In order to answer these Exam style Question, please review attached Chapter Texts. You may wish to take notes as this will be helpful when taking this Course as well. The numbers next to each question (to the right) represent how many marks are available based on your answers.

You may type or hand write your answers. The AICE Exam is a handwritten Exam.

Chapter 1: The Scientific Method

1. Design a laboratory-based experiment to test the hypothesis that algae need light to grow. [6]

2. A field-based experiment was carried out that investigated the distribution of two different species of fish in an estuary. Total Marks [5]

    a. Suggest environmental factors that could affect the distribution of fish in an estuary. [3]
    b. These factors cannot be controlled during the experiment. Explain what should be done instead. [2]

Chapter 2: Marine Ecosystems and Biodiversity

1. a. Explain what is meant by each of the following terms
    i. Population [1]

    ii. Community [1]

    iii. Trophic Level [1]

    iiii. Species [1]

    v. Ecosystem [1]

b. Many forage fish species (for example sardines or herrings) form shoals.

    i. Discuss the advantages of shoaling [4]

    ii. discuss the disadvantages of shoaling [2]

Total Marks [11]

2. Please answer the following below.
   a. Describe the relationship between coral and zooxanthellae. [3]
   b. Define succession [1]
   c. Outline the succession that leads to the formation of a coral reef [3]
   d. Discuss why coral reefs contain narrow ecological niches [4]

Chapter 3: Energetics of Marine Ecosystems

1. Please answer the following below.
   a. i. Describe what is meant by the term productivity. [3]
      ii. Give three factors that can affect the productivity. [3]
      iii. Briefly describe a simple method to measure productivity [3]
   b. Explain why productivity is increased during the spring and summer. [4]
2. Please answer the following
   a. Describe the process of photosynthesis. [4]
   b. i. Why does photosynthesis not occur at hydrothermal vents on the ocean floor? [2]
      ii. Describe how energy enters the ecosystem found t the hydrothermal vents on the ocean floor. [4]
   c. The solar energy falling on the oceans is 1.7 x 10^6 kJ m^-2 year ^-1 and the phytoplankton ae able to use 18,754 kJ m^-2 year^-1 of this.
      i. Calculate percentage of the sun's energy that is used by phytoplankton. Show your working [2]
      ii. Explain why 100% of the energy is not used. [3]

Chapter 4: Nutrient Cycles in the Marine Ecosystems

1. Please answer the following below. Total Marks [11]
   a. Fill in the Table below to show the uses of different nutrients [3]

Nutrient	Biological Use
Nitrogen	
Calcium	
Phosphorous	

   b. Describe the process of run-off. [3]
   c. Describe the process of run-off of nitrogen fertilizers on producers. [3]
   d. Explain how this will affect the consumers in the food chain. [3]

Chapter 5: Coral Reefs and Lagoons

1. Please answer the following below. Total marks [10]

   A. Describe each of the following reef types:
      i. Fringing reef [2]
      ii. Barrier reef [2]
      iii. Atoll [2]

   B. Outline the Darwin-Dana-Daly theory od atoll formation. [4]

2. Please answer the following below Total Marks [7]
   a. Describe the relationship shared by the following pairs of organisms
      a. Coral polys and zooxanthellae [2]
      b. Butterflyfish and coral polyps [2]
   b. Explain how parrotfish lead to reef erosion [3]

Chapter 6: The Ocean Floor and the Coast

1. A. Define what is meant by the term intertidal zone. [1]
   B. Compare the physical factors affecting organisms living on a rocky shore to those living on a sandy shore. [4]
   c. i. Define the term vertical zonation [1]
   ii. Explain how the physical and biological factors of a rocky shore ecosystem contribute to vertical zonation of the organisms that live there. [2]

   Total Marks [8]

2. A. Describe the habitat where you would expect to find mangrove trees. [2]
   B. List and explain two adaptations mangroves have in order to survive within their habitat. [2]
   C. Explain how red mangroves benefit coastal ecosystems [4]

   Total Marks [9]

Chapter 7: Physical and Chemical Oceanography

1. Please answer the following below. Total Marks [13]
    a. Outline the principles behind the Coriolis Effect. [4]
    b. Explain the impact of the Coriolis Effect on tropical cyclones. [3]
    c. The table below shows the air pressure at different distances from the center of a tropical cyclone.

Distance from the center of the cyclone (km)	Air pressure/ millibars
100	980
80	976
60	970
40	964
20	956
0	916
20	956
40	964
60	970
80	976
100	980

    i. Plot these data on a graph [4]
    ii. Explain why the lowest pressure is at the center of the cyclones. [2]

2. a. Compare the summer monsoons in India with those in the winter. [8]

    b. Discuss the impacts of monsoons on the people of India. [2]

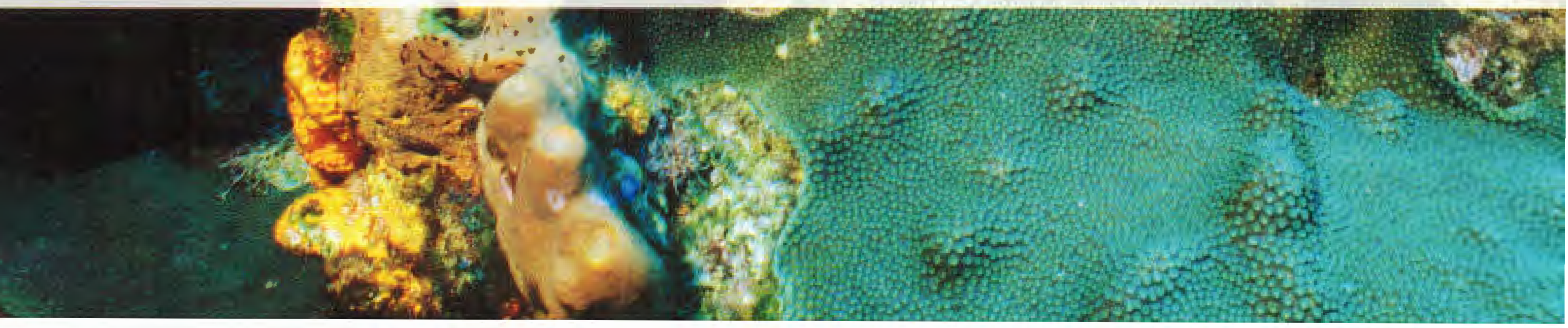
Total Marks [10]

Chapter 1
Scientific method

Learning outcomes

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

- describe the steps in the scientific method
- explain how observations and questions are used to formulate a hypothesis
- use the scientific method to design experiments to test a hypothesis
- ensure that experimental results are valid by identifying independent, dependent and control variables
- explain how to make the results of an experiment reliable
- choose appropriate equipment to make accurate measurements and reduce the uncertainty in experimental results.



1.1 The history of the scientific method

The Ancient Greek philosopher Aristotle is believed to be the first person who realised that it is necessary to take measurements in order to increase our knowledge. More than 2000 years have passed since he made this suggestion and scientific enquiry is still based on his idea. The philosophers and scholars who followed him added to his idea and refined it so that we now have a standard way to carry out scientific enquiry. In the Middle Ages a monk named Roger Bacon described a scientific method that he used to investigate nature. He made observations, formulated a **hypothesis** and carried out experiments. This sequence of events in scientific enquiry is probably familiar to most of us today. Galileo has been called the father of modern science and he also contributed to the development of the scientific method. He began to standardise measurements so that experimental results could be checked by other people.

The scientific method requires a logical approach in order to collect measurable results. Measurements are taken in an experiment designed to test a hypothesis. The results will then be used to either support or contradict the hypothesis. Because experimental data are naturally variable there will often be uncertainties in the results. The level of uncertainty can be reduced by ensuring that large numbers of accurate measurements are taken. **Variables** other than the one being investigated should be kept constant or, if this is not possible, measured. If enough evidence is gathered to support a hypothesis, then it may become a **theory**.

In this chapter you will begin to consider the use of the scientific method to formulate and test hypotheses. You will also learn how to plan controlled experiments to collect results to support or **refute** a hypothesis.

> **KEY TERMS**
>
> **Hypothesis:** an explanation of an observation that can be tested through experimentation
>
> **Variable:** a condition in an experiment that can be controlled or changed
>
> **Theory:** a well-substantiated explanation of an aspect of the natural world that has been repeatedly tested and confirmed through observation and experimentation
>
> **Refute** (a hypothesis)**:** submitting evidence that shows that a hypothesis is not correct

1.2 Steps in the scientific method

There are several steps in the scientific method that should be followed whenever an experiment is planned (Figure 1.1). It is important to remember that the scientific method is a process. Even if a hypothesis is supported, ideas can change in the future if new observations are made.

Observations, questions and hypotheses

The first stage in the process is making observations. For example, you might observe that phytoplankton are found in the upper layers of the ocean. Initial observations are often **qualitative** rather than **quantitative**. This means that they are descriptive rather than having an amount or numerical value. In this case, the position of the phytoplankton is observed and its position in the ecosystem is described. A hypothesis is then formulated to try and explain the observation. A hypothesis is one possible answer to the question 'why?'. Your question might be: Why are the phytoplankton observed in the upper layers of the ocean? So your hypothesis could be that phytoplankton need light to grow. At this stage a **prediction** can also be made. A prediction states what you think will happen in the experiment and is linked to the hypothesis. To continue with the same example, your prediction might be: The more light phytoplankton are given, the more they will grow.

> **KEY TERMS**
>
> **Qualitative data:** descriptive data about a variable, for example colour or behaviour
>
> **Quantitative data:** numerical data that give the quantity, amount or range of a variable, for example concentration of oxygen or number of eggs laid
>
> **Prediction:** a statement of the expected results in an experiment based on the hypothesis being tested

Testing the hypothesis

The next stage is to design an experiment to test your hypothesis. The experiment needs to produce quantitative data that can be evaluated and used to support or refute (disprove) the hypothesis. All experiments involve variables:

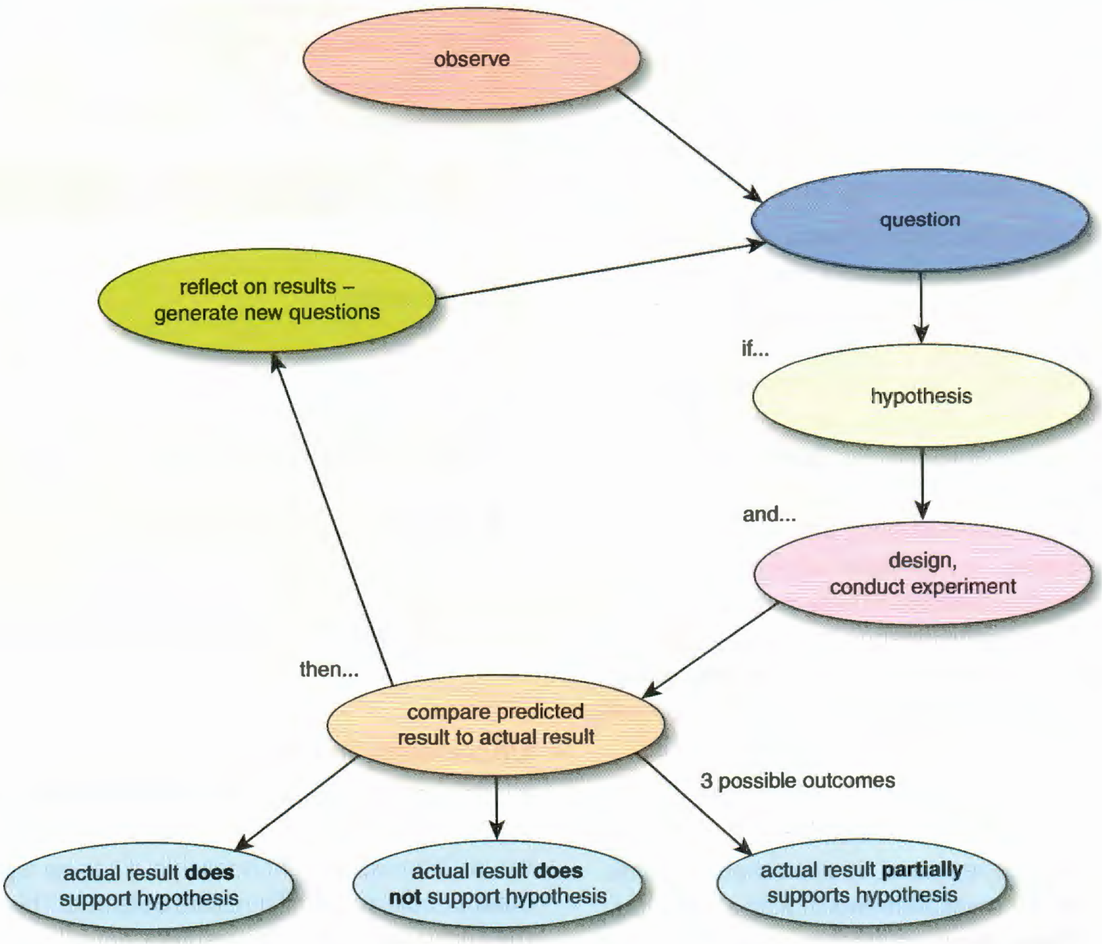


Figure 1.1. Steps in the scientific method.

these are the conditions that can be changed. The **independent variable** is the one that is changed during the experiment and the **dependent variable** is the one that is measured. To test your hypothesis that phytoplankton need light to grow you would need to change the light intensity. You would then measure the growth of the phytoplankton at different light intensities. This could be done by counting samples of the cells under a microscope.

KEY TERMS

Independent variable: the variable being changed in an experiment

Dependent variable: the variable being measured in an experiment

Control group: a group within an experiment or study that receives exactly the same treatment as the experimental groups with the exception of the variable being tested

Control variables: variables that are not being tested but that must be kept the same in case they affect the experiment

A **control group** should normally be included in the experiment. The control group is treated in the same way as the experimental groups apart from the independent variable. This gives you results to use as a comparison. If you are testing the hypothesis that phytoplankton need light to grow, the control group would be phytoplankton that are given no light. To obtain valid results, all variables other than the independent variable must be kept the same. If more than one variable is changed at the same time it would be impossible to say which one caused any changes in the measurements. The variables that are kept the same are the **control variables**. A control variable is any variable that could affect the dependent variable. Important examples to consider when deciding on the control variables are:

- temperature
- carbon dioxide concentration
- oxygen concentration
- pH

- light intensity
- light wavelength.

Obviously these can only be controlled if they are not the independent variable and there may be other controls depending on the experiment being carried out.

It is much more difficult to control the variables in field-based experiments than in laboratory-based experiments. Clearly you cannot control the temperature or amount of light available on a seashore, for example. To help analyse the results, measurements should be taken of any variable that might affect the dependent variable. These are generally the same variables that would be controlled in the laboratory, for example the pH or light intensity. These are measured at the same sampling sites as the dependent variable and recorded. Any trends or patterns in the results can then be related to changes in these measurements as well as to changes in the independent variable. You may also see these variables referred to as **confounding variables**. A confounding variable is something that could affect the results of the experiment but that cannot be controlled.

To make sure that the results are **reliable** each treatment needs to be repeated. You can then calculate mean values for your measurements. It also allows you to identify any **anomalous** results that could affect your conclusions. Anomalous results are individual results that do not fit the pattern of the rest of the data. They may be caused by errors in measurement or difficulties in controlling the variables. It can be difficult to tell whether an anomalous result is due to natural variation within the variable being measured or genuine problems with the data. For this reason repeated readings are important to help to identify any anomalies by comparing them with the other readings taken at the same point in the experiment.

KEY TERMS

Confounding variable: a variable that could affect the dependent variable. In laboratory experiments these are the variables that must be controlled. In field experiments they are normally just measured and recorded

Reliable: results that can be replicated by other people

Anomaly: a result or observation that deviates from what is normal or expected. In experimental results it normally refers to one repeated result that does not fit the pattern of the others

SELF-ASSESSMENT QUESTIONS

1 Copy and complete Table 1.1 to summarise the different variables in an experiment.

type of variable	description
independent	
dependent	
control	
confounding	

Table 1.1. Types of variables.

2 A student observes that there are more algae growing in a fish tank in summer than in the winter. Suggest a hypothesis to explain this and predict the results of an experiment to investigate it.

Uncertainty in data

It is sometimes difficult to be certain about the results of experiments because the measurements will vary to some extent. If an experiment is reliable, it can be repeated by other people and similar results obtained. This decreases the uncertainty about the results. Controlling all variables apart from the independent variable also reduces uncertainty because you know that only the independent variable could have altered the measurements. Finally, all measurements must be taken as accurately as possible. This means choosing the most appropriate equipment to take the measurements and then reading the results properly. For example, when measuring liquids the **meniscus** is used. The meniscus is the curve in the upper surface of a liquid that is held in a container. A concave meniscus curves downwards and is seen when measuring the volume of water, for example. A convex meniscus curves upwards and is seen in mercury thermometers. In both cases it is the centre of the meniscus that is the point used to take the measurement. The meniscus must also be at eye level so that it can be read accurately (Figure 1.2). The correct equipment to measure a liquid is normally a measuring cylinder and the smallest appropriate size should be chosen. Measuring 8 cm^3 in a 10 cm^3 cylinder is more likely to be accurate than using a 200 cm^3 cylinder because it will be easier to read the correct value from the scale. For volumes of liquid that are less than 10 cm^3, a pipette or a syringe would be more accurate.

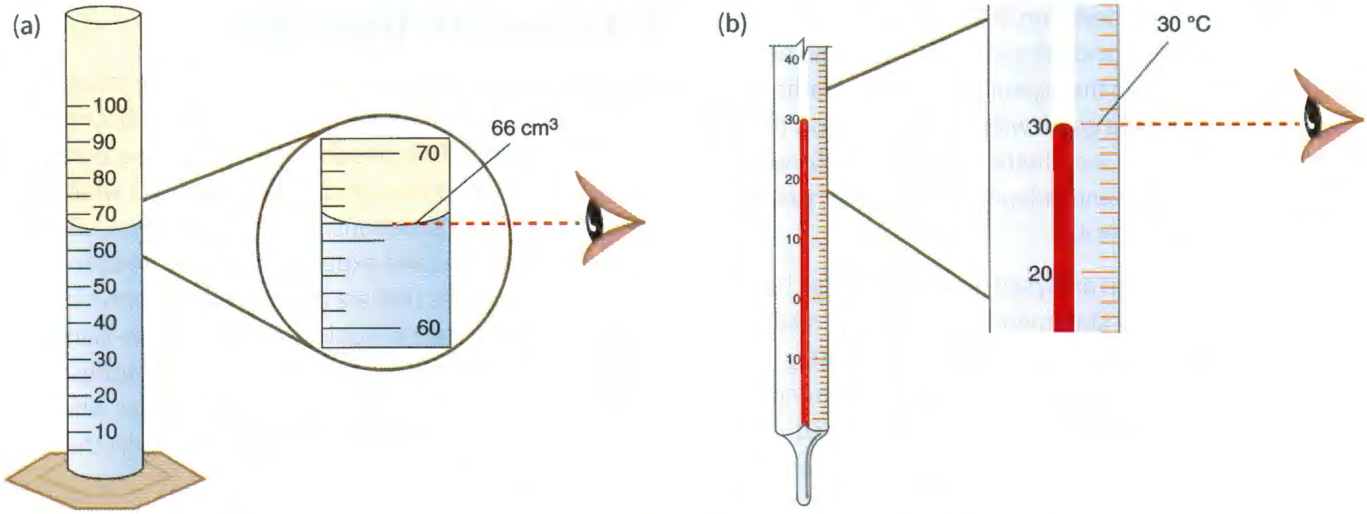


Figure 1.2. Reading the meniscus at eye level (a) in a measuring cylinder and (b) on a thermometer.

KEY TERM

Meniscus: the curve in the upper surface of a liquid inside a container. It is caused by surface tension and can be concave or convex

SELF-ASSESSMENT QUESTIONS

3 Suggest the most appropriate equipment to measure the following accurately.

a $86\,cm^3$ of water

b $0.5\,cm^3$ of water

c The mass of seaweed found in $1\,m^2$

4 Figure 1.3 shows three measurements of volume being taken.

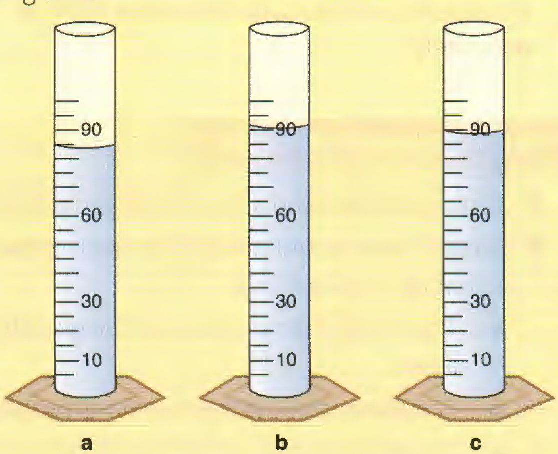


Figure 1.3. Three different measurements of the volume of liquids.

