that has been measured during the experiment) should be on the *y*-axis. A sensible scale should be used for each axis, for example 2 units per square of graph paper. The graph should fill at least ¾ of the available space on the graph paper and also be easy to plot and read the data afterwards. Scales that involve 3 units per square are difficult to plot and even more difficult for someone else to interpret and so should be avoided. It is not always necessary to start the scale at zero, but if the scale starts with another number this should be indicated by drawing two lines through the axis. Both the *x* and *y* axis need to be labelled with a description of the variable and the units that have been used.

When the points have been plotted, a line can be drawn. On a scatter graph this will be a line of best fit, showing the relationship between the two variables. Try to make sure that equal numbers of points are on either side of the line. For a line graph in biology, the line will often simply be straight lines drawn with a ruler between the points. This is because the actions of living organisms make it difficult to tell what happens between each point. A smooth curve of best fit can be drawn if there is reason to believe that the intermediate points would fall on the curve.

To interpret a graph it is important to both describe and explain what the data are showing. Think of describing a graph as answering the question: What do you see? You should state the key points that can be seen and give data from the graph to illustrate your answer. Explaining a graph by contrast means answering the question: Why does it happen? You should give the reasons for the shape of the graph and any changes that you see.

Worked example

The data in the table show the fertiliser consumption per hectare in the USA

year	fertiliser consumption per hectare/kg
1880	1.4
1890	1.9
1900	2.9
1913	5.8
1922	7.0
1937	8.7
1957	23.4
1999	108.3

Table 4.8. Fertiliser consumption per hectare in the USA

1 Plot a graph to show this data.

Remember that the independent variable must be on the *x*-axis, which in this case is the year. The dependent variable is the fertiliser consumption, and this should be on the *y*-axis: remember to include the units (kg). The points should be joined with a straight line because you cannot predict what might have happened in the intervening years.

A graph of these data should look something like Figure 4.17.

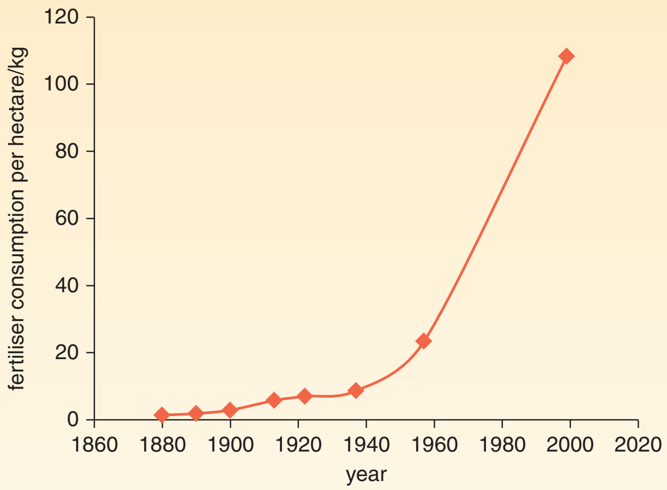


Figure 4.17. Fertiliser consumption in the USA from 1880 to 1900

2 Describe the shape of the graph.

Remember, to describe you need to say what is happening and quote figures from the data. So a description of this graph needs to include the slow increase between 1880 and 1922, followed by a much more rapid increase to 108.3 kg hectare^{-1} in 1999.

3 Suggest an explanation for the shape of the graph.

One possible explanation is the increase in availability of commercially prepared fertiliser. Another explanation could be that the price decreased or that increased demands for food meant that more fertiliser had to be used to increase crop yields.

Questions

1 The data in Table 4.9 show the amount of phosphate fertilisers used between 1975 and 2005.

year	amount of phosphate fertiliser used/tonnes
1975	124 000
1980	87 000
1985	62 000
1990	38 000
1995	27 000
2000	27 000
2005	22 000

Table 4.9 Phosphate fertiliser use between 1975 and 2005

a Plot these data as a graph on graph paper.

b Describe the shape of the graph.

2 The graph in Figure 4.18 shows the increase in the amount of carbon dioxide measured in the atmosphere in America.

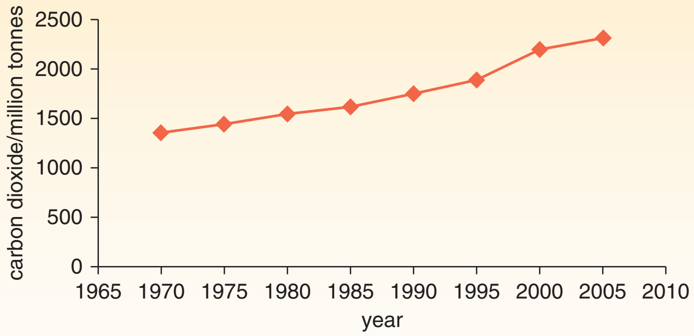


Figure 4.18. Changes in carbon dioxide concentration in America between 1970 and 2005

a Describe the graph.

b Suggest one human activity that could increase the amount of carbon dioxide in the atmosphere.

c Suggest the effect of increasing carbon dioxide in the atmosphere on the concentration of carbon dioxide dissolved in seawater.