Describe how you would accurately read off the amount of liquid in each cylinder and write down the volume contained in each one.

Analysing the results

During any experiment, the results must be clearly and accurately recorded. The best way to do this is in a results table. This should be drawn before the experiment begins and must have space to fit in all the data to be collected. Normally, the independent variable is placed in the first column of the table. All the columns should have headings that describe the variables and state the units that will be used to measure them (Table 1.2).

light intensity / lux	number of algae present in sample after 2 days		
	trial 1	trial 2	trial 3
0			
2000			
4000			
6000			
8000			
10 000			

Table 1.2. A results table for an experiment investigating the effect of light intensity on the growth of algae.

The first stage in analysing the results is to calculate a mean from each set of repeated measurements. If one repeat is obviously different to the others and does not fit the pattern it may be an anomaly. Anomalies that have been caused by random errors in measurements can be ignored when calculating the mean. Standard deviation can also be calculated, which is a measure of the spread of data around the mean (see the Maths skills box in Chapter 10).

The larger the standard deviation, the larger the range of the data. Percentages, rates and rates of change may also be calculated depending on the experiment (see the Maths skills box in Chapter 3). Often, a graph will be drawn to show the data more clearly and to see whether there is a relationship between the dependent and independent variables (see the Maths skills box in Chapter 4).

Once the data have been analysed a conclusion can be drawn. This should be a statement describing the results and any patterns obtained. The data obtained during the experiment are used to illustrate each point. The trends and patterns in the results should then be explained and linked back to the prediction. In general, the more accurate the measurements taken, and the less variation there is within repeated results, the more valid the conclusions will be.

A good conclusion will come from an experiment with the following features:

- repeated readings are taken
- anomalous results are identified and explained
- sufficient measurements of the dependent variable are made to show a clear pattern
- other variables are controlled and recorded
- the measurements of the variables are made accurately using appropriate equipment.

Evaluation of the hypothesis

If the results match the prediction, they support the hypothesis. If the results do not quite match the prediction, they do not support the hypothesis and it may need to be refined. If the results are completely different to the original prediction, they may be used to refute the hypothesis. This means arguing that the hypothesis is incorrect. You may then need to generate new questions by observing the data and making a new hypothesis that explains all of the data you now have. Alternatively, the original hypothesis may be refined to include the new observations.

SELF-ASSESSMENT QUESTIONS

5 Explain what an anomalous result is.

6 Describe the relationship between the prediction and the results if those results support a hypothesis.

1.3 Scientific theories

If a hypothesis is consistently supported by the results of many observations and experiments, it may become a scientific theory. Theories are intended to be accurate models of the world that can be used to predict what will happen in different situations. Theories can be modified as new observations and experimental data are collected. Examples of theories that are discussed later in this book are the theory of plate tectonics and the Darwin–Dana–Daly theory of atoll formation. Both of these theories started as hypotheses and only became theories when large amounts of evidence were found to support the original hypothesis.

1.4 Steps in planning valid laboratory-based experiments

Once a hypothesis and prediction have been made, an experimental approach to testing them must be planned. In order to obtain accurate results and to make valid conclusions, you should take the following steps.

1 Decide on the independent variable and the range of values to use.

2 List all the control variables that could affect the experiment and that must therefore be kept the same.

3 Decide how to keep the control variables the same.

4 Decide how many repeats to carry out.

5 Decide the timescale of the experiment.

6 Plan which measurements to take of the dependent variable and which equipment to use to do so accurately.

SELF-ASSESSMENT QUESTIONS

7 Distinguish between a hypothesis and a theory.

8 Suggest two control variables for each of the following investigations.

 a The effect of temperature on the growth of algae.

 b The effect of pH on the number of zooplankton.

 c The effect of light intensity on the growth of seagrass.

Summary

- The scientific method is a series of steps that are used to investigate scientific phenomena.
- Observations are made first and used to formulate a hypothesis.
- A prediction is made based on the hypothesis.
- An experiment is planned to test the hypothesis by changing the independent variable and measuring the dependent variable.
- All other variables must be controlled in order to obtain valid results.
- There may be uncertainties in the results because of variability in the data and the accuracy of measurements.
- If the results match the prediction, they support the hypothesis.
- If the results do not match the prediction, they refute the hypothesis.
- A hypothesis that is supported by many sets of observations and experimental results may become a theory.

Exam-style questions

1 Design a laboratory-based experiment to test the hypothesis that algae need light to grow. **[6]**

[Total mark: 6]

2 An investigation into the growth of coral at different temperatures was carried out. Samples of coral were grown in the laboratory at different temperatures and the increase in surface area was measured in $cm^2 week^{-1}$. The results are shown in Table 1.3.

temperature / °C	increase in surface area / $cm^2 week^{-1}$			mean increase in surface area / $cm^2 week^{-1}$
	trial 1	trial 2	trial 3	
14	0.3	0.5	0.2	0.33
16	0.6	0.6	0.8	
18	0.8	0.9	1.1	0.93
20	1.4	0.1	1.3	1.35
22	1.6	1.5	1.8	1.63
24	1.7	1.4	1.8	1.63

Table 1.3. Growth of coral at different temperatures.

a **i** Calculate the missing mean for 16 °C. **[2]**

ii Identify the anomalous result in the table. **[1]**

iii Describe the pattern shown by the results. **[2]**

b The researchers devised the following hypothesis to explain the results: Coral grows faster at higher temperatures.

i Explain whether the results support or refute the hypothesis. **[2]**

ii Give two factors that should have been controlled during the experiment. **[2]**

c Design a laboratory-based experiment to investigate the effect of salinity on the growth of coral. **[6]**

[Total mark: 15]

3 A field-based experiment was carried out that investigated the distribution of two different species of fish in an estuary.

a Suggest three environmental factors that could affect the distribution of fish in an estuary. **[3]**

b These factors cannot be controlled during the experiment. Explain what should be done instead. **[2]**

[Total mark: 5]

CASE STUDY

Barnacle distribution

A student made the observation that two species of barnacle appeared to be distributed unevenly on a rocky shore. She noticed one species (*Chthamalus stellatus*) living nearer the high water mark than the other (*Semibalanus balanoides*). She decided to investigate her observation using the scientific method and so formulated a hypothesis. Her hypothesis stated that *Chthamalus stellatus* was more able to resist drying out than *Semibalanus balanoides* (Figure 1.4)

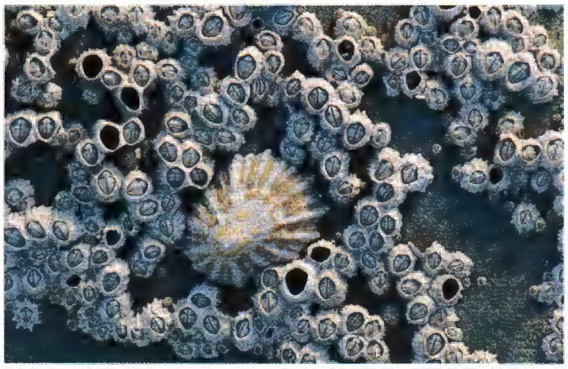


Figure 1.4. Barnacles growing on rocks.

She marked out a 50 mm^2 area just above the low-water mark and counted the number of each species that was present. She then repeated this at 5 m intervals from the low-water mark to the high-water mark at the top of the shore.

Her results are shown in Table 1.4.

distance from low water mark / m	number of *Semibalanus balanoides*	number of *Chthamalus stellatus*
0	12	0
5	9	8
10	11	0
15	6	0
20	0	10

Table 1.4. Distribution of two species of barnacle on the shore.

The student concluded that her results supported her hypothesis. Some of the other students in her class were not sure and argued that there were problems with her results and with her method.

Questions

1 State the independent and dependent variables in this investigation.

2 It is often difficult to control variables when not in the laboratory: suggest a variable that the student could have controlled.

3 Which result do you think is most likely to be anomalous and why?

4 Suggest what might have caused the anomalous result.

5 Suggest how the experiment could be improved.

6 Do you agree with her conclusion?

Chapter 2
Marine ecosystems and biodiversity

Learning outcomes

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

- understand and use the key terms ecosystem, community, habitat, ecological niche, succession, biodiversity, population, species, producer, consumer, predator, prey, trophic level, food chain and food web
- describe types of interspecific marine relationship, including mutualism and parasitism
- explain how fluctuations in populations of predator and prey may be linked
- define the key term shoaling and explain its benefits, using examples
- use examples from deep-sea vents and whale-fall ecosystems to describe succession
- understand how the biodiversity of marine environments is affected by how stable and extreme they are, and provide examples
- explain the terms specialised and generalised niches and provide marine examples
- explain the relationship between the breadth of ecological niches and level of biodiversity
- apply what you have learnt to new, unfamiliar contexts.

2.1 An aquatic home

From space, the Earth appears blue because water dominates the surface of our planet. There are five **oceans** on Earth today: the Arctic, Atlantic, Indian, Pacific and Southern. These oceans cover approximately 70% of the globe and their marine ecosystems are crucial for life on Earth. Oceans are where life evolved more than 3.5 billion years ago and they are home to an enormous biodiversity of sea creatures.

The interface between the oceans and the land has also proved crucial to shaping the planet we live on. Competition within life in the oceans, as well as changes in its temperatures and salinity, propelled some marine plants and animals to start colonising the land over 425 million years ago. The **seas** are where the oceans and land meet, producing a variety of coastline habitats (such as sandy, rocky, muddy). Marine biologists have also investigated the estuarine interface, where seas extend inland to meet the mouth of a river. In **estuaries** fresh water and seawater are mixed by the daily and seasonal rhythm of tides. Many marine organisms start their life here before venturing out to spend their adult life in the ocean.

The term ecology is derived from the Greek word 'oikos' meaning 'house'. Marine ecology is the study of marine organisms in their homes or habitats. Marine ecologists study the connections between marine organisms and their environments and aim to understand the factors that control the distribution and abundance of life in the oceans. To do this, it is important to understand the range of relationships between organisms. Ecologists also strive to understand how marine organisms are adapted to their aquatic environment and how both they and humans can alter that environment.

KEY TERMS

Ocean: a continuous mass of seawater on the Earth's surface, its boundaries formed by continental land masses, ridges on the ocean floor or the equator

Sea: a continuous mass of seawater on the Earth's surface, part of the ocean, that is partially enclosed by land, so seas are found where the ocean and land meet

Estuary: a partially enclosed, tidal, coastal body of water where fresh water from a river meets the salt water of the ocean

2.2 Fundamental principles of marine ecology

Ecosystems

Life on Earth can be divided into subunits called **ecosystems**. An ecosystem is all the living organisms in an area plus the non-living environmental factors that act on them.

The **biotic** components of an ecosystem are the living factors, such as producers, consumers and decomposers. Biotic components also include feeding relationships, for example predator–prey relationships, which can be shown as food chains and webs. The **abiotic** components of a marine ecosystem are the environment's geological, physical and chemical features:

- geological features include substrate type, topography and suspended sediment
- physical features include temperature, exposure to wind and sunlight wave action, tides, currents, hydrostatic pressure, light intensity and wavelength
- chemical features include organic nutrients, pH, salinity, oxygen, carbon, nitrogen and phosphorus.

KEY TERMS

Ecosystem: the living organisms and the environment with which they interact

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

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

Habitat: the natural environment where an organism lives

Habitat

A **habitat** is the natural environment where organisms live. Habitats are areas in which organisms can find food, protection, shelter and a mate. Marine environments form a range of habitats in estuaries, on the shoreline and in shallow and deep ocean water. Estuaries are brackish areas where fresh and salt water mix. Sediments from streams often settle in estuaries, creating a number of important habitats where marine species can feed and breed. These habitats include swampy areas called wetlands, mangrove forests and salt marshes.

The habitat an organism occupies can be defined by where it lives and how it moves. For example:

- planktonic organisms, such as phytoplankton and zooplankton, drift in ocean currents
- nektonic organisms, such as fish, marine reptiles and mammals, can actively swim
- benthic organisms, such as tube worms, starfish, crabs and sea cucumbers, live on the seabed.

Some organisms cross from one habitat to another during their life cycles. For example, crabs and clams both start out as planktonic larvae but become benthic adults.

Habitats are not always geographical; for example, parasitic worms live inside their host species.

Species

A **species** is defined as a group of similar organisms that can interbreed naturally to produce fertile offspring. Each species is given a name composed of two parts, both of which are in Latin. This naming system is called the binomial system of nomenclature. It was first formulated in 1736 by Carolus Linnaeus, a Swedish botanist. The first part of the name refers to the genus, and the second part refers to the species. The genus is given a capital letter, whereas the species is always lower case. In print, a binomial always appears in italic. For example, the Latin binomial name for the Galapagos penguin is *Spheniscus mendiculus*. When you write a binomial name by hand, you should underline it, for example Spheniscus mendiculus.

KEY TERMS

Species: a group of similar organisms that can interbreed naturally to produce fertile offspring

Population: all the individuals of the same species that live at the same place and time

Population

A **population** is all the organisms of the same species that live at the same place at the same time, and are able to reproduce. For example, the squat lobsters living off Otago, New Zealand, are a population. Similarly, all the salmon in the Atlantic Ocean make up the Atlantic salmon population.

The number of individuals in any population often increases and decreases. Population increases are caused by reproduction or by new individuals joining the population area. Population decreases are caused by death or by individuals leaving the population area.

The largest population that can be sustained by the available resources is called the carrying capacity. If some resources are less than optimal, or get completely used up, they are called limiting factors and result in reduced growth in the population. Limiting factors can be either biotic or abiotic. Biotic limiting factors include competition and predation. Abiotic limiting factors affect growth, survival and reproduction, and include living space, food, water temperature, pH and light intensity.

Community

A **community** is an association of all the different populations of species occupying a habitat at the same time. An example is the mollusc community on a Californian rocky shore, which would include all the different species of molluscs living in this habitat. Biomes are communities that extend over large areas of the globe and are classified according to the predominant vegetation. Marine biomes include intertidal, rocky, sandy and muddy shores, coral reefs and the seabed. Each biome has a characteristic community.

Biodiversity

Biodiversity describes the enormous variation in organisms living on the Earth. Life on Earth evolved in the marine environment, the seas and oceans, which have an extremely high biodiversity.

KEY TERMS

Community: all the different populations occupying a habitat at the same time

Biodiversity: a measure of the numbers of different species present

Ecological niche: the role of a species within an ecosystem

Ecological niche

Ecological niche is defined as the role of a species within an ecosystem. The term also takes into account interrelationships with other organisms.

- Feeding relationships: for example, both sperm whales and killer whales are top predators. Sperm whales consume predominantly squid, whereas killer whales consume a wider variety of prey, including elephant seals and baleen whales. These two species of whale therefore occupy different ecological niches.

- Spatial relationships: two species may have the same feeding relationships but occupy that niche in different parts of the ocean. For example, if a prey species is found throughout the water column, one predator may feed on it in the surface photic zone (where there is light) while another feeds deeper down in the aphotic zone (where there is no light).
- Temporal relationships: two species may have the same feeding relationships but occupy the niche at different times, for example if a prey species is found in the same location throughout each day, one predator may feed at night (nocturnal) while another feeds in the daytime (diurnal).

2.3 Symbiosis within marine ecosystems

Symbiosis literally means 'living together'. The term refers to an interspecies relationship between two or more organisms from different species living in close physical association. The smaller partner in the symbiosis is called the symbiont and the larger one is called the host.

There are many forms of symbiosis including:

- **mutualism**, when both species benefit from the relationship
- **parasitism**, when one organism (the parasite) benefits at the expense of the host.

Other types of interspecies relationship include:

- **competition**, when both species are negatively affected by trying to fill the same ecological niche
- **predation**, feeding that involves hunting, killing and eating another animal.

KEY TERMS

Mutualism: [illegible]

Parasitism: [illegible]

Competition: [illegible]

Predation: [illegible]

Marine mutualism

Examples of marine mutualism include:

- coral and zooxanthellae
- chemosynthetic bacteria and tube worms
- cleaner fish and shrimps and their hosts.

Coral and zooxanthellae

The tissues of corals are host to symbiotic single-celled algae called zooxanthellae (see Chapter 5).

Zooxanthellae photosynthesise and provide the coral with nutrients such as oxygen and glucose:

zooxanthellae photosynthesis:
carbon dioxide + water ⟶ glucose + oxygen

As the coral grows, it respires aerobically and provides the zooxanthellae with the carbon dioxide required for photosynthesis:

coral polyps aerobic respiration:
glucose + oxygen ⟶ carbon dioxide + water

The zooxanthellae are provided with a safe habitat with a large surface area for maximum absorption of light. They also obtain other minerals from the coral's waste products: nitrogenous compounds are used to make proteins, ATP and DNA, and phosphates are used for DNA, ATP and membranes.

Chemosynthetic bacteria and tube worms

Tube worms (for example *Riftia* and *Tevnia* species) are associated with deep-sea vents (see Chapter 3). They live in the 'midnight' or aphotic zone where there is no light. Because there is no light, photosynthesis is not possible so photoautotrophic producers cannot survive in this zone. Tube worms have followed a very different evolutionary pathway compared with photoautotrophic producers. They host colonies of chemosynthetic bacteria that produce organic matter from the chemicals available at deep-sea vents. These symbiotic chemosynthetic bacteria live in an organ inside the tube worm called the trophosome. The plume at the tip of a tube worm takes in hydrogen sulfide, carbon dioxide and oxygen. Carbon dioxide and hydrogen sulfide are carried in the blood of the tube worm to the chemosynthetic bacteria in the trophosome (Figure 2.1).

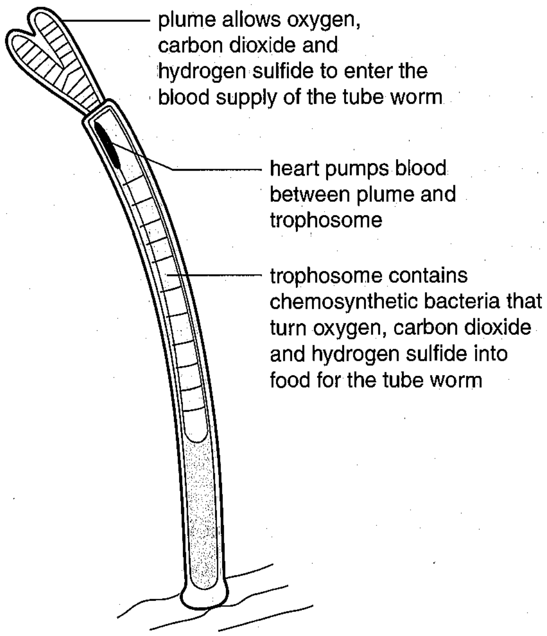


Figure 2.1. Chemosynthetic bacteria and tube worm mutualism.

In this way the chemosynthetic bacteria gain a safe environment and nutrients while the tube worms use the organic matter for cellular respiration to create the ATP energy they require to grow. The tube worms form part of the food chain for other organisms colonising the vent, such as polychaete worms, octopuses, giant clams, mussels, limpets, crabs and vent fish. Eventually, a complex community consisting of many different species is established.

Cleaner fish, shrimps and grouper

Cleaning stations are often located on the top of a coral head. Reef fish, sea turtles and sharks congregate to have parasites removed by numerous species of cleaner fish (especially wrasses and gobies) and cleaner shrimps. When the host animal approaches a cleaning station, it opens its mouth wide as a signal to the cleaner species. The cleaner species then remove and eat the parasites from the host's skin, mouth and gills. The cleaners benefit by gaining nutrients from the dead skin and parasites that they remove. They also gain protection from predators while they are cleaning. The host fish benefit from reduced infection.

Other examples of cleaning mutualism include:

- pilot fish cleaning sharks
- Pacific cleaner shrimps and bluesteak cleaner wrasses cleaning eels.

Marine parasitism

Parasitism is a relationship in which the parasites obtain benefit at the expense of the host.

Finding the next host is paramount for a parasite, and a large portion of a parasite's energy is used for reproduction. Parasites can be divided into two main groups: ectoparasites and endoparasites.

Ectoparasites

Ecotoparasites live on the outside of their host. The salmon louse is a species of copepod that is an ectoparasite on Pacific salmon (Figure 2.2). The lice attach to the skin, fins and gills of juvenile and adult salmon, and feed off the mucus or skin. The parasite can be fatal to juvenile salmon. For adult salmon, the lice can carry diseases between wild and farmed salmon (for example infectious salmon anemia, which can lead to the collapse of fish farms).

Other ectoparasitic copepods feed on the body fluids of flying fish and spread disease. Others attach to the eyes of Greenland sharks and cause inflammation, which reduces the shark's vision and its ability to survive and reproduce.

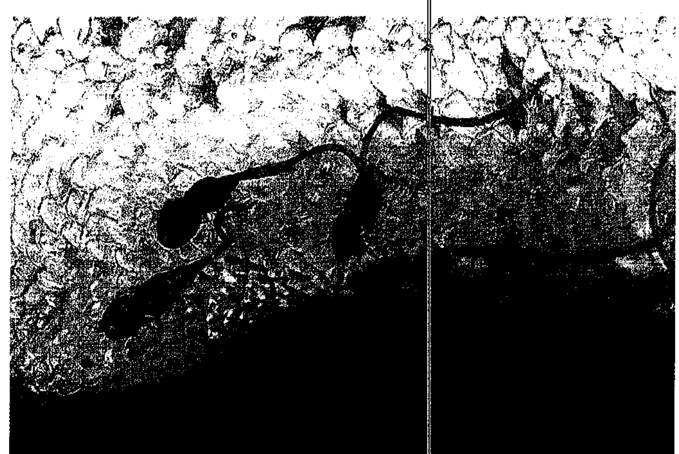


Figure 2.2. Fish lice on salmon.

Endoparasites

Endoparasites live inside their host, for example in the digestive system, attached to gills or in muscle tissue. They are considered to be parasites because they may weaken the host individual. Nematodes or roundworms are common endoparasites in tuna (Figure 2.3).

Another example of an endoparasite is the small tapeworm that derives food and shelter by living in the guts of whales.

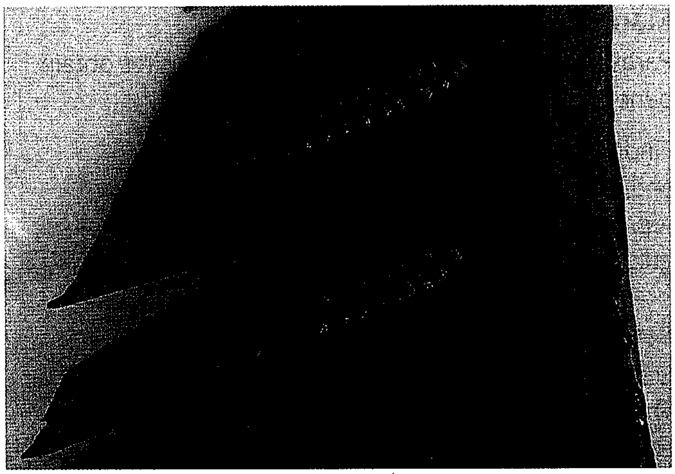


Figure 2.3. Endoparasites living on the gills of a tuna.

2.4 Feeding relationships

Producers

Producers provide food for virtually all other organisms in food chains and food webs. As autotrophs, they are 'self-feeders' and synthesise organic 'food' from simple inorganic compounds and an energy source. There are two types of producer:

- **photoautotrophs**, which use light energy
- **chemoautotrophs**, which use chemical energy.

KEY TERMS

Producer: [illegible]

Photoautotroph: [illegible]

Chemoautotroph: [illegible]

Photoautotrophs

Photoautotrophs use pigments (for example chlorophyll) to trap light energy from the Sun, in the light-dependent stage of photosynthesis. Marine photoautotrophs include seagrass, mangroves, seaweed, kelp, cyanobacteria and phytoplankton. Phytoplankton include diatoms and dinoflagellates and are essential to life on Earth because they produce half of the world's oxygen and are a major sink for carbon dioxide. Diatoms are single-celled organisms with a silicon shell. Dinoflagellates can form enormous ocean blooms or red tides that are sometimes visible from space.

Chemoautotrophs

Chemoautotrophs use energy from the oxidation of sulfur in hydrogen sulfide to make their own food energy. Aerobic chemoautotrophs (such as mutualistic bacteria that live in tube worms) need oxygen, whereas anaerobic chemoautotrophs (such as bacteria that live in deep-sea vent sediment) do not need oxygen. Chemoautotroph producers will be covered in greater details in Chapters 3 and 6.

aerobic chemosynthesis $CO_2 + H_2O + H_2S \rightarrow (CH_2O) + H_2SO_4$

anaerobic chemosynthesis $CO_2 + 6H_2 \rightarrow (CH_2O) + CH_4 + H_2O$

SELF-ASSESSMENT QUESTIONS

1 Using the following symbols, complete Table 2.1 showing different interspecies relationships.

- 0, species is unaffected
- –, species is harmed
- +, species benefits

	host	symbiont
mutualism		
parasitism		
competition		
predation		

Table 2.1. Different interspecies relationships.

2 Name and explain the main similarity and difference between the two ways that producers can synthesise food energy.

3 Concentrations of phytoplankton are lower in Antarctica's Southern Ocean than oceans closer to the equator. How might the abiotic conditions of the Southern Ocean inhibit photosynthesis?

Consumers

The term **consumer** refers to an organism that obtains its energy requirements by feeding on other organisms. The rate at which consumers convert the chemical energy of their food into their own biomass is called secondary productivity.

Consumers include:

- predators (for example sharks) that kill and eat prey animals (for example fish)
- herbivores that eat plants (for example manatees)

- suspension feeders that filter the water for food (for example mussels)
- grazers that scrape algae (for example limpets, sea urchins and parrot fish).

Zooplankton are important consumers and include copepods, foraminifera and krill. Copepods are small herbivores that feed on diatoms. Foraminifera are single-celled animals with calcium carbonate shells. Krill are shrimp-like carnivores that feed on other zooplankton species and phytoplankton. Krill are important food sources for birds, fish, seals and baleen whales.

KEY TERMS

Consumer: an animal that feeds on other organisms to gain its food energy

Food chain: a way of describing the feeding relationships between organisms

Food web: a way of describing how food chains are interrelated in an ecosystem

Trophic level: a position in a food chain or food web

2.5 Food chains and food webs

A **food chain** shows the linear sequence of organisms feeding on other organisms. A series of interlinked food chains forms a multi-branched **food web**. In food chains and food webs, arrows represent the direction in which energy, biomass and nutrients are transferred. The term **trophic level** refers to the 'feeding level' in a food chain or web. Producers occupy the first trophic level, primary consumers occupy the second trophic level, secondary consumers occupy the third trophic level, and so on.

producer → primary consumer → secondary consumer → tertiary consumer → quaternary consumer

1st trophic level → 2nd trophic level → 3rd trophic level → 4th trophic level → 5th trophic level

Primary (first level) consumers are also known as herbivores. Secondary (second level) consumers are carnivores that feed on herbivores. Tertiary (third level) or quaternary (fourth level) consumers are carnivores that feed on carnivores. If carnivores are at the end of a food chain, they are called top predators. Organisms can be grouped into different consumer types depending on the specific food chain being discussed. For example, an omnivore feeds on plants (making it a primary consumer) and other consumers (making it a secondary consumer).

Detritivores (for example worms, fish, crabs, starfish and urchins) eat detritus (dead and decaying material). This makes it easier for decomposers (for example bacteria and fungi) to convert the organic molecules in detritus back to inorganic nutrients. Detritivores and decomposers both gain their energy from recycling the nutrients and energy in detritus (see Chapter 4).

Food webs illustrate how species feed on a number of other species so that they are not dependent on one food source. As a result, if the population of one prey species declines, alternative sources of food are still available. Food webs can also be used to illustrate the different feeding relationships that one species might have at different stages of its life cycle. For example, herring change the prey they feed on as they develop from young fish into mature adults.

Predators and their prey

Predator–prey relationships are an integral part of the niche of a consumer. A **predator** is an animal that catches, kills and eats another animal. Predators are secondary, tertiary and quaternary consumers in food chains. Marine predators include sharks as well as carnivorous fish that eat plankton (planktivores) or fish (piscivores). Predators have adaptations such as speed, agility, camouflage, teeth, poison and the ability to hunt in packs.

Prey are animals that are eaten by predators. Survival adaptations for prey animals include camouflage, defensive spines, the ability to hide in safe places and the ability to flee.

Some predator–prey relationships are an example of coevolution, where the predator and prey species have evolved together in response to changes in each other's morphology and physiology.

Predator–prey relationships are crucial for keeping a healthy balance of populations within the ecosystem. For example, without starfish (Figure 2.4a) there would be no natural predators to control the numbers of mussels, sea urchins and **shellfish**. Left unchecked, these organisms can destroy a kelp forest. Similarly, butterfly fish (Figure 2.4b)

KEY TERMS

Predator: an animal that kills and eats animals for food

Prey: an animal that is eaten by predators

Shellfish: aquatic invertebrates that are used as food, including shelled molluscs, crustaceans and echinoderms, such as bivalves, crabs, lobsters and sea urchins are herbivores that prey on marine algae growing on coral reefs. Without this crucial predator–prey relationship, the algae would overgrow the coral and limit the light reaching the zooxanthellae. This would eventually kill the coral.

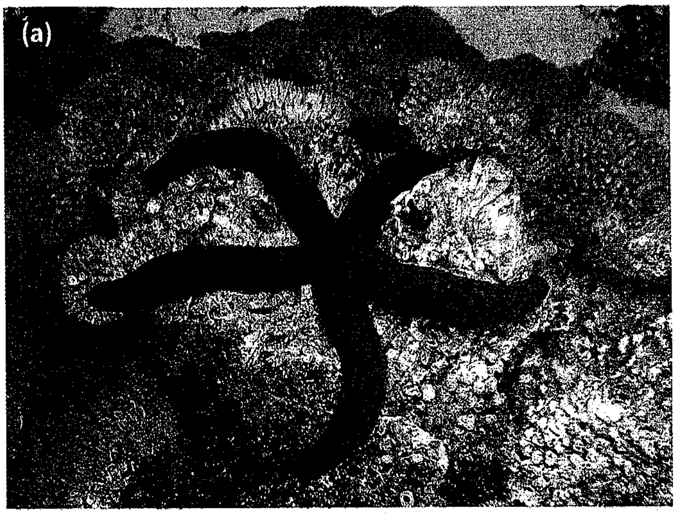


Figure 2.4. (a) Starfish; (b) butterfly fish.

Population changes in predator–prey relationships

The predator population is usually smaller than its prey population. This is because individual predators often have a larger biomass than individual prey, and there is a significant loss in energy between trophic levels.

The availability of food is a major limiting factor that affects the location and numbers of predators in an ecosystem. The spatial distribution of predators is often linked to their prey. For example, predators such as swordfish, sharks and gannets follow their sardine prey along their annual migration route. But predator and prey locations are not always linked. For example, a predator may have many alternative prey species and not closely follow prey that is a minor source of food energy.

Organisms in an ecosystem are interdependent, so when one species changes in population size, other species in the community may also be affected. When the availability of food (the number of prey organisms) increases, the number of predators also increases. This is because when predators have more food energy available, they have an increased chance of surviving and reproducing. The opposite is also true: when the number of prey decreases, the number of predators also decreases.

For example, if a fish population increases because it finds a new food source, the predator shark population also increases because the sharks have more food. If the fish population decreases because of over-fishing, the population of sharks also reduces because the sharks have less food. Conversely, if the shark population decreases as a result of sickness, the fish population would experience less predation and increase.

Lionfish

The numbers of prey and predators in interrelated populations fluctuate through time, with the number of predators lagging behind the number of prey. An example of this interrelationship can be seen between the predatory lionfish and the native Atlantic Ocean fish species that they prey on. An increase in the population of predatory lionfish causes a reduction in native fish stocks. When the fish stocks are too low to sustain the increased lionfish population, lionfish numbers begin to decrease. The drop in predatory lionfish therefore 'lags behind' the drop in numbers of its prey. A reduction in the lionfish population results in less predation of the Atlantic fish, and the fish population begins to recover. After a time lag, the rising prey population results in an increase in the predatory lionfish population. These oscillations in the predator–prey cycle continue with decreasing amplitude until a more stable ratio of predators to prey is reached (Figure 2.5).

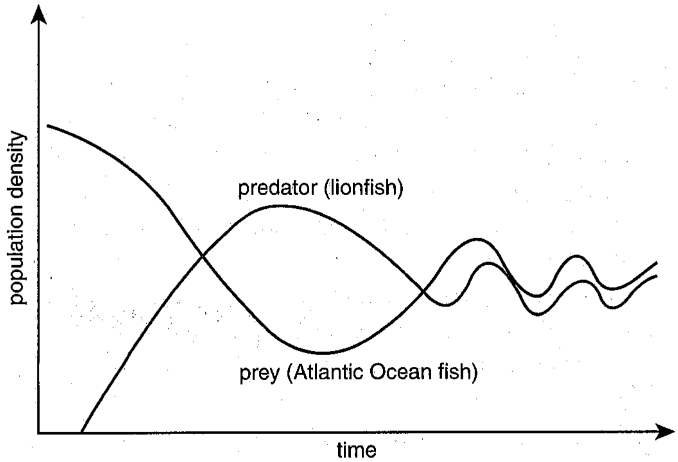


Figure 2.5. Predator–prey relationship for lionfish and Atlantic Ocean fish.

Crown-of-thorns starfish

The crown-of-thorns starfish predates corals on the Great Barrier Reef. The numbers of predators (starfish) and prey (corals) have fluctuated over a 25-year period (Figure 2.6). Between years 4 and 16, the coral population (measured by percentage cover) decreased from 52% to 6%. This led to a reduction in the relative number of starfish from 16 to 3. The drop in starfish numbers did not start until year 10: there was a time lag of 6 years between the drop in coral prey and the drop in starfish predators. The time lag resulted in a maximum number of predators as the prey population was in decline. The coral recovered between years 16 and 25 because the relative numbers of starfish were low. From 21 years, as the coral cover increased, the relative number of starfish also began to increase. Again there was a time lag between the increase in coral cover and the increase in relative number of starfish.

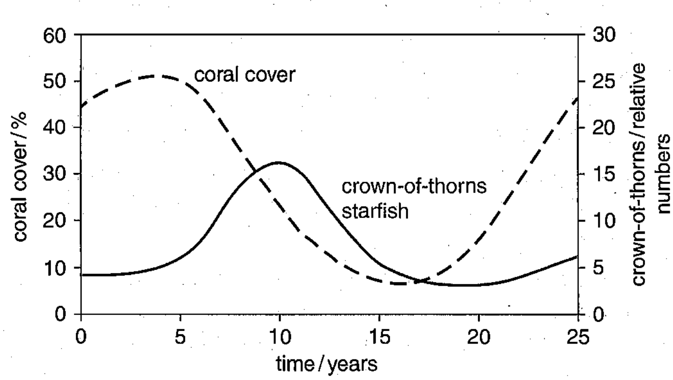


Figure 2.6. Predator–prey graph for crown-of-thorns starfish and coral cover.

KEY TERM

Keystone species: a consumer that affects biodiversity to a greater extent than would be expected from its population numbers

Keystone species

Keystone species are consumers that affect biodiversity to a greater extent than would be expected from their population numbers. Keystone species are likely to occur near the top of the food chain, although they are not necessarily the top predator. Keystone species control other species by means of predation and competition. They may also be capable of ecosystem engineering by physically modifying the habitat. Keystone species are important in conservation programmes that focus resources on maintaining such species, rather than attempting to protect and manage all endangered species in a habitat that is at risk.

Starfish are an example of a keystone species in coral reef communities. Starfish (for example *Pisaster ochraceus*) are not top predators, because they are prey for sharks, rays and sea anemones. Starfish themselves feed on a range of species, including sea urchins and mussels. If starfish are removed, mussel and sea urchin populations increase dramatically, because those species have no other natural predators. An explosion in the mussel population would drive out other molluscs (for example limpets, chitons and barnacles) by outcompeting them for the limited space available on reefs (competitive exclusion). An increased sea urchin population would feed unhindered on the coral and lead to a decrease in coral biomass. Starfish thus promote biodiversity by controlling mussel and sea urchin populations. They are key to the delicate interrelationship between other organisms within the coral reef community. Without starfish, the ecosystem biodiversity would be significantly reduced.

SELF-ASSESSMENT QUESTIONS

4 Over-fishing of cod in seas off Maine, USA, led to a population explosion of one of its prey, sea urchins. The rapid increase in sea urchin numbers nearly wiped out kelp forests in the area, the habitat for lobsters. Predict and explain what would consequently happen to the lobster population.

5 Sea urchins are considered a delicacy in many parts of the world (for example Japan and New Zealand). How could fisherman in Maine have responded to the change in populations in question 4?

PRACTICAL ACTIVITY 2.1

Intertidal zonation studies

Introduction

[illegible]

Equipment

- Tape measure, [illegible]
- Quadrat or other sampling equipment
- Species identification chart
- Recording sheets [illegible]

Figure 2.3 Students taking a rocky shore transect at [illegible]

Method

- [illegible]

Conclusions

- Use of percentage cover estimates and the ACFOR scale for vegetation coverage is a qualitative measure and hence more subjective than quantitative data.
- Kite diagrams (Figure 2.8) can be used to show the zonation patterns graphically.
- Secondary data, for example records from previous years' field trips, can be used to investigate whether there are any zonation changes over time or whether zonation patterns are dependent on the time of year.

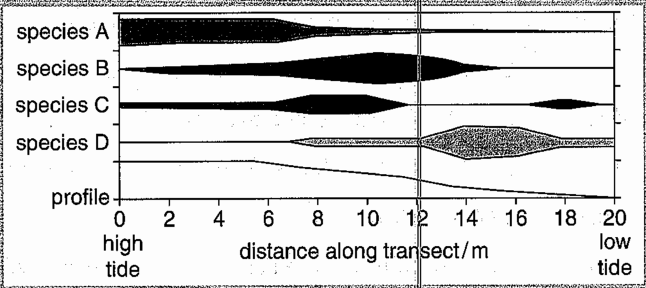


Figure 2.8: A kite graph representing zonation patterns on a rocky shore. Biotic data are shown as kites and abiotic data as lines. Y axis is relative and will vary for each species. For example plants may be measured in percentage of cover, while animals may be measured in number.

Maths skills

Mean, median, mode and range

The mean is the average of your data. To find the mean, add up all the data values (Σx) and then divide by the number of data entries (n).

The median is the middle value in the list of data values. To find the median, list your data in numerical order from lowest to highest. Identify the middle value: this is the median.

The mode is the data value that occurs most often. If no data value is repeated, there is no mode for the sample. There can be more than one mode.

The range is the difference between the largest and smallest data values.

Worked example

A student recorded the following data for the number of periwinkles found on a rocky shore transect.

quadrat	number of periwinkles
1	17
2	92
3	116
4	54
5	11
6	3
7	0
8	0
9	0

Table 2.2. Periwinkle numbers.

To work out the mean number of periwinkles recorded:

$\Sigma x = 17 + 92 + 116 + 54 + 11 + 3 + 0 + 0 + 0 = 293$

Mean $= \Sigma x / n = 293 / 9 = 33$ (0 decimal places)

The median is the middle value, so you have to rewrite the list in order from lowest to highest:

0, 0, 0, 3, 11, 17, 54, 92, 116

There are nine data values in the list, so the middle one will be the fifth data value. The median is therefore 11.

The mode is the number that is repeated more often than any other. The mode for this data set is 0 because it is repeated three times.

The largest data value in the list is 116, and the smallest is 0, so the range is 116–0 = 116

Questions

1 Trophic level transfer efficiency (TLTE) measures the amount of energy that is transferred between trophic levels. TLTE is calculated by:

TLTE = energy trophic level^{n+1} / energy trophic level^{n} × 100

trophic level^{n+1} is the trophic level above trophic level^{n}

Figure 2.9 shows a pyramid of energy for a marine ecosystem (in arbitrary units).