Summary

- Nutrient cycles show the movement of nutrients through the abiotic and biotic parts of the ecosystem.
- In the abiotic stage nutrients are found as gases in the atmosphere, as well as dissolved in water and as part of rocks.
- An important reservoir of dissolved nutrients is found in the upper layers of the ocean.
- Nutrients move to the biotic phase through uptake and assimilation by producers such as phytoplankton.
- When phytoplankton are eaten, organic compounds containing the nutrients are digested and absorbed by consumers and then assimilated into consumer biomass.
- From here they can be removed from the ecosystem altogether by harvesting.
- Once organisms die they can sink to the bottom of the ocean, where they form part of the sediment.
- Nutrients can also become incorporated into coral reefs.
- More nutrients are added to the reservoir in the surface layers by dissolving from the atmosphere, running-off the land or upwelling from nutrient-rich deeper waters
- The main nutrients are:
  - Nitrogen, which is needed for proteins
  - carbon, which is found in all organic molecules including glucose and lipids
  - magnesium, which is needed for chlorophyll
  - calcium, which is needed for bones, shells and coral
  - phosphorus, which is needed for DNA and bone.

Exam style questions

1 The diagram in Figure 4.19 shows the marine magnesium cycle.

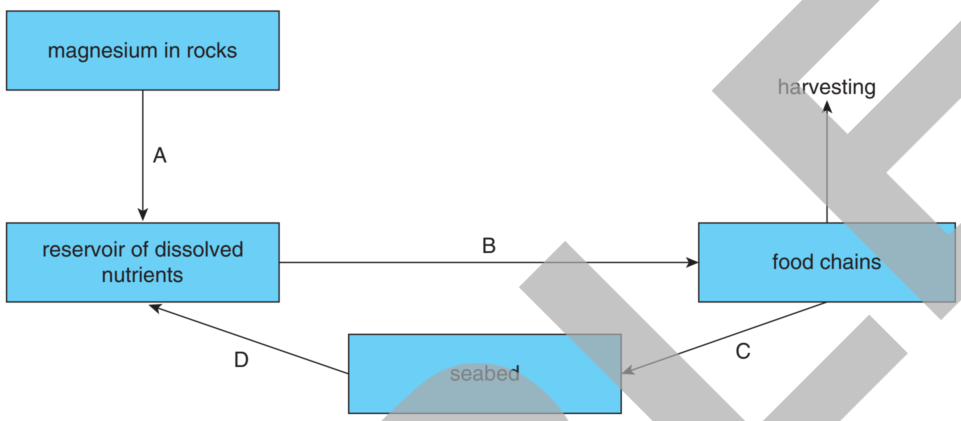


Figure 4.19. the marine magnesium cycle

a Name the process shown by arrow D. **(1)**

b Describe how the magnesium found in rocks on land ends up in sediments on the seabed. **(4)**

c **i** Suggest what will happen to the concentration of magnesium over time. **(1)**

ii Provide an explanation for your answer. **(3)**

[Total mark: 9]

2 **a** **i** Describe how nutrient-rich water from deep in the ocean enters the reservoir of nutrients at the surface. **(2)**

ii Suggest two other ways in which nutrients enter surface waters. **(2)**

b **i** Suggest a benefit of increased nutrients in surface waters. **(2)**

ii Suggest how increased nutrients in surface waters could be harmful. **(2)**

[Total mark: 8]

3 **a** **i** State how carbon dioxide enters surface water from the atmosphere. **(1)**

ii Describe the effect this has on the pH of the water. **(2)**

iii Name a biological compound that contains carbon. **(1)**

b **i** Give two ways in which phosphorus can enter surface water. **(2)**

ii Describe the effect of increasing phosphorus levels on producers. **(3)**

[Total mark: 9]

4 a Fill in Table 4.10 to show the uses of different nutrients. **(3)**

nutrient	biological use
nitrogen	
calcium	
phosphorus	

Table 4.10 The uses of different nutrients

b i Describe the process of run-off. **(3)**

ii Describe the effect of run-off of nitrogen fertilisers on producers. **(3)**

iii Explain how this will affect the consumers in the food chain. **(2)**

[Total mark: 11]

5 a Describe how calcium in limestone on land can be incorporated into coral. **(5)**

b i Give one biological use of calcium apart from in coral. **(1)**

ii Why does the level of calcium in the seawater stay constant? **(4)**

c i Name a nutrient whose levels are increasing in seawater. **(1)**

ii Suggest an explanation for this increase. **(2)**

[Total mark: 13]

EXTENDED CASE STUDY

The importance of salmon to the growth of trees

Harvesting by humans is an important way in which nutrients are removed from the marine environment. However, nutrients are also removed by migrations of marine organisms such as salmon (Figure 4.20) to fresh-water areas where they are eaten by predators like bears and eagles. Pacific salmon spend most of their life at sea. The juveniles tend to feed on zooplankton and the adults feed on krill and smaller fish such as herring. In this way the nutrients from the water that are taken up by the phytoplankton end up being assimilated by the salmon.