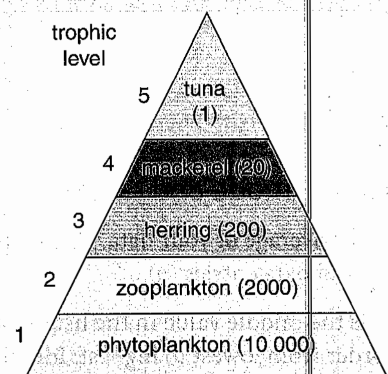


Figure 2.9. Pyramid of energy for a marine ecosystem (in arbitrary units).

Calculate the TLTE for:

a phytoplankton – zooplankton

b zooplankton – herring

c mackerel – tuna

2 Calculate, to the nearest whole number, the mean, median, mode and range for the list of TLTE values given in Table 2.3.

energy trophic level^{n}	energy trophic level^{n+1}	TLTE / %
seal	polar bear	4
krill	blue whale	4
squid	Weddell seal	4
arctic cod	Weddell seal	4
copepod	arctic cod	8
krill	arctic cod	10
krill	squid	10
arctic cod	squid	10
diatom	krill	12
krill	copepods	15
diatom	copepod	20

Table 2.3. TLTE values.

Shoaling

If fish come together in an interactive, social way, they are said to be **shoaling**. The fish adjust their behaviour to remain close to the other fish in the group. Shoaling fish can be of one species (a school) or include fish of different sizes and of mixed species. Fish in a shoal function in a coordinated way even though they appear to have no leader. The individual fish tend to keep a constant distance between each other, turning, stopping and starting in near perfect unison. The shape of a shoal depends on the type of fish and what the fish are doing. Fast-moving shoals usually form a wedge shape, while shoals that are feeding tend to become circular. Shoals that are travelling can form long thin lines, squares or ovals. For example, mullet can form 'chains' of shoals 100 km long.

KEY TERM

Shoaling: when fish swim together in a group

Why fish shoal

The formation of a shoal has a number of advantages to the fish.

- Small fish (for example sardines, herrings, anchovies and menhaden) are preyed on by larger predators (for example tuna, sharks, dolphins, sea birds, seals and whales). The small fish compensate for their size by forming shoals as a defence against predators. These shoals can become huge when migrating across open oceans. The synchronised movement of large shoals of fish may confuse a predator: the shoal may split into several groups or surround the predator. This makes it difficult for the predator to concentrate on just one fish. Some shoals form 'bait balls' to protect themselves from predators. The fish at the centre are relatively protected whereas those on the outside are more vulnerable. Tightly shoaling fish usually have silvery sides (like anchovies) and may swim to produce a wave-like effect on the outside of the shoal to confuse predators further.
- With so many eyes, it is more likely that a predator will be seen. Fear chemicals are then secreted that help alert other individuals in the shoal when an attack is imminent.
- With large numbers of fish, there are many eyes to search for food, so the time taken to find food is decreased. Fish in shoals share information by closely monitoring each other's behaviour. The feeding behaviours of one fish quickly stimulate food-searching behaviour in other members of the shoal.
- Shoaling also leads to a reproductive advantage. The close proximity of males and females increases the chance of finding a mate or fertilising externally released eggs.
- During migrations, swimming efficiency is improved because most of the fish can take advantage of the slipstream produced by the fish in front. This reduces the water resistance (drag) for the fish swimming behind so the shoal can swim faster and save energy.

There are also disadvantages of shoaling.

- Some predators are more efficient at attacking shoals than individual fish.
- The large numbers of fish swimming close together cause excretory waste to build up, while oxygen and food supplies are depleted.

However, there must be a net survival advantage to shoaling otherwise this behaviour would not have been evolutionarily successful. The energy saved by shoaling can be used to increase an individual's potential to survive, reproduce and pass on its gene alleles to the next generation.

Examples of shoaling

- ***Sardines*** are small, oily fish related to herrings. Sardines are a shoaling forage fish that form 'bait balls' (Figure 2.10) to minimise their chance of being taken by predators. Individual sardines are more likely to be eaten than a large group swimming together.
- ***Herring*** are forage fish whose small shoals aggregate together into much larger shoals during migration. In the North Atlantic, up to 3 billion fish can be in one shoal. Herring shoals have precise arrangements that allow them to maintain a constant speed. Herring shoals react rapidly to predators because they have excellent hearing.
- ***Skipjack tuna*** are predatory shoalers that swim in large groups of up to 50 000 individuals when migrating to find food. Simultaneous attack by large numbers of tuna helps break up the sardine 'bait balls' that they prey on. Skipjack tuna sometimes shoal with other tuna species or other fish of similar size. Shoaling improves the tuna's chance of finding prey because there are more individuals to sense the prey.

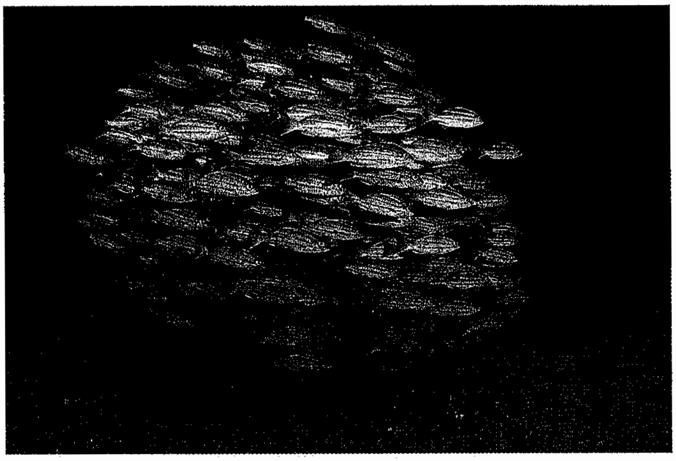


Figure 2.10 A 'bait ball' of bluelined snapper.

2.6 Succession

The term **succession** refers to the gradual process of change that occurs in community structure over a period of time. This temporal change in the composition of species in a particular area is predictable and can be measured by ecologists. There are three stages in succession (Figure 2.11).

- Colonising stage: the first community of organisms to colonise a new habitat appears (a pioneer community).
- Successionist stage(s): stage(s) in which the biodiversity or species richness in a community increases during succession. Communities move through several different successionist stages. A seral stage is a stage when a new species successfully establishes within the community. The halosere is the entire range of communities that succeed one another at a salt-water site.
- Climax stage: a complex community of many species is finally formed. Over time, producers, consumers and decomposers change. Gradually, the community changes less and less frequently until the structure and species composition become stable. This is the climax community.

Types of succession

There are two types of succession: primary succession and secondary succession.

Primary succession occurs in newly formed habitats where there has never been a community before. The new habitat is a bare substrate with no life present. These new habitats can be natural, for example new islands formed as a result of underwater volcanic eruptions. Alternatively, the new habitats can be unnatural, as a result of human activity, for example the structure of a deep-sea oil rig.

Secondary succession occurs on sites that have previously supported a community that is now no longer there, for example because of habitat destruction caused by a cyclone or tsunami.

KEY TERM

Succession: the change in community structure over time

Coral reefs

Both primary and secondary succession occur on coral reefs. Primary succession occurs as a volcano erupts and

Figure 2.11. Primary succession in a coral reef.

lava creates a new habitat with no plant life (Figure 2.11). Coral is the first to colonise and grow on the lava flow, so is a pioneer species. Coral reefs also undergo secondary succession, for example after an area of the reef has been removed by deep-sea trawlers.

Hydrothermal vents

A hydrothermal vent is a gap in the Earth's surface that releases geothermally heated water.

Succession occurs around hydrothermal vents in deep oceans. Hot water forced from hydrothermal vents brings up nutrients from the rocks beneath the seabed. The first organisms to grow near the vent fluid are chemosynthetic archaebacteria. Tube worms (*Tevnia* species) are early pioneer species that inhabit a hydrothermal vent, forming symbiotic relationships with the archaebacteria. *Tevnia* is later replaced by the much larger (up to 2 m long) and faster-growing *Riftia* tube worms. The nutrients produced by the tube worms allow other organisms to colonise the vent (for example polychaete worms, octopuses, clams, limpets, crabs, mussels, hagfish and vent fish). Eventually, a complex climax community consisting of many different species is established (Figure 2.12).

Whale fall

A whale-fall community is formed when a whale dies and sinks to the ocean floor (Figure 2.13). The pioneer species of this community are detritivores, such as sharks, hagfish and amphipods. They eat the decaying flesh of the carcass. Within a year, most of the whale's flesh will have been removed. Crabs, small fish, snails and worms then eat the organic leftovers in the sediment. When only the skeleton remains, heterotrophic bacteria decompose the oils in the whale bones. The decomposition of the whale's body enriches the surrounding sediments with nutrients. Decomposition also releases compounds that serve as energy sources for chemosynthetic archaebacteria. Mussels, clams, snails, crabs and worms feed on these bacteria.

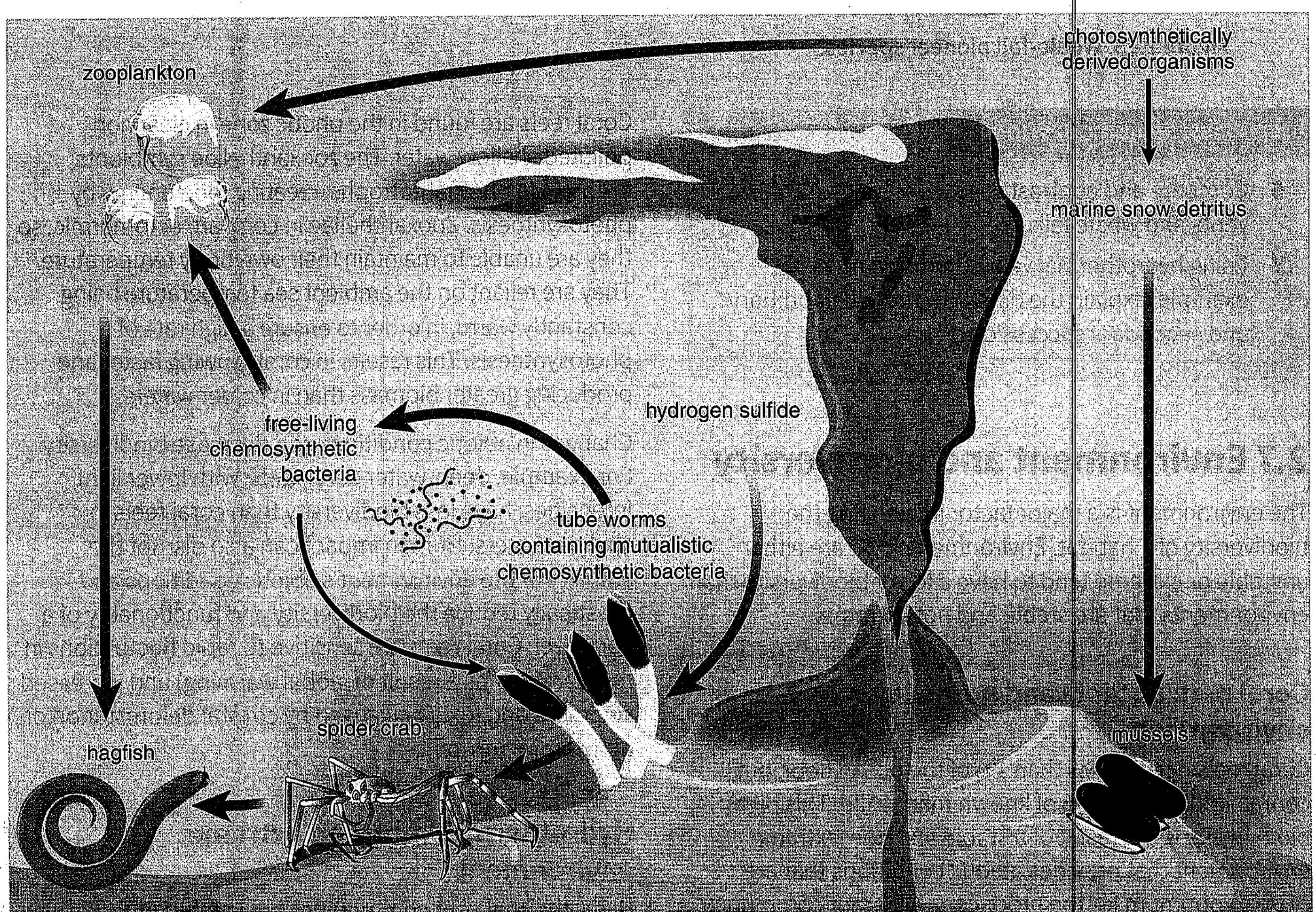


Figure 2.12. Hydrothermal vent food web.

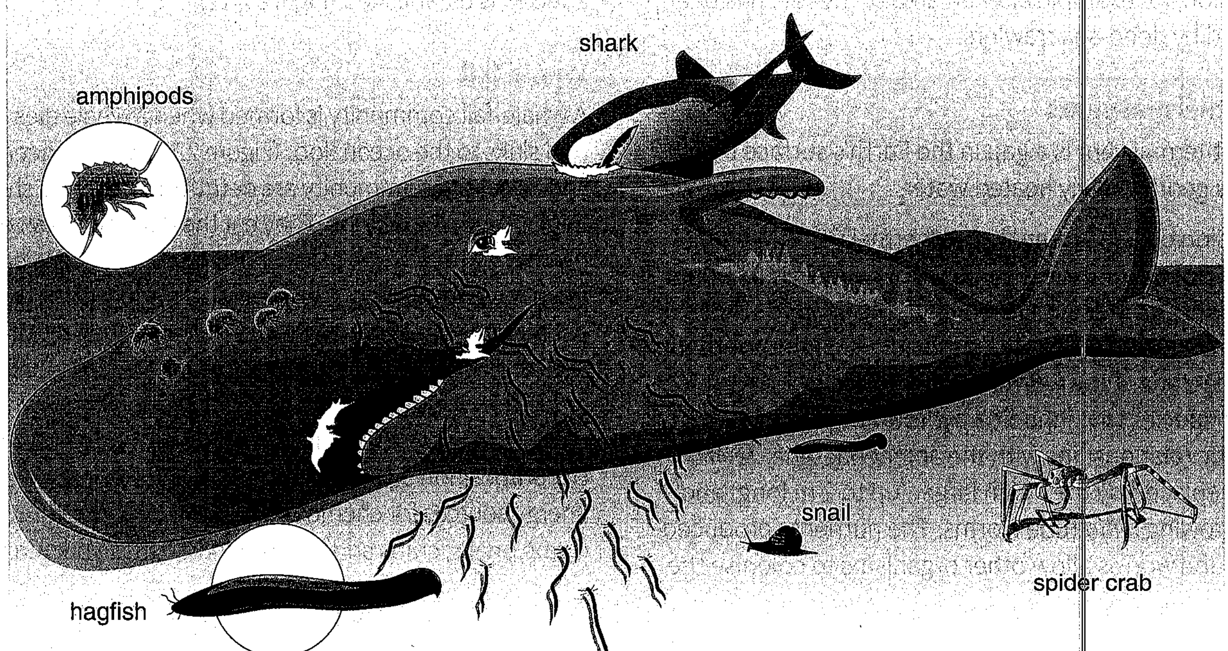


Figure 2.13. Whale-fall pioneer species.

SELF-ASSESSMENT QUESTIONS

6 Compare and contrast succession at hydrothermal vents and whale falls.

7 Using hydrothermal vent communities as an example, explain the difference between primary and secondary succession.

2.7 Environment and biodiversity

The environment is a major factor influencing the biodiversity of a habitat. Environments that are either unstable or extreme tend to have a lower biodiversity than environments that are stable and not extreme.

Coral reef: a stable and non-extreme environment

Coral reefs occupy less than 1% of the ocean floor, but contain more than 25% of known marine life. This high biodiversity is the result of a stable and non-extreme environment that provides abiotic conditions that are close to optimum for the producers. A vibrant community of producers provides the foundation for long food chains and a diverse food web.

Coral reefs are found in the photic zone in clear non-polluted shallow water. The zooxanthellae symbionts in coral are photoautotrophs, creating food energy by photosynthesis. Zooxanthellae in coral are ectothermic, so they are unable to maintain their own body temperature. They are reliant on the ambient sea temperature being constantly warm, in order to ensure a high rate of photosynthesis. This results in coral growing faster and producing greater biomass than in colder waters.

Changes in abiotic conditions can decrease biodiversity. For example, deep-water coral reefs, with lower light intensities, have less biodiversity than coral reefs in shallow waters. Human impact can also disrupt the stability of the environment's abiotic conditions and drastically reduce the biodiversity and functionality of a coral reef. Coral reefs are sensitive to rapid fluctuations in temperature (as a result of global warming) and increased sediment and toxicity (caused by coastal deforestation or agricultural run-off).

Hydrothermal vents: an extreme environment

Hydrothermal vent communities are located in an environment that is extreme because the abiotic conditions, including toxins, temperature, pH, hydrostatic pressure and light, are outside the zone of tolerance for most organisms.

The hot water from a hydrothermal vent contains dissolved minerals from the Earth's crust below the vent. As the hot vent water meets the cold oceanic water, it rapidly cools, causing the dissolved minerals to solidify. The high concentration of hydrogen sulfide gas, as well as minerals such as copper, lead, zinc and sulfur, create an environment that is toxic to most organisms. The water surrounding hydrothermal vents can reach temperatures as high as 320 °C with a pH as acidic as 2.8. To survive here, the chemosynthetic bacteria have specialised enzymes that can resist denaturing of their active sites. The bacterium *Thermus aquaticus* has an optimum temperature range of 75–80 °C.

Hydrothermal vents can occur at depths of up to 4 km. Few organisms can live at this depth because the hydrostatic water pressure may be up to 300 atmospheres. Deep hydrothermal vents are also in the aphotic zone. Producers that require light for photosynthesis are unable to grow here, so there is less energy and fewer nutrients to support consumers further up the food chain.

As few organisms are adapted to live in the extreme conditions, hydrothermal vents have a low biodiversity.

CASE STUDY

Our deep-sea pharmacy

The World Health Organization (WHO) estimates that antibiotic treatments add an average of 20 years to all of our lives. But since the introduction of penicillin in 1942, our society's overuse of antibiotics has led to the emergence of many more antibiotic-resistant strains of bacteria. These untreatable superbugs mean that what were once considered to be easily treated infections are becoming fatal again. In 2013, more patients died of MRSA (methicillin-resistant *Staphylococcus aureus*) than of AIDS (acquired immune deficiency syndrome).

Many pharmaceutical drugs are derived from plants, animals, fungi or bacteria. The European Union PharmSea initiative has provided £9.5 million to research a variety of marine organisms to discover whether they can supply the next superdrug with antibiotic, anti-cancer or anti-inflammatory properties.

Deep-sea trenches are the largest unexplored habitat on Earth. Trenches are inhabited by extremophile organisms with unique and unusual biochemistry, allowing them to survive in severe temperatures, pressure and pH. Marine scientists are bioprospecting a number of these ocean trenches (Figure 2.14), including the Kermadec Trench off New Zealand, the Mariana

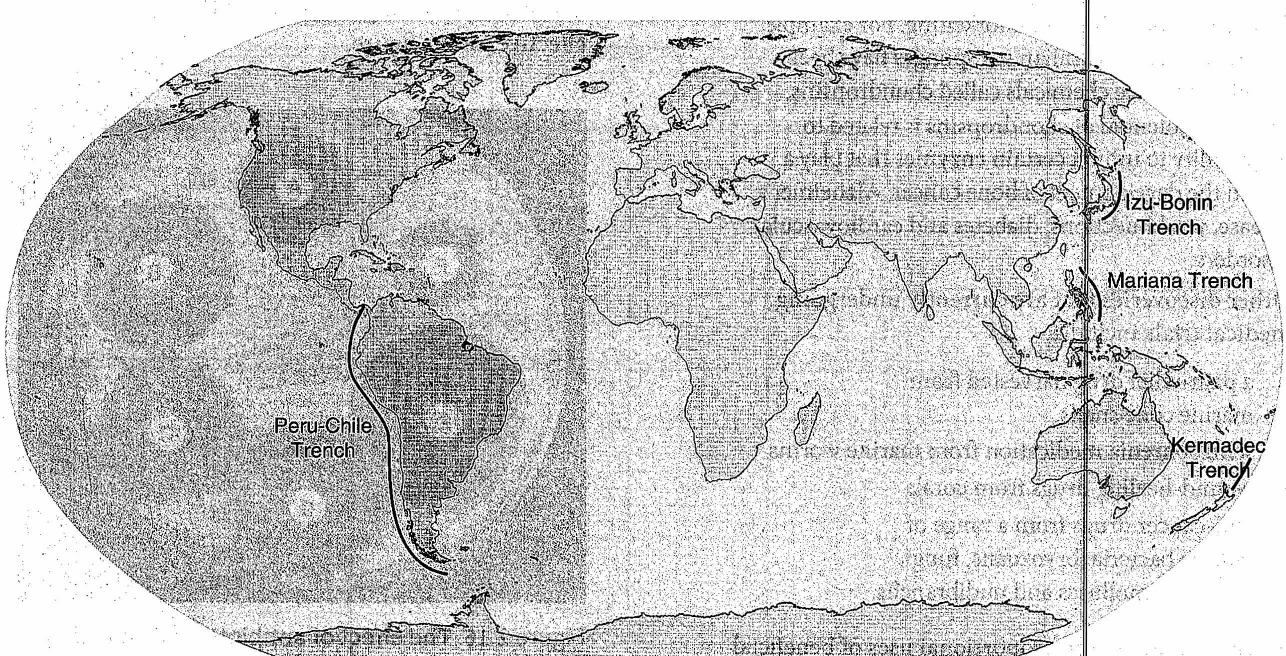


Figure 2.14. The location of deep-sea trenches, which provide habitats for extremophile organisms.

Trench in the western Pacific, the Izu-Bonin Trench off Japan and the Peru–Chile Trench.

Engineers access the benthic sediment either by deep-sea submarines or dropping a long coring device to the ocean floor. It takes at least 4 h for the coring apparatus to sink to the seabed at a depth of 8000–11 000 m.

Organisms in the trench sediment are pressure-sensitive and need high-pressure chambers to survive and grow in laboratories at sea-level. Researchers extract and test the bioactive compounds produced by these organisms for medicinal properties. Zebrafish are used to test new medicines as they have a similar physiology to humans.

Dermacoccus abyssi is a bacterium retrieved from sediment in the Mariana Trench. This organism produces dermacozines, a new biochemical that may help protect against the parasite that causes African sleeping sickness.

Lake Hodgson is a fresh-water lake in Antarctica. It is another source of microbes that may provide future medicinal drugs. This lake has been sealed beneath 4 m of ice for at least 11 000 years. Analysis of sediment taken from beneath the subglacial waters has shown that about a quarter of the DNA present comes from previously unknown species.

Marine organisms living on the benthic floor of more shallow waters may also be potential sources of medicinal drugs. Such organisms can be collected by dredging, scuba diving or snorkelling. For example, three species of Australian sea sponges have been found to produce chemicals called chondropsins. The drug potential of chondropsins is related to their ability to inhibit certain enzymes that play a role in the development of bone cancer, Alzheimer's disease, viral infections, diabetes and cardiovascular disorders.

Other discoveries that are currently undergoing medical trials include:

- a pain-relief drug harvested from marine cone snails
- schizophrenia medication from marine worms
- wound-healing drugs from corals
- anti-cancer drugs from a range of marine bacteria, bryozoans, fungi, tunicates, molluscs and nudibranchs.

Figure 2.15 shows the proportional uses of beneficial chemicals derived from marine organisms.

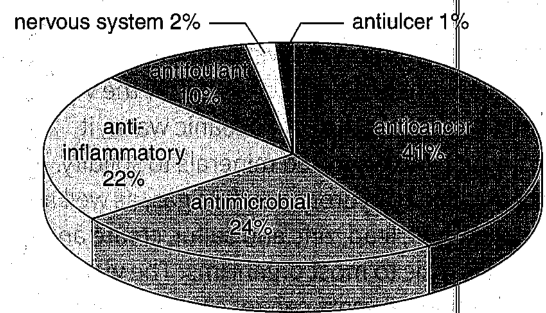


Figure 2.15. Use of beneficial chemicals derived from marine organisms.

Questions

1 What is the mean of the data shown in Figure 2.15?

2 Australian sea sponges act as mutualistic hosts for bacteria that produce chondropsins. Explain how the sponge and bacteria both benefit by living together.

3 Figure 2.16 shows different strains of marine bacteria (A–F) that have been harvested from sponges. The sponge-derived bacteria produce powerful antibiotics against a range of drug-resistant bacteria. The effect of the antibiotic can be measured by the radius of its inhibition zone. An inhibition zone is an area where bacteria cannot grow because of the production of an antibiotic. On Figure 2.16 it is measured by the diameter of no bacteria around each disc (A–F). Explain which drug-resistant antibiotic-producing strain (A–F) is the most effective in this figure.

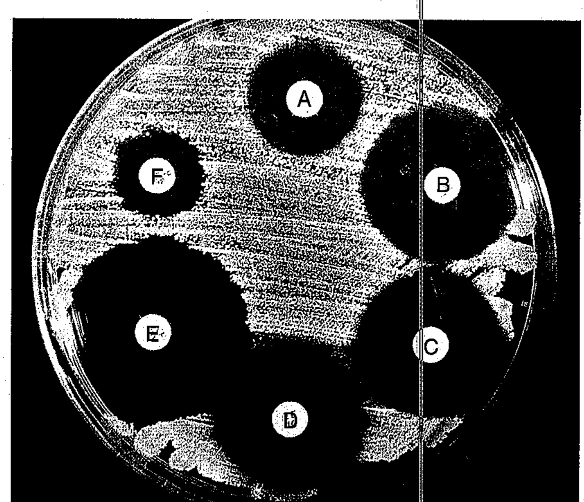


Figure 2.16. The effect of antibiotics produced by different strains of sponge-derived bacteria (A–F).

Sand on a reef slope: an unstable but non-extreme environment

Reef slopes are the steep, sometimes vertical, walls at the front (fore) of a reef. These fore-reef zones absorb most of the energy and damage from incoming waves and stormy seas. This means the sandy substrate of a reef slope is easily eroded by currents, waves and wind, and it is difficult for marine plants to grow there. Lack of biomass in primary producers and the usual loss of energy between trophic levels means that food chains are short and the environment cannot support species at higher trophic levels.

The organisms that can successfully use the reef slope sand habitat include animals that burrow into the sand, such as worms, clams, sand fleas and crabs. Although the physical conditions are not extreme, they are constantly changing so the environment is described as unstable. Not many marine organisms are adapted to survive in such condition, so biodiversity is low.

Rocky shore: a stable and non-extreme environment

Like coral reefs, rocky shores are a stable, non-extreme environment. They support a greater number of species than sandy shores because they are better at resisting wave action and erosion. The rock provides a good attachment surface for molluscs and seaweeds, so there is less chance of the organisms being washed away. Rocky shores also provide protective habitats such as rock pools and crevices. They are less porous than sandy shores so organisms are less prone to drying out and dying from desiccation.

SELF-ASSESSMENT QUESTIONS

8 Explain why hydrothermal vents have low biodiversity.

9 Explain why rocky shores have a higher biodiversity than hydrothermal vents.

2.8 Specialised and generalised ecological niches

An ecological niche can be defined as the role of an organism in an ecosystem. Marine organisms may have either a specialised or a generalised niche in their specific environments.

Specialised ecological niches

If an organism can survive only within very narrow physical, biological or chemical parameters, it is considered to have a very specialised niche. Organisms with a specialised niche have a narrow range of food requirements or live in a specific habitat. Coral reefs have a high number of organisms with specialised niches, such as butterfly fish and emperor angelfish. Butterfly fish are territorial and live closely associated with a specific area of coral. They are highly adapted to surviving on coral reefs. For example, they have thin snouts to reach into the crevices of rocks to feed on the corals and sea anemones. Emperor angelfish live in Indo-Pacific ocean reefs and have a specialised niche, feeding on coral sponges as well as parasites and dead skin from larger fish.

Generalised ecological niches

Generalised niches are held by organisms that can exploit a wide range of habitats and food sources. Marine examples include the northern bluefin tuna. This fish follows the nutrient-rich cold ocean currents feeding on a wide range of prey, including fish, rotifers, molluscs, squid and crustaceans. Unlike many cold-blooded animals, tuna can increase their body temperature compared with the temperature of the surrounding ocean. As a result, tuna are able to swim rapidly and tolerate a broad range of water temperatures. This ensures that tuna can inhabit a broad thermal niche and be found throughout the Atlantic Ocean.

Another marine organism that has a generalised niche is the bottlenose dolphin, whose diet includes a large variety of fish and squid species and whose habitat extends throughout the world's oceans except for the polar regions. Similarly, mako sharks are opportunistic feeders, eating a range of shoaling fish such as tuna and mackerel (Figure 2.17). Sharks can live in a wide range of different conditions, surviving at different temperatures and depths. They can move easily between habitats and hence hunt in different prey locations.

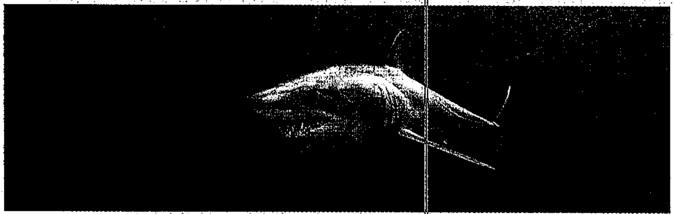


Figure 2.17 Mako shark.

High biodiversity and narrow ecological niches

High biodiversity means that many different species live within one ecosystem. Each species has its own niche or ecological role within the ecosystem. Niches are determined by factors such as habitat, food, reproduction and behaviour. All of these factors are sources of competition between species.

Competition is a relationship between organisms that strive for the same resources in the same place. There are two different types of competition:

- intraspecific competition, which occurs between individuals of the same species (for example two male fish of the same species competing for female mates in the same area)
- interspecific competition, which occurs between members of different species (for example predators of different species competing for the same prey).

Interspecific competition can lead to overlap between ecological niches. The species that is less well adapted has access to fewer resources and is less likely to survive and reproduce: this could lead to the species becoming extinct. However, interspecific competition more often leads to greater niche adaptations and niche specialisation.

The fundamental niche is the niche of a species where that species experiences no competition with others. The fundamental niche can also be defined as the tolerance range for all important abiotic conditions, within which individuals of a species can survive, grow and reproduce. But all organisms are part of complex food webs, sharing the ecosystem with other species, and all competing for the same biotic and abiotic resources. As these resources are limited, this leads to interspecific competition.

The competitive exclusion principle predicts that, in a stable ecosystem, no two species can be in direct competition with each other. If the niches for two species are identical, one species will die out as a result of interspecific competition. For example, if an introduced species is added to an existing marine habitat then the new species may have the same niche as a native species (for example two top predators feeding on the same prey at the same time in the same habitat). Interspecific competition between the two species will occur, as they compete for this niche. One of the two species will be better at hunting the prey, therefore will thrive and increase in population size. The population of the other species will be less ecologically or reproductively viable, eventually dying out.

Coral reefs

Coral reefs are home to many different species, including corals, fish, anemones, turtles, crabs, sharks and dolphins. Estimates of the number of reef species worldwide are between 600 000 and more than 9 million. A survey by the Smithsonian National Museum of Natural History found that coral heads with a surface area of 6.3 m² have 525 different species of crustacean. This is almost as many crab species as found in all of the seas of Europe.

The high biodiversity of coral reefs results from high productivity and each organism is intrinsically linked to the other animals, plants and microorganisms in the food web. The nutrient and energy flow between trophic levels is highly efficient. With so many species in such small areas, organisms avoid competition by narrowing their ecological niches.

All species living in the same habitat do something slightly different compared with the other species in order to narrow their niche and so prevent competitive exclusion. For example, if two species share the same food source, they may feed at different times (one species feeding at night, another feeding in daylight); this is temporal separation. Alternatively, a niche may be narrowed by spatial separation, for example, different fish species living at different levels of the reef to avoid competing for food.

The coral reef environment is stable and not extreme, it has high productivity and high biodiversity. When there is a high biodiversity, the realised niche of each species narrows to reduce interspecific competition. As the productivity is high, there is still sufficient energy and resources for species to survive and reproduce.

Low biodiversity and ecological niches

The open sea has fewer species and therefore lower biodiversity. Species such as tuna and sharks are able to exploit a wider range of food sources and hence have more general realised niches. This is a result of there being less interspecific competition in the open sea. If a species narrows its realised niche in a region of low biodiversity, the energy and resources available for it to grow may be insufficient, leading to less reproduction, and eventually the species dying out.

In unstable ecosystems, for example where there are regular tropical cyclones and tornados, the instability can interfere with competitive exclusion, allowing other species to have a chance in the habitat and hence increasing biodiversity. An example of this can be seen on rocky shores where strong storms regularly remove competitively dominant mollusc species, allowing other normally competitively excluded species to survive.

In an area where there is a lot of one species, such as a large school of fish, the strain on resources is a lot larger, so the species must expand its realised niche, feeding on organisms that might not otherwise be part of the diet.

Summary

- The structure of marine ecosystems can be described using the key terms environment and habitat.
- The key terms species, population, community and biodiversity help us describe the organisms that live in marine habitats.
- There are a variety of roles, or niches, that organisms perform in their aquatic environment. These include producers, consumers and decomposers.
- The feeding connections between different organisms can be described using food chains, food webs and trophic levels.
- The biological, chemical and physical parts of the environment are linked by energy and nutrient flows.
- There is a rich variety of relationships between species. These include mutualism, parasitism, competition and predator–prey.
- Shoaling is an example of the importance of studying fish biology and behaviour.
- How stable or extreme a habitat is helps determine the complex and delicate balance of life it supports. This leads to variation in the number and type of niches, as well as biodiversity, that exists between coral reefs, hydrothermal vents, sandy and rocky shores.

Exam-style questions

1 **a** Explain what is meant by each of the following terms.

i Population **[1]**

ii Community **[1]**

iii Trophic level **[1]**

iv Species **[1]**

v Ecosystem **[1]**

b Many forage fish species (for example sardines or herrings) form shoals.

i Discuss the advantages of shoaling. **[4]**

ii Discuss the disadvantages of shoaling. **[2]**

[Total mark: 11]

2 Figure 2.18 below shows the interdependence of ocean temperature and predator–prey cycles.

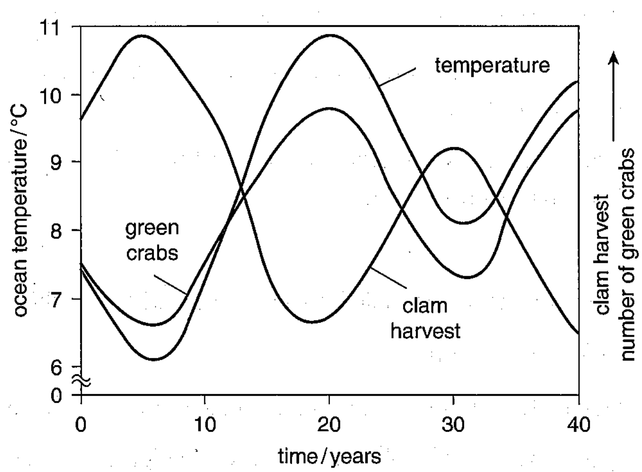


Figure 2.18. The interdependence of ocean temperature and predator–prey cycles.

a Use Figure 2.18 to find the range of ocean temperatures. [1]

b How might global warming affect the green crab population? [1]

c Describe the relationship between the green crabs and clams and suggest an explanation for this relationship. [3]

d Explain how populations of marine predators may be spatially linked to their prey. [2]

e Suggest how ecologists could have collected the green crab data. [4]

(Total mark: 11)

3 Figure 2.19 shows a marine food web.

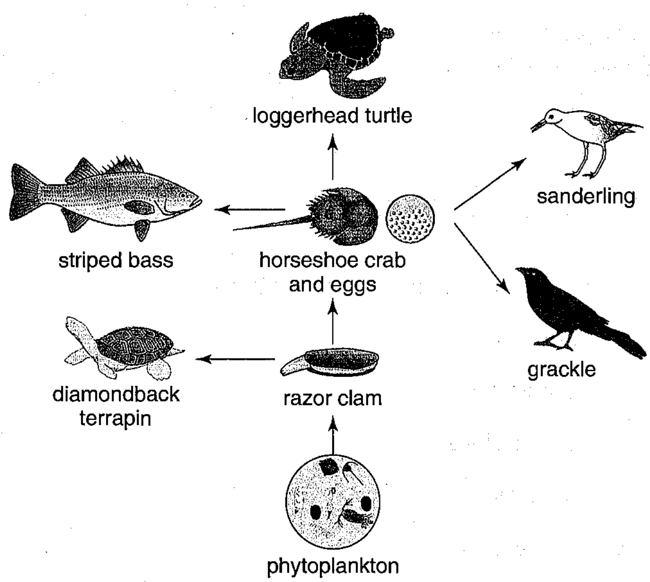


Figure 2.19. A marine food web.

a What is the primary source of energy for this food web? [1]

b Write a food chain based on the food web including a tertiary consumer. [2]

c Explain what the arrows between organisms represent. [2]

d With reference to Figure 2.19, explain the term predator. [2]

e Suggest one biotic factor, other than predation, that may affect the horseshoe crab population. [1]

f Ecologists studied a total of 130 horseshoe crabs and found 10 with ciliate parasites. Explain the term parasite. [3]

(Total mark: 11)

4 a Describe the relationship between coral and zooxanthellae. [3]

b Define succession. [1]

c Outline the succession that leads to the formation of a coral reef. [3]

d Discuss why coral reefs contain narrow ecological niches. [4]

(Total mark: 11)

5 Figure 2.20 shows a food web for the Arctic.

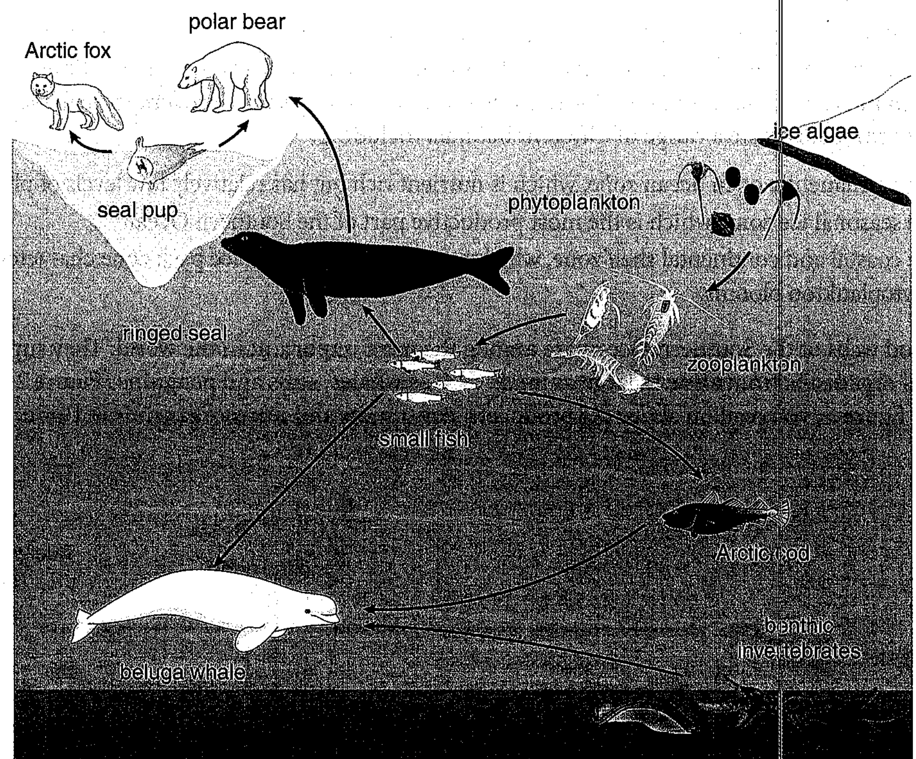


Figure 2.20. An Arctic food web.

a Draw a food chain with polar bears as a quaternary (4th level) consumer. **[1]**

b Beluga whales are hunted in Canadian Alaskan and Russian Arctic regions for their meat, blubber and skin. Explain how this could affect the population numbers of each of the other species in the food chain: phytoplankton – zooplankton – small fish – Arctic cod – beluga whale. **[4]**

c A study of the stomach contents of seals found that they included a variety of invertebrate prey: 73 crabs, 55 clams, 47 snails, 32 amphipods and 18 shrimps. Calculate the mean percentage of invertebrates in the stomachs. **[1]**

d Discuss the effects of global warming on the following species:

i polar bear **[1]**

ii ice algae **[1]**

e When moulting, seals spend time out on ice packs while replacing their fur and skin. In 2011, several species of ice-dependent seals were found dead or sick with abnormal coats. Discuss why some scientists believe abnormal coats may be linked to global warming. **[2]**

f In 2015, global warming led to the seal-hunting season in north-western Alaska being the shortest in memory. The season lasted less than a week, compared with the usual 3 weeks. Why might this have been caused by decreased ice packs? **[1]**

(Total mark: 11)

Southern Ocean ecosystem

The Southern Ocean encircles the Antarctic and encompasses between 10 and 20% of the global ocean area, including the Earth's largest current, the Antarctic circumpolar current. The Southern Ocean is not uniform in either productivity or biodiversity. Localised changes in ice coverage, seabed topography and oceanic currents create a range of different habitats including:

- the permanently open ocean zone, which is nutrient rich but has relatively low levels of photosynthesis
- the seasonal ice zone, which is the most productive part of the Southern Ocean
- the coastal and continental shelf zone, which contains a permanent ice pack zone characterised by large phytoplankton blooms.