Figure 4.20. Adult Pacific salmon

Figure 4.21. Spawning Pacific salmon moving upstream

Figure 4.22. Bear catching salmon

Each year salmon return to the fresh-water streams and lakes where they were born in order to breed (Figure 4.21) For successful reproduction, the fish need the streams to be shaded by trees so that the water is not too warm. Warm water also contains less oxygen, which would mean that fewer of the eggs would be able to survive. The trees help to prevent soil erosion, stopping sediment from entering the streams and keeping the water clear for the salmon. Large populations of insects live in the leaves and needles of trees that provide food for the young salmon once they hatch. The trees are therefore important for the survival of the salmon. The majority of the trees that grow in these forests tend to be conifers such as spruce.

What has become clear is that not only do the salmon need the trees, but the trees need the salmon. As millions of salmon move through the waters of the Pacific Northwest coast of the USA, they provide huge amounts of food for bears and eagles (Figure 4.22). It has been estimated that each bear fishing in British Columbia, for example, can catch 700 salmon during the spawning period. Although the bears kill the salmon in the water, they move away from the water to eat. Roughly half of each salmon carcass is consumed by the bear, with the rest feeding scavenger species and insects.

The nitrogen compounds from the decomposing salmon carcasses eventually find their way into the soil as part of the nitrogen cycle. Proteins are broken down and converted into nitrates by a series of different types of bacteria. Proteins are broken down into amino acids by decomposers. The amino acids are then converted to ammonia in the process of ammonification. Ammonia is then converted to nitrite and finally nitrate by nitrifying bacteria. The trees take in the nitrates through their roots and are able to use it to form amino acids which are then built up into plant proteins. As nitrate is normally a limiting factor for plant growth, increasing the level of nitrates increases the growth of the trees. The fish provide up to 120 kg nitrogen per hectare of forest, which enables the trees to grow up to three times faster than they would without the added nitrates.

Researchers have used different isotopes of nitrogen to investigate the uptake of nitrates from the salmon. Isotopes are forms of the same element that have different numbers of neutrons and therefore different relative atomic masses, although they have the same chemical properties. The nitrogen 15 isotope is far more abundant in marine ecosystems than in terrestrial ecosystems and so can be used as a marker for the nitrogen that has come from marine sources. Small samples of wood can be extracted from the tree trunk and the isotopes compared. Using this method it has been shown that larger trees have higher levels of nutrients that originate in the salmon than smaller trees. In addition, the closer the tree is to the spawning sites, the higher the levels of nutrients from the salmon. In this way a positive feedback loop is formed. The more salmon that are deposited, the better the trees grow, and the better the trees grow, the better the conditions in the stream for the spawning of salmon (figure 4.23).

Figure 4.23. Spruce trees growing near a river in Montana

This has important implications for conservation of both salmon and forests, as each helps the other to survive. Since the 1990s there have been sharp declines in the numbers of Pacific salmon, which could cause problems not only for the bears that feed directly on them, but for the growth of trees. This would of course also affect all the other species that live in and around the forests, and which need the spruce trees for their habitat. Eventually it would also affect the salmon themselves, as fewer trees would mean worse conditions for spawning. Therefore, in order to conserve the salmon populations the forests must be protected, and in order to conserve the forests there need to be enough salmon spawning each year.

Questions

1 a Explain why the growth of trees is important for the survival of salmon.
  b Explain how the salmon increase the growth of the trees.

2 a Researchers have used different isotopes of nitrogen to trace nutrients derived from marine sources. Describe the possible route from the ocean to a tree of a nitrogen atom contained in an ammonia molecule.
  b Most of the nitrogen appears to come from the salmon carcasses abandoned by the bears. Suggest another way that extra nitrogen is provided by the salmon.

3 Name another nutrient present in the salmon and suggest where it would be found within the salmon.

4 Suggest a type of organism other than the trees that would benefit from the nitrogen within the salmon.

5 a Suggest how some of the nitrogen in the forest is returned to the marine ecosystem.
  b Why must salmon and forest conservation take place at the same time?