The food webs of the Southern Ocean are among the most important in the world. They support a wide range of local organisms from algae to large animals such as whales, seals and penguins (Figure 2.21). You can refer to this figure as you read on about the producers, consumers and microorgansims in this ecosystem.

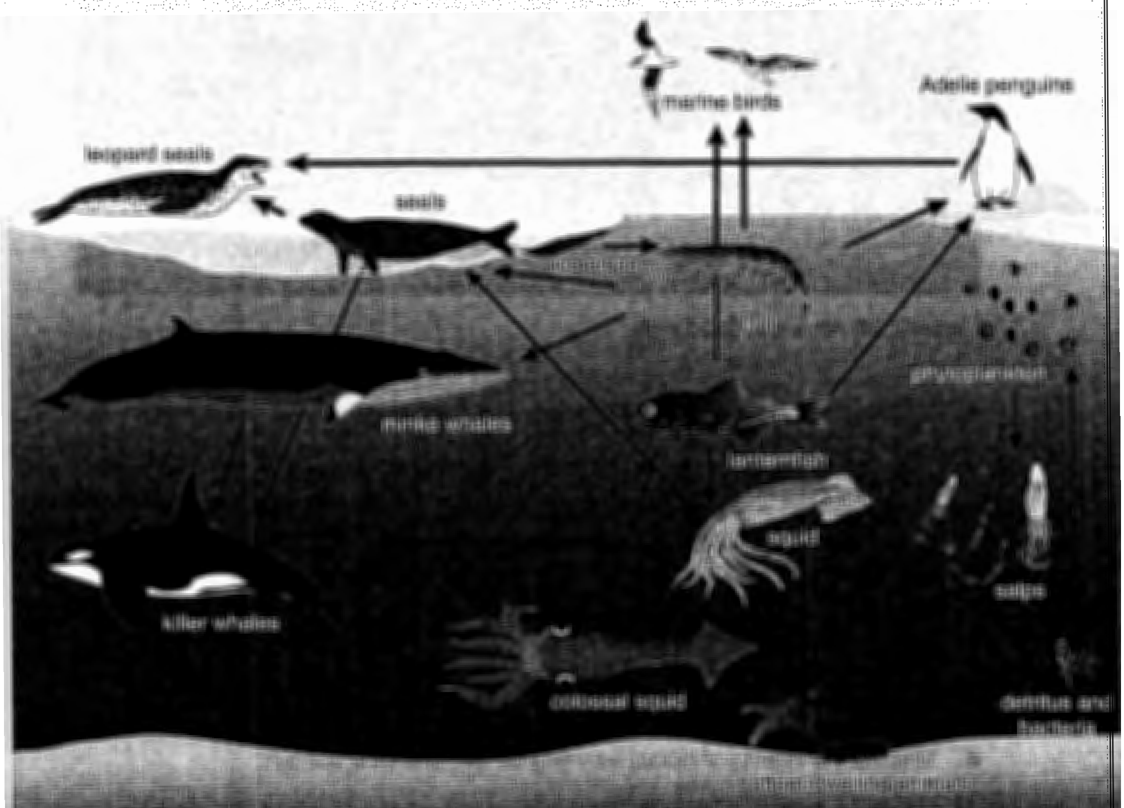


Figure 2.21. Antarctic food web.

Producers

Open ocean waters are rich in single-celled organisms that have different cellular characteristics from animal and plant cells. These organisms are called protoctists and include phytoplankton (for example diatoms, cyanobacteria and dinoflagellates). These are the producers that organisms in higher trophic levels depend on. Phytoplankton can be divided into three groups depending on their size:

- picoplankton (2.0–2 μm)
- nanoplankton (2–20 μm)
- microplankton (20–200 μm).

The ocean water around Antarctica is often frozen and covered by ice for long periods of time. Under the ice, the light intensity is too low for phytoplankton to photosynthesise but algae can grow and are an important food source for herbivorous zooplankton, for example krill. There are also more than 700 species of seaweed found in Antarctica's shallow coastal waters. Water temperature and depth are important limiting factors that control seaweed distribution.

Consumers

Zooplankton are consumers that feed on phytoplankton. Some zooplankton species complete the whole of their life cycles as plankton (haloplankton) while other species are only planktonic in their larval stages (meroplankton).

Melting ice in spring and summer produces a layer of less saline water on the Southern Ocean's surface, together with increased nutrients and sunlight. These changes in abiotic conditions lead to a massive increase in phytoplankton, known as a bloom. The phytoplankton blooms feed krill and other herbivorous zooplankton, which subsequently become very abundant. Krill can produce swarms that contain 30 000 individuals per cubic metre. They form a major amount of the biomass in the Southern Ocean.

Krill are a group of about 80 different species of crustaceans. The main species in the Southern Ocean is Antarctic krill. Antarctic krill have a high reproductive capacity: the females can lay up to 10 000 eggs. Krill form a vital part of Antarctic food chains, being consumed by a variety of organisms, including fish, birds, squid, whales, seals and penguins. Krill are also a target species for commercial fisheries and over-harvesting of krill can lead to a decrease in the krill population. This allows the population of phytoplankton to produce even larger phytoplankton blooms. These large blooms can produce toxins harmful to other organisms in the ecosystem.

Zooplankton besides krill include copepods, salps and larval fish. Like krill, copepods are crustacea that can produce very high populations. In the waters around King George Island they can form up to 87% of the summer zooplankton biomass. Copepods are an important food source for fish, which are then eaten by seals, penguin and sea birds.

Salps are planktonic sea squirts that can produce huge colonies and filter vast amounts of phytoplankton (Figure 2.22). Salps are eaten by fish that are in turn consumed by squid and then Southern bluefin tuna. Salp populations increase and krill populations decrease in years when ocean temperatures and currents cause the sea ice to retreat.

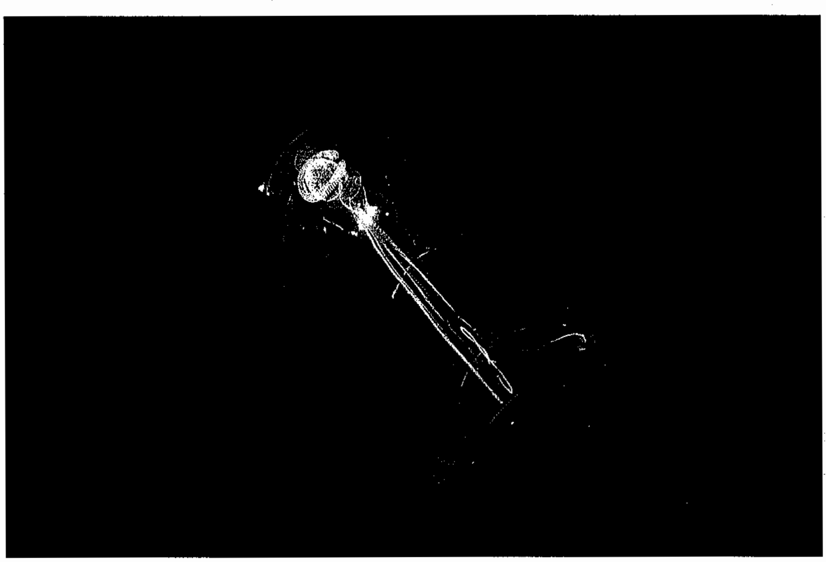


Figure 2.22. A salp.

The Southern Ocean contains extremely few fish. Most live in coastal benthic waters (for example Antarctic cod) and very few are found in open waters (for example lanternfish).

Antarctic squid are one of the most important species in the Southern Ocean food web, with a total biomass of 110 million tonnes. Squid are a major component of the diets of seals and killer whales. The main diet of Antarctic squid is not krill but lanternfish that have fed mainly on copepods. Squid populations can fluctuate dramatically, so are highly susceptible to over-fishing.

Benthic habitats provide rich habitats for an array of bottom-dwelling animals. These include filter feeders (for example anemones, soft corals, sea squirts, molluscs and tube worms) and mobile scavengers and predators (for example sea urchins, starfish, giant sea spiders and ribbon worms) (Figure 2.23).

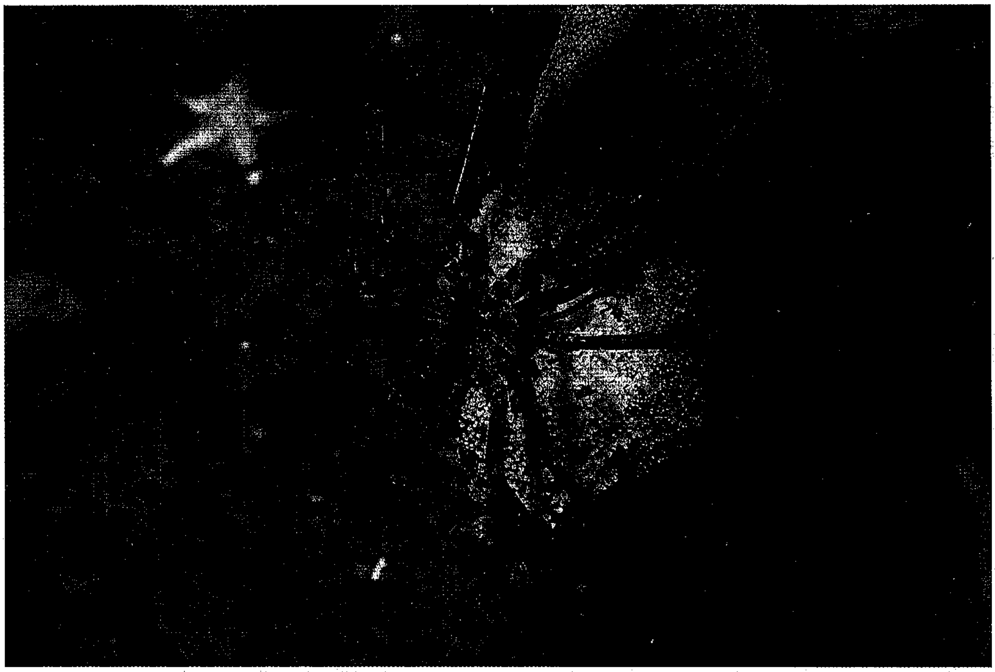


Figure 2.23. Giant sea spider.

Microorganisms

Microorganisms (for example bacteria and viruses) form a crucial link in the Southern Ocean's food web. Coastal and continental shelf areas of Antarctica have rich benthic bacterial communities. Water temperatures of the continental shelf are generally low and stable. Oxygen (from photosynthesis) and organic matter (from detritus) is produced in seasonal pulses by the biotic communities in the surface water. Bacteria feed on dissolved organic matter and, as decomposers, they break down detritus and remobilise inorganic nutrients for the growth of phytoplankton. Bacteria are consumed by protoctists, who are in turn eaten by zooplankton.

Viral infection accounts for about 50% of the death of marine bacteria and may be one of the major sources of dissolved organic matter in the sea. Viruses are also capable of inhibiting phytoplankton growth by up to 80%.

Questions

1 a Under the ice shelf the main producer is algae rather than phytoplankton. Explain why algae can photosynthesise under the ice far better than phytoplankton.

b When snow covering the ice sheet blows away, there is an increase in oxygen bubbles trapped under the ice. Explain why this occurs.

c Suggest why cracks in the sea ice may be important to the survival of penguins.

2 Using data from Figure 2.21:

a Draw a food chain for krill that has a quaternary consumer.

b Why can krill can be considered to be a keystone species for the Southern Ocean?

3 Global warming is decreasing the amount of sea ice around Antarctica and leading to a change in penguin populations. Some penguin species are increasing in population size while others are declining.

a Adelie penguins on Anvers island have lost 70% of their population or 10 000 breeding pairs in the past 30 years. To the nearest 1000, calculate the original number of Adelie penguins in this population.

b Gentoo penguins are increasing in numbers and are breeding on the Antarctic peninsula for the first time in 800 years. Adelie penguins are dependent on krill whereas gentoo penguins have a more flexible diet feeding on squid and fish. Describe how the differing niches of the two penguin species may affect their chances of surviving.

c Adult Emperor penguins need 3-4 weeks of solid sea ice in order to replace worn out feathers (moult). Feathers help keep the birds insulated, waterproof and free from skin infections. During a warm period in the 1970s, the population of Emperor penguins on the coast of Adelie land declined by 50%. Suggest a reason why.

d In winters when it is colder, the survival rate of Emperor penguins increases but they lay fewer eggs. Suggest a reason why.

4 A reduction in sea ice as a result of global warming results in reduced numbers of phytoplankton. Suggest reasons why this leads to a reduction in benthic organisms.

Chapter 3
Energetics of marine ecosystems

Learning outcomes

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

- explain how the energy in sunlight is captured during photosynthesis
- explain how the energy in dissolved minerals can be captured by chemosynthesis
- compare and contrast the processes of photosynthesis and chemosynthesis
- describe the relationship between photosynthesis and respiration
- calculate gross primary productivity and net primary productivity and explain the meaning of each of these terms
- describe different methods that can be used to measure productivity
- explain how high productivity influences the food chain
- calculate the energy losses along food chains and give the reasons for these losses
- calculate the efficiency of energy transfer between trophic levels
- give reasons for differences in the efficiency of energy transfer
- illustrate food chains by drawing pyramids of number, biomass or energy
- apply what you have learnt to new, unfamiliar contexts.

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3.1 Where does the energy for life come from?

All life on Earth is dependent on the energy that can be fixed into carbohydrates by **autotrophic** organisms. An autotroph is able to make its own food by forming organic substances from simple inorganic molecules. In marine ecosystems, the autotrophs are either **photosynthetic** or **chemosynthetic**. Photosynthetic organisms capture the Sun's energy, whereas chemosynthetic organisms are able to use the energy in chemicals that are dissolved in the water.

Photosynthesis can only take place in the sunlit upper layer of the ocean. About 90% of all marine life is therefore found in this area. The ability of the chemosynthetic organisms to produce carbohydrates is an important adaptation to living in extreme conditions. The hydrothermal vents where they are found have no light so photosynthesis is not possible. Until the vent communities were discovered in the 1970s, it was thought that the only way in which energy would reach the lower parts of the ocean was when organisms died and fell to the bottom.

Other organisms have to obtain their energy by feeding on the autotrophs. These are known as **heterotrophic** organisms or consumers. The **primary productivity** of an ecosystem relates to how much energy is fixed into **carbohydrates** (new organic matter). The most productive ecosystems per unit area are estuaries, swamps and marshes. However, the most productive ecosystems overall are the oceans, because they cover such a high proportion of the Earth's surface. Over a billion people rely on marine ecosystems for their food. Although we tend to think that increased productivity is always an advantage, this is not always true. Marine dead zones are areas where the productivity has reached such a peak that the ecosystem becomes unbalanced. Eventually oxygen levels are reduced and there is very little life.

KEY TERMS

Autotroph (autotrophic): an organism that can capture the energy in light or chemicals and use it to produce carbohydrates from simple molecules such as carbon dioxide

Photosynthesis (photosynthetic): the process of using light energy to synthesise glucose from carbon dioxide and water

Chemosynthesis (chemosynthetic): the production of organic compounds by bacteria or other living organisms using the energy derived from reactions with inorganic chemicals

Heterotroph (heterotrophic): an organism that cannot make its own food and instead relies on consuming other organisms; all animals, fungi and protozoans are heterotrophic, as well as most bacteria

Primary productivity: the rate of production of new biomass through photosynthesis or chemosynthesis

Carbohydrate: organic compounds occurring in living tissues that contain carbon, hydrogen and oxygen, for example starch, cellulose and sugars; carbohydrates can be broken down in the process of respiration to release energy

3.2 Productivity

Primary productivity is the rate of production of new biomass (living material) by autotrophic organisms through either photosynthesis or chemosynthesis (Figure 3.1). It allows light or chemical energy to be fixed into useable organic molecules, and as such is the basis of all food chains and food webs. In all ecosystems illuminated by the Sun, the main way in which energy is fixed is through photosynthesis. On land the majority of photosynthesis is carried out by green plants, but in the oceans it is mainly carried out by **phytoplankton**. Most of these tiny algae are single-celled and simply float with the current in water. As well as the phytoplankton there are also much larger algae (macroalgae), such as kelp and rooted plants called seagrass. These organisms are all photoautotrophs: they make their own food using light energy. You will learn about the adaptations of each of these producers in Chapter 8.

Photosynthesis

Photosynthesis is a process in which the inorganic compounds carbon dioxide and water are combined to produce glucose. Glucose is a useable organic compound. Oxygen is produced as a byproduct.

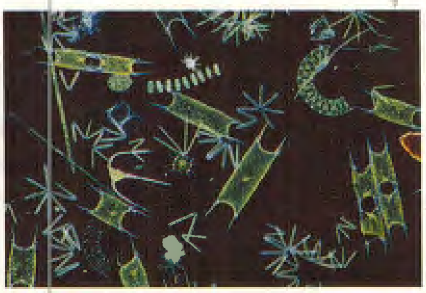
carbon dioxide + water → glucose + oxygen

The energy to do this comes from sunlight and must be absorbed by pigments in the plants or algae.

KEY TERM

Phytoplankton: microscopic photosynthetic organisms that live in the upper, sunlit layers of water

(a)



(b)

(c)

Figure 3.1. Important producers in marine ecosystems: (a) phytoplankton; (b) seagrass; (c) kelp.

The most common pigment is **chlorophyll**, which is found in organelles called chloroplasts (Figure 3.2). You can read more about the different pigments needed for photosynthesis in Chapter 8.

KEY TERM

Chlorophyll: a pigment found in plants and algae that is used to absorb sunlight for photosynthesis

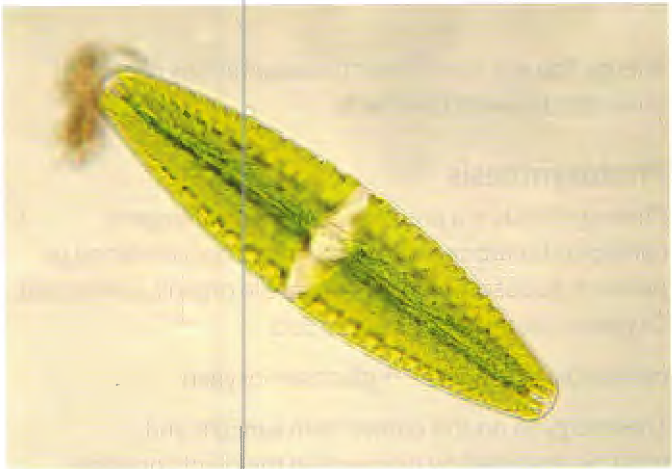


Figure 3.2. Single-celled alga with green chloroplasts visible.

Factors affecting photosynthesis

The rate of photosynthesis can be affected by several different factors. These include:

- nutrients
- amount of light
- temperature
- concentration of carbon dioxide.

In a marine environment, the most important factors are likely to be the availability of nutrients and light.

Temperature and carbon dioxide

Clearly there is always an abundance of water, and the water contains dissolved carbon dioxide. Although temperature affects the rate of the reactions taking place during photosynthesis, the temperature of the ocean is much more stable than air temperature on land.

Nutrients

Algae and plants both need nutrients in the form of mineral ions in order to grow. A lack of a particular nutrient therefore affects the rate of productivity of new biomass because it affects the rate of growth. Nutrient availability is discussed in more detail in Chapter 4.

Light

The layer of the ocean that has enough light for photosynthesis is relatively thin compared with the total depth. This sunlit zone is called the photic zone and all photosynthesis must take place here (Figure 3.3). This means that the vast majority of the biomass in the open ocean is contained within the upper 200 m of water.

Water both absorbs and scatters the sunlight. The amount of light reflected will depend on the state of the water. When there are waves, more light is reflected because the waves act like lenses and focus the light. When the light penetrates the surface of the water it is refracted because light travels more slowly in water than in the air. Finally, solid particles within the water also scatter and absorb the light. The availability of light within the water and methods to measure the light penetration are discussed further in Chapter 8.

The absorption of sunlight by the water also increases the temperature of the water. When the temperature increases, the molecules of water have more kinetic energy and are moving more quickly so the water is less dense and therefore more buoyant than cold water. The thin layer of warm water floats on top of the colder deep water and the transition between the two is called the **thermocline**. It can also be referred to as a **pycnocline**, which is simply related to the different densities of the layers rather than the temperature. There is little mixing between the two layers because a source of energy (such as wind) is needed to push the warm water down. This is very important to the phytoplankton as it keeps them floating near the surface where they have access to light.

KEY TERMS

Thermocline: a boundary between two layers of water with different temperatures

Pycnocline: a boundary between two layers of water with different densities

Deep chlorophyll maximum: the maximum concentration of chlorophyll below the surface of a body of water

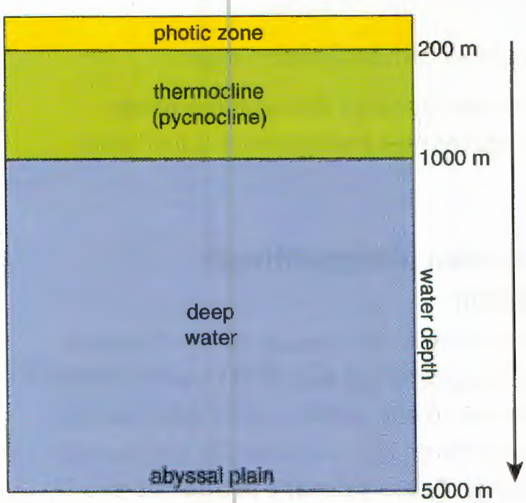


Figure 3.3. Layers of water in the ocean.

Without the thermocline, there would be much more mixing of the water and currents would carry the phytoplankton down and away from the light. This would reduce the rate of photosynthesis and therefore the productivity. However, the thermocline also prevents nutrient-rich water from mixing with the upper layers and therefore limits the productivity. Generally the deeper the water the higher the nutrient levels but the lower the light. There is normally a point near the thermocline where the productivity is highest as there is enough light for photosynthesis and enough nutrients for growth. This level is known as the **deep chlorophyll maximum** (DCM) because it is the area with the highest concentration of chlorophyll.

The light varies with the seasons, particularly at high latitudes. In spring the average length of the day and the intensity of light both increase. This is clearly an advantage in terms of photosynthesis, and productivity is therefore higher in spring and summer than it is in winter. Often it is nutrient availability that limits the rate of photosynthesis in spring and summer, and light which limits it during autumn and winter.

SELF-ASSESSMENT QUESTIONS

1 State the two ways in which new biomass is produced in the ocean.

2 Explain why ocean productivity is limited to the first 200 m in depth.

Chemosynthesis

There are some ecosystems, such as those found around hydrothermal vents, where light is not available for productivity. Chemosynthesis is a process where carbon dioxide is turned into useable organic molecules using the energy stored in dissolved chemicals. The chemicals dissolve in heated water in the undersea crust as it makes its way back to the surface to emerge from the vents. Chemoautotrophs are species of bacteria that are able to make their own food using chemical energy. There are several species of chemosynthetic bacteria, including *Beggiatoa* and *Thiothrix* species. Each species uses different chemicals as their energy source and produces different sugars. One common pathway is:

hydrogen sulfide + oxygen + carbon dioxide → sugar + water + sulfur

Chemosynthetic bacteria were first discovered in hydrothermal vents in the ocean floor in 1977. The vents are found at depths varying from around 2000 m in the Galapagos

Ridge to 7700 m in the Mid-Atlantic Ridge. Clearly at these depths there is no light, there are no phytoplankton and therefore there can be no photosynthesis. Chemosynthesis is the only way in which life is possible in such an inhospitable environment. The species able to survive here are all examples of **extremophiles**, which means that they are able to survive very harsh conditions. At these vents there is extremely high pressure, as well as water temperatures that can vary from 2 °C to 400 °C.

Chapter 2 discusses the symbiotic relationship between giant tube worms (*Riftia* species) and chemosynthetic bacteria (Figure 3.4). Up to 75% of animal species at hydrothermal vents depend on mutualistic relationships with chemosynthetic bacteria for at least some of their food. For example, mussels at these vents have mutualistic bacteria living in their gills but also filter feed.

Figure 3.4. Giant tube worms at hydrothermal vents have a symbiotic relationship with chemosynthetic bacteria.

KEY TERMS

Extremophile: an organism that is adapted to survive extreme temperature, pressure, salinity or pH

Respiration: the process by which all living things release energy from their food by oxidising glucose

Similarities and differences between photosynthesis and chemosynthesis

Both photosynthesis and chemosynthesis use carbon dioxide and require an energy source to produce sugars. In photosynthesis, oxygen is produced as a byproduct whereas in chemosynthesis the byproducts vary depending on the chemicals that are used, although sulfur is often produced. There is therefore only one possible equation for photosynthesis compared with several different equations for chemosynthesis. In both processes the sugars produced are used to provide metabolic energy through **respiration**, or built up into the other chemicals needed by the organism.

SELF-ASSESSMENT QUESTIONS

3 Explain why the organisms living at hydrothermal vents are called extremophiles.

4 Copy and complete Table 3.1 to compare photosynthesis and chemosynthesis in ocean ecosystems.

	process	
feature	chemosynthesis	photosynthesis
energy source		
products		
type of organism		
main location in ocean		

Table 3.1. Photosynthesis and chemosynthesis.

Respiration

Respiration is the process by which all living things release the chemical energy stored in organic molecules such as carbohydrates. This energy is then used to carry out all the different metabolic reactions within the organism. Aerobic respiration requires a supply of oxygen and glucose and produces carbon dioxide and water.

glucose + oxygen → carbon dioxide + water

As well as the useable energy the organism needs, respiration produces heat energy, which is lost to the environment.

The link between photosynthesis and respiration

Primary productivity is the amount of new biomass made by the producers, but not all of this is available for the consumers to eat. Some of the carbohydrate produced is not stored but is oxidised in respiration to provide energy. **Gross primary production** (GPP) is the amount of energy that primary producers are able to fix in a given length of time and within a given area. **Net primary production** (NPP) is the amount left over to create new biomass after respiration (R) has been taken into account. This can be shown by the following equation:

$$NPP = GPP - R$$

It is this net primary production that is available to pass on to the consumers. **Secondary production** is the amount of biomass produced by heterotrophs after eating the producers. Hence the more productive an ecosystem, the more energy is available to pass along the food chain. In the marine environment, there is no large-scale accumulation of biomass as there is in savannahs and forests on land. However, the reproductive rate of the phytoplankton is very high so there is a constant source of new organisms to photosynthesise. Carbon dioxide from the atmosphere dissolves in the water and is then available for photosynthesis. When it is fixed into glucose it is stored as phytoplankton biomass. Much of this 'locked up' carbon dioxide sinks to the floor of the ocean when organisms die. This process is discussed in detail in Chapter 4.

KEY TERMS

Gross primary production: the amount of light or chemical energy fixed by producers in a given length of time in a given area

Net primary production: the amount of energy that is left over after respiration to be made into new plant biomass

Secondary production: the rate of production of new biomass by consumers, using the energy gained by eating producers

PRACTICAL ACTIVITY 3.1

Investigating the compensation point

The compensation point is the light intensity at which respiration is equal to photosynthesis. Below this point producers use more carbohydrate in respiration than they can produce in photosynthesis so their biomass decreases.

Hydrogencarbonate indicator is red in atmospheric conditions but turns yellow if the amount of carbon dioxide increases and purple if the amount decreases.

Apparatus

- Four boiling tubes with bungs
- 150 cm^3 hydrogencarbonate indicator
- 20 cm^3 measuring cylinder
- Pondweed such as *Cabomba* (available from aquatic shops) or seaweed if available
- Boiling tube rack
- Square of aluminium foil 15 cm × 15 cm
- Square of muslin cloth 15 cm × 15 cm
- Bench lamp
- Elastic bands

Method

- Pour a small amount of indicator into each boiling tube, swirl it around and then pour away; do the same with the measuring cylinder.
- Carefully wrap one of the tubes in the foil and secure with an elastic band.
- Wrap a second tube in muslin cloth and secure with elastic bands.
- Measure 20 cm^3 of indicator into each boiling tube.
- Place equally sized pieces of pondweed into each of the wrapped tubes and one of the unwrapped tubes.
- Leave the fourth tube empty apart from the indicator.
- Place bungs into each tube.
- Leave the tubes in the boiling tube rack with a bench lamp shining on them for at least 1 h.
- Copy out the results table and predict the colour of the indicator in each tube.
- Remove the wrapping on the tubes and record the colour of the indicator in your results table.

Risk assessment

Hydrogencarbonate indicator should be freshly made by qualified staff using a fume cupboard.

To make the stock solution

- Dissolve 0.20 g of thymol blue and 0.1 g of cresol red in 20 cm^3 of ethanol.
- Dissolve 0.85 g of sodium hydrogencarbonate in about 200 cm^3 of freshly boiled distilled water.
- Add the ethanol solution from the first step and dilute to 1000 cm^3 with water.

→

When it is ready to use:

- Dilute the stock solution ten times with freshly boiled distilled water.
- Bubble air through the diluted solution to equilibrate it with atmospheric carbon dioxide.

Avoid exhaling near the solution as it is very sensitive to changes in carbon dioxide concentration.

Precautions should also be taken to avoid burns or dazzle from a hot bench lamp.

Safety glasses should be worn in case of cold indicator splashing onto the hot light bulb and causing it to shatter.

Prediction and results

Predicted and observed results

tube	predicted colour	observed colour
unwrapped with pondweed		
wrapped in muslin with pondweed		
wrapped in foil with pondweed		
unwrapped but empty		

Table 3.2. Results.

Conclusions

1. Why was it important to rinse all the equipment in the indicator before the experiment is started?
2. What was the reason for the tube without any pondweed in it?
3. Why did the tubes need to have bungs in?
4. How well did your results match your predictions? Were there any results that surprised you?
5. Explain the colour in each of your tubes.
6. Suggest a way to extend the investigation to make it more precise or to investigate photosynthesis further.

Measuring productivity

There are several ways in which primary productivity can be estimated:

- using the rate of photosynthesis of producers
- using the rate of increase in the biomass of producers
- looking at the amount of chlorophyll in an ecosystem.

For example, the higher the rate of growth of producers, the higher the amount of chlorophyll present. Net primary production and gross primary production are usually given as units of energy per unit area per unit of time, for example kJ m^{-2} $year^{-1}$. However, the units used vary depending on the method of measurement chosen.

Rate of photosynthesis

The rate of photosynthesis can be found by looking at the change in either the oxygen or carbon dioxide concentrations. If photosynthesis is taking place, there will be a decrease in the concentration of carbon dioxide and an increase in the concentration of oxygen.

Because the majority of marine producers are single-celled phytoplankton, they are easy to keep in a closed system such as a bottle. If a bottle is placed in the light, both photosynthesis and respiration will take place. If a bottle is in the dark, there will be no photosynthesis but respiration will continue. If you assume that the rate of respiration remains relatively constant, you can compare the readings of bottles kept in the dark and light to work out the rate of photosynthesis (Figure 3.5). The levels of oxygen in the water can be measured with a dissolved oxygen sensor. You need to take three readings:

- the initial reading before the experiment begins
- the reading in the light bottle at the end of the experiment
- the reading in the dark bottle at the end of the experiment.

The results would be tabulated as shown in Table 3.3.

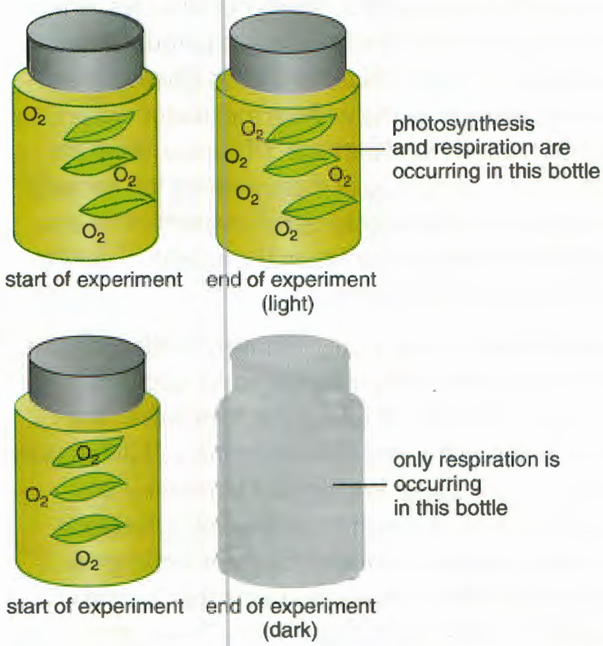


Figure 3.5. The light- and dark-bottle method for measuring productivity. The LH bottles represent start of experiment and RH bottles represent end of experiment.

bottle	amount of oxygen / mg dm^{-3} h^{-1}
start of experiment	6
end of experiment in the light	16
end of experiment in the dark	1

Table 3.3. A sample set of results from the light- and dark-bottle method.

The amount of oxygen in the light bottle increases because the rate of photosynthesis is higher than the rate of respiration. In the dark bottle, the only process taking place is respiration so the amount of oxygen in this bottle decreases.

The net primary production is therefore the difference between the oxygen in the bottle at the start and the oxygen in the light bottle at the end. The respiration is the difference between the oxygen at the start and the oxygen in the dark bottle at the end. The gross primary production is the difference between the light and the dark bottles at the end of the experiment.

In this example:

NPP = 16 – 6 = 10 mg O_2 dm^{-3} h^{-1}

Respiration = 6 – 1 = 5 mg O_2 dm^{-3} h^{-1}

GPP = 16 – 1 = 15 mg O_2 dm^{-3} h^{-1}

This technique can be extended to investigate the effect of light on productivity. Samples are removed from different depths in the water and placed into pairs of light and dark bottles. The bottles are then suspended at the same depth the samples were removed from. The calculations are carried out as described to work out the net primary production, gross primary production and respiration at each depth.

The productivity generally increases as you move down towards the deep chlorophyll maximum, and then decreases as the amount of light begins to limit the rate of photosynthesis (Figure 3.6). At the point where the rates of respiration and photosynthesis are equal, there is no change in the amounts of carbon dioxide or oxygen and the net productivity is zero. The light intensity at this depth is known as the **compensation point**. Below this depth, there is still light available but producers are unable to survive because the rate of respiration would be greater than the rate of photosynthesis. This part of the photic zone is sometimes called the disphotic zone. Around 90% of marine life is therefore found above the depth of the compensation point. This upper area, with sufficient light for photosynthesis is called the euphotic zone.

KEY TERM

Compensation point: the light intensity at which the rate of photosynthesis and the rate of respiration are equal

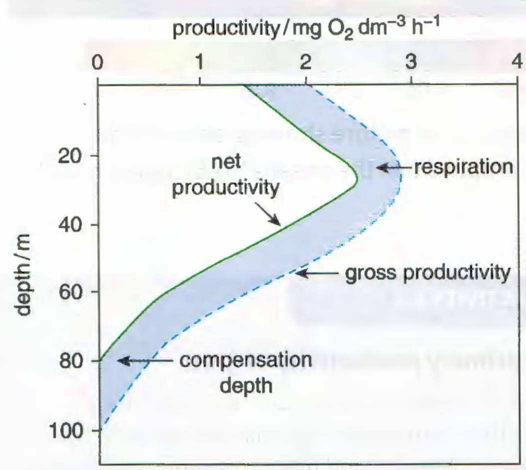


Figure 3.6. Productivity at different depths as measured by the light- and dark-bottle method.

Changes in biomass

A second way to measure productivity is to look at the rate of accumulation of biomass. This can be achieved by harvesting producers after a set amount of time, drying them to remove variations in the water content, and then finding the mass. If you know the size of the area the producers came from, you can then work out the biomass per unit area per year to give an estimate of the net primary production. As the producers would have been respiring while growing, you are unable to measure the gross primary production. There are difficulties with this method however, as you cannot measure the biomass that has already been consumed by heterotrophic organisms. This may also be true for the light- and dark-bottle method if small heterotrophic organisms are not sieved out before the experiment begins.

Satellite imagery

The other main way in which scientists monitor the productivity of the oceans is by using satellite imagery to measure the colour of the surface layers of water. This can be used to follow the changes in chlorophyll concentration and therefore the amount of producers present (Figure 3.7).

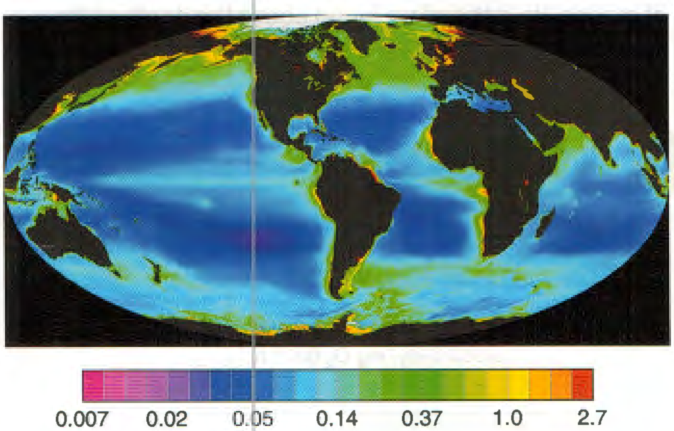


Figure 3.7. False-colour picture showing annual mean amount of chlorophyll *a* in the oceans (NASA *aqua modis*).

From Figure 3.7 you can see that the most productive areas are in the tropics and at the higher latitudes, which are shown in green and orange. The least productive areas, shown in pink and blue, tend to be where there is a smaller supply of nutrients from the deeper waters, perhaps because of wind patterns. Of course, there are problems with this method of measurement too because the relationship between chlorophyll concentration and biomass is not fixed. It depends on the individual species present and their adaptations.

The satellites can indicate only relatively shallow depths and certainly cannot penetrate the entire euphotic zone where production is taking place. However, the satellite images give a very useful summary of differences in productivity and enable scientists to monitor any changes. Recently, researchers at Sheffield University discovered that water from melting giant icebergs in the Southern Ocean contains nutrients that increase the growth of the local phytoplankton. These giant icebergs are more than 18 km in length. Scientists studied the satellite images and found that the increased productivity caused by these icebergs lasts for at least a month after they pass through an area and extend for hundreds of kilometres.

SELF-ASSESSMENT QUESTIONS

5 Explain the difference between gross primary production and net primary production.

6 **a** If the GPP = 53 kJ m^{-2} $year^{-1}$ and the NPP = 31 kJ m^{-2} $year^{-1}$ calculate the amount of energy used in respiration.

b Explain why organisms need to respire.

PRACTICAL ACTIVITY 3.2

Measuring primary productivity of grass

Primary productivity is the rate of production of new biomass. It is this biomass that is available to pass to the next trophic level through feeding. In this experiment, grass is grown with and without light and the biomass is found using two different methods. This allows you to estimate the net primary productivity of the grass plants. This experiment takes 3–4 weeks.

Apparatus

- Potting compost
- Grass seeds (for example rye grass), readily available from garden centres and online
- two plastic germination trays (also available from garden centres and online)
- Aluminium foil
- Balance

- Drying oven or blotting paper and plant press
- Spoons or small trowels
- Light source

Method

- Label the trays 'light' and 'dark'.
- Fill both germination trays with the potting compost until three-quarters full.
- Scatter the grass seed on top of the soil so that there is approximately 5 mm between each seed.
- Cover the seeds with a thin layer of compost.
- Leave the trays in sunlight or under lamps.
- Water regularly and grow for about 2 weeks until the seedlings are around 3 cm tall.
- Carefully remove all the plants from a 50 mm × 50 mm area.
- Remove as much of the soil as possible and weigh the plants, recording the wet mass in a copy of the results table.
- Place the plants in a drying oven for 48 h at 95 °C. If no oven is available they can be dried for the same length of time using blotting paper and a plant press.
- Weigh the plants and record the dry mass in your results table.
- Carefully cover the tray labelled dark with aluminium foil.
- Leave both trays for another week, remembering to water regularly.
- Carefully remove another 50 mm × 50 mm area of plants from each tray and record the wet masses in your table.
- Dry each sample using the same method as before and record the dry masses in your table.
- Complete the calculations and answer the questions.

Risk analysis

There are few risks associated with this experiment. Care should be taken with compost to avoid accidentally ingesting it.

Results and analysis

	light tray	dark tray
initial wet mass / g		n / a
final wet mass / g		
initial dry mass / g		n / a
final dry mass / g		

Table 3.4. Results.

Final mass in the light – initial mass = net primary productivity.

Final mass in the dark – initial mass = respiration (will be negative as the plants lose mass).

Gross primary productivity = net primary productivity + respiration (use the figure, ignoring the – sign).

Do these calculations for both the wet and dry masses.

All the masses were taken from areas of 2500 mm^2 so you can convert them to g m^{-2} by multiplying your answers by 400. The units of time depend on how long you leave the seedlings between the two measurements but it will probably be g m^{-2} $week^{-1}$.

Conclusions

1. What is the difference in your calculations using wet and dry masses?
2. What does the tray in the dark show you?
3. Why did you need to harvest and weigh plants at the beginning of the experiment?
4. Compare your results with the rest of your class. Which method gave you the most reliable results? Why do you think this is?
5. What assumptions have you made during this practical?

The influence of changes in productivity on the food chain

The higher the productivity, the more biomass accumulated by the producers and therefore the more biomass available for the consumers to eat. This means that, in general, higher productivities lead to more abundant populations of consumers, or longer food chains. The most productive areas of the oceans tend to be those areas with high levels of nutrients from upwelling. In tropical areas, there are high levels of light but it is also warm, which leads to a strong thermocline and little mixing of nutrients from deeper waters. In contrast, polar waters are nutrient rich because it is very cold and there is therefore only a weak thermocline. However, productivity is only high in the summer when the light levels are higher.

There does come a point when productivity can be too high. This leads to effects that are similar to the process of eutrophication seen in fresh-water ecosystems. If the levels of nutrients increase too much or too rapidly, phytoplankton may rapidly increase in a phenomenon known as an **algal bloom**.

In these circumstances, up to 5 million cells per litre can be produced, which is very damaging to the ecosystem. This density of algae is so high that it can clog the gills of fish so that they are unable to obtain enough oxygen. Once the algal cells die they are broken down by decomposers such as bacteria so there is also an increase in bacterial populations. The bacteria respire and grow and use up the oxygen in the water, which can lead to **hypoxic** conditions (lacking oxygen). This also kills heterotrophic organisms because without oxygen they cannot respire.

If the algal species involved also produce toxins, the effects can be even worse because the organisms that ingest them will be poisoned. This can cause mass mortality in aquatic organisms such as dolphins, manatees and whales, as well as food poisoning in people who eat contaminated shellfish. You can read more about these harmful algal blooms in Chapter 8.

KEY TERMS

Algal bloom: a rapid increase in a population of algae

Hypoxic: an area of water with a low concentration of dissolved oxygen

SELF-ASSESSMENT QUESTIONS

7 **a** Evaluate the use of different methods to measure ocean productivity.

b Explain why giant icebergs increase productivity of the oceans.

8 **a** Explain why it can be damaging for nutrient levels in water to increase too much.

b Suggest why waters at high latitudes normally have higher productivity than tropical waters.

CASE STUDY

The Peruvian anchoveta fishing industry

Anchovies are small forage fish found in the open ocean away from the seabed or the shore. A forage fish is a fish that is used by other predators for food. Anchovies are mainly filter feeders: water is taken in through the mouth and zooplankton is filtered out by the gill rakers. Forage fish are an important part of the food chain. They provide food for:

- larger fish such as tuna and salmon
- mammals like dolphins and whales
- sea birds including gulls and pelicans.

The Peruvian anchoveta fishery is the biggest single species fishery in the world. Anchoveta are a species of anchovy that live for up to 3 years and can grow to be 20 cm in length (Figure 3.8).

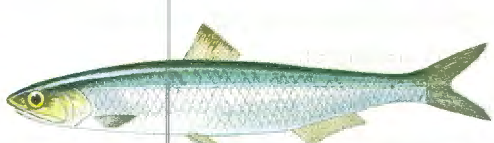


Figure 3.8. Peruvian anchoveta.

In the 1960s, catches of anchoveta off the coast of Peru were more than 10 million tonnes $year^{-1}$. In 1971, the catch was 13.1 million tonnes (Figure 3.9). In 1972, the industry collapsed because of over-fishing and the El Niño phenomenon. El Niño is a change in the trade winds in the Pacific Ocean. These winds normally stimulate upwelling of cold, nutrient-rich waters into the warmer sunlit water above. During an El Niño year, the thermocline deepens, which effectively blocks the cooler water underneath from mixing with the warm water at the top. Lack of nutrients therefore limits the primary productivity in the sunlit zone, leading to reductions in the numbers of fish.

After the collapse of the anchoveta populations, the industry shifted to fishing sardines for several years until the waters cooled again and anchoveta numbers increased (Figure 3.9). There was another reduction in numbers during an El Niño event in the early 1980s, but by the mid-1990s the catch was back up to 12.5 million tonnes. In 2014, only 2.2 million tonnes were caught after the second fishing season was cancelled because of the El Niño phenomenon.

It is not just the fishing industry that is affected by El Niño. Guano (excrement from sea birds) is an important fertiliser. When there are fewer fish, there is less food for the sea birds, which are their predators, and therefore less guano is produced.

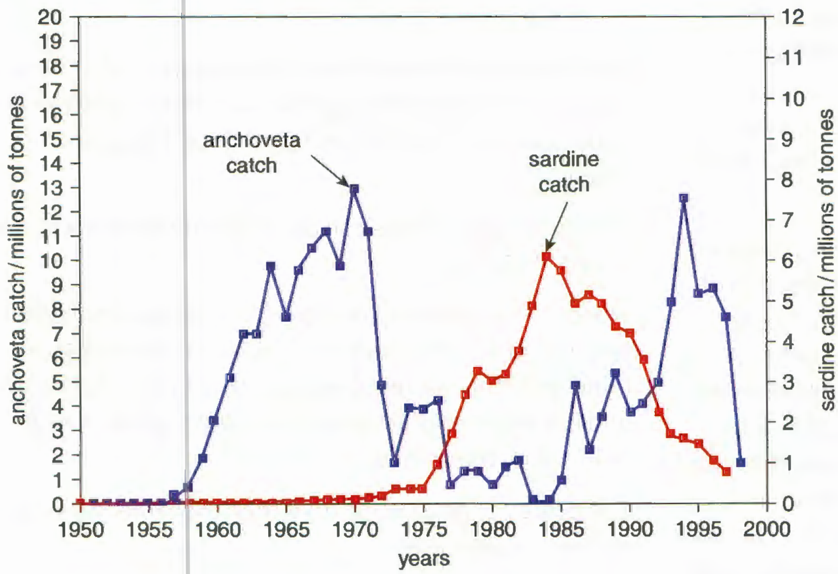


Figure 3.9. Anchoveta and sardine catches between 1950 and 2000.

Questions

1. Explain how a reduction in the nutrients in the upper layers of the ocean could lead to a decrease in the numbers of forage fish such as anchoveta.
2. Anchoveta feed on large zooplankton whereas sardines feed mainly on phytoplankton. Use this information to suggest why sardine numbers are less likely to collapse during an El Niño event.
3. Look at the graph in Figure 3.9 and suggest two years other than 1971 that could have had El Niño events. Explain your answer.

3.3 Energy transfer

Only a small amount of the radiation from the Sun is fixed by the Earth's producers. Some of the radiation never reaches the producers because it is reflected back into space. Of the light that does reach the ocean, some is absorbed, reflected or scattered by the water.

The remainder is available to the producers but even then it cannot all be used. Some is the wrong wavelength for the pigments of producers to absorb. Chlorophyll, for example, absorbs red and blue light but reflects green light (which is why it appears to be green). Of the light that is the correct wavelength, some will miss the chloroplasts and still not be absorbed (Figure 3.10).

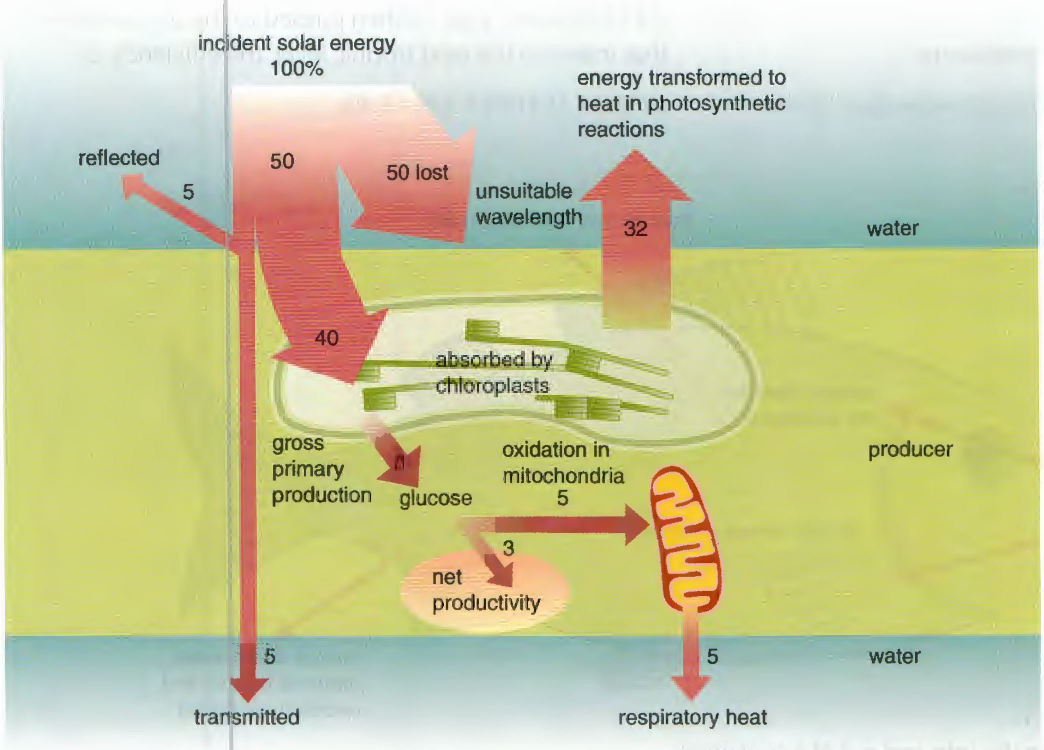


Figure 3.10. The fate of light energy falling on producers in the ocean.

The process of photosynthesis itself is not completely energy efficient. During the various chemical reactions that must take place, energy is lost as heat. Worldwide it has been estimated that producers such as green plants and phytoplankton fix about 0.06% of the total energy radiating from the Sun. But this figure can be as high as 1% in aquatic ecosystems and 2–3% on land.

Producers need some of the carbohydrates they produce for respiration. This means that only the net production of biomass is available to the next trophic level. The energy stored in biomass is passed to heterotrophic organisms when they ingest, digest and absorb the nutrients from the producers. These nutrients can then be assimilated into new biomass. If the producers are phytoplankton, then the entire cell is usually ingested by the primary consumers, passing on all the available energy. However, in the case of macroalgae and rooted plants like seagrass, there are parts of the producer that are not eaten (the roots, for example). The energy stored in these areas is therefore not available to the next trophic level, although it may later re-enter the ecosystem through decomposition when the plant dies.

Secondary production is the production of new biomass by the consumers. It can involve animals eating the phytoplankton, macroalgae and seagrass, or animals eating other animals. Decomposers such as bacteria and fungi break down dead organic matter to obtain the nutrients they need. This also releases nutrients back into the ecosystem (see Chapter 4). Secondary production depends on:

- the biomass available in the producers
- the amount of energy lost through respiration by the consumers
- the amount of energy lost in waste products such as urine (Figure 3.11).

Most salt-water fish only lose small amounts of urine and excrete most of their nitrogenous waste through their gills in the form of ammonia. Undigested food is egested as faeces.

These energy transfers can also be expressed as a formula: C = P + R + F + U

Where C is the energy consumed, R is the energy used in respiration, F is the energy in faeces, U is the energy in urine and other excreted waste products of metabolism, and P is the energy left over for the production of new biomass by the animal.

The energy of production (P) is then available to pass on to the next trophic level.

The efficiency of energy transfer

The efficiency of the energy transfer can be expressed as a percentage. This can be shown as:

$$\frac{\text{energy transferred to new trophic level}}{\text{energy in previous trophic level}} \times 100$$

For example, if the energy radiating from the Sun is 1 600 000 kJ m^{-2} year^{-1} and phytoplankton captures 153 000 kJ m^{-2} year^{-1} in photosynthesis, the efficiency is:

153 000 ÷ 1 600 000 × 100 = 9.6%

If 12 856 kJ m^{-2} year^{-1} is then passed to the zooplankton that make up the next trophic level, the efficiency is:

12 856 ÷ 153 000 × 100 = 8.4%

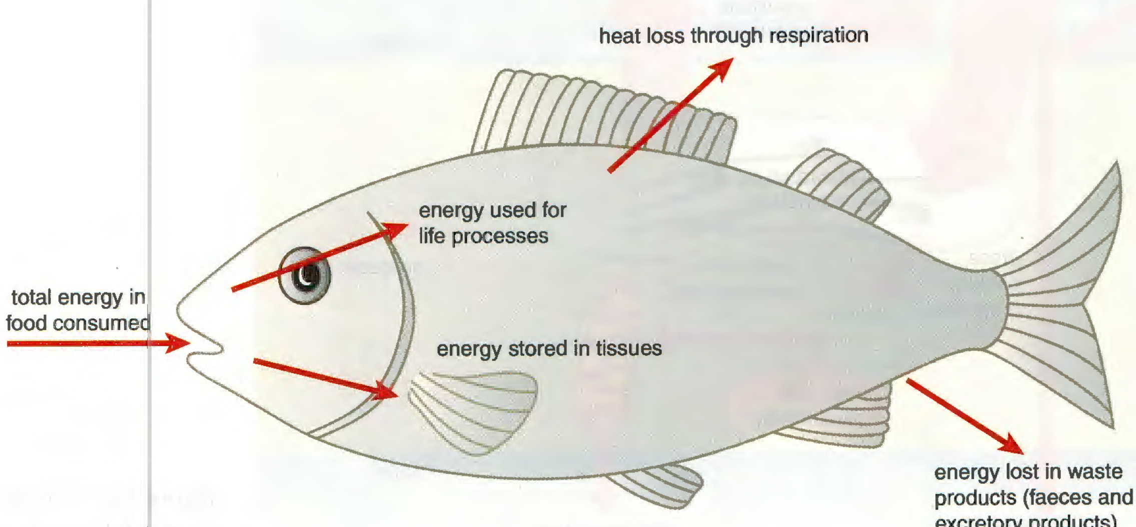


Figure 3.11. Energy transfer into and out of a consumer.

Typically the efficiency of transfer between trophic levels is around 10%, but it varies depending on:

- how much of the food is eaten
- how easy it is for the consumer to digest and assimilate the nutrients
- how much energy is used for movement
- how much is lost in the waste products of metabolism.

Some organisms are easier to digest and assimilate than others: generally, consumers find it easier to assimilate the energy in other animals than the energy in producers. If it is easier to assimilate the energy, then more of it will be passed to the next consumer. In addition, some organisms at each trophic level escape being eaten and the energy stored in their biomass will never pass to the next level.

Most fish are **ectothermic**, which means that their body temperature varies with the environmental temperature. The ocean sunfish, for example, is a secondary consumer that eats zooplankton, tiny animals present in the water that feed on the phytoplankton. The ocean sunfish is ectothermic and does not use energy in respiration to keep its body temperature higher than that of the surrounding water.

Tuna are **endothermic**, which means that they must expend energy maintaining their body temperature. Tuna occupy two trophic levels in the same food web, as secondary consumers eating zooplankton, and as tertiary consumers eating small crustaceans that have already fed on the zooplankton.

Small sharks feed on both the sunfish and the tuna but the efficiency of energy transfer is higher from the sunfish. Assuming that the sunfish and tuna take in similar amounts of energy, the tuna use more of this in respiration to keep warm so there is less to pass to the sharks. In general, the efficiency of transfer from ectothermic organisms ranges from 5% to 15% and from endothermic organisms ranges from 1% to 5%. The efficiency of transfer between the different trophic levels determines how many levels there are in the ecosystem. The higher the efficiency of transfer, the more trophic levels the ecosystem can support.

KEY TERMS

Ectothermic: an organism that maintains its body temperature by exchanging heat with its surroundings

Endothermic: an organism that maintains its body temperature by generating heat in metabolic processes

SELF-ASSESSMENT QUESTIONS

9 The total solar energy falling on phytoplankton is 1 000 000 kJ m^{-2} $year^{-1}$ and the efficiency of transfer to the phytoplankton is 1%.

a Calculate the GPP.

b If 30% of the GPP is used in respiration, then what is the NPP?

10 Describe the factors that determine how efficient the transfer of energy is.

Maths skills

Interpreting energy diagrams and calculating percentage efficiency

Energy diagrams are another way of showing the flow of energy through an ecosystem (Figure 3.12). They show the energy entering the ecosystem from the Sun, moving through producers and being lost as a result of respiration and excretion. The main point to remember is that all the energy has to go somewhere, so the values on the arrows going into a box must always equal the sum of the values on those coming out. The units can be given as kJ m^{-2} $year^{-1}$ or simply arbitrary units. Arbitrary units are relative units of measurement to allow comparison. For example, if there is twice as much energy in producers as in primary consumers the arbitrary units could be 5 and 10 or 50 and 100, it does not matter.

Worked example

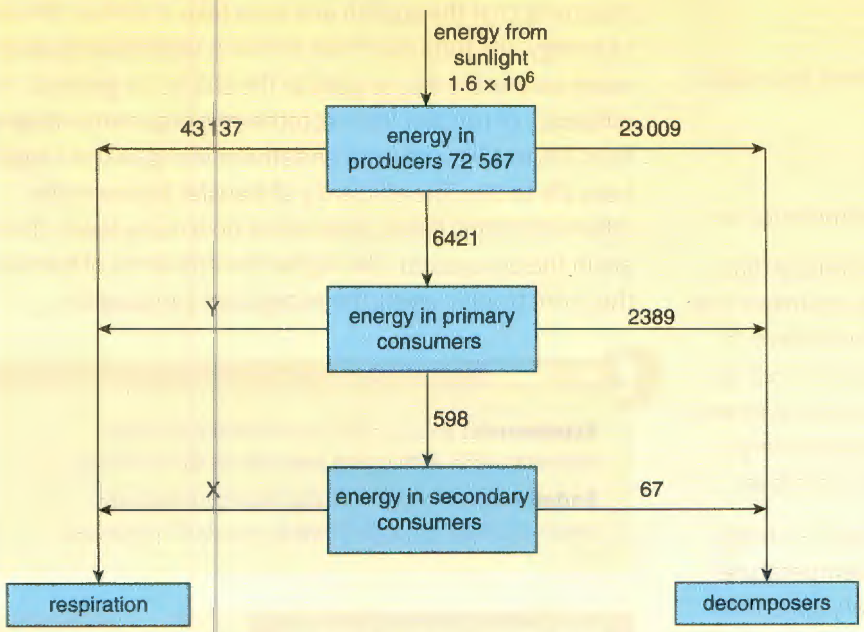


Figure 3.12. Worked example of an energy flow diagram (units are kJ m^{-2} $year^{-1}$).

1 How much energy is being lost in respiration by the secondary consumers?

Remember that the energy entering the secondary consumers must equal the energy leaving.

From the diagram you can see that 598 kJ m^{-2} $year^{-1}$ enters the secondary consumers (the 'in arrow'); 67 kJ m^{-2} $year^{-1}$ ends up being passed to the decomposers. On this diagram the only other arrow is the respiration arrow (labelled X). So the energy lost in respiration, X, must be equal to 598 – 67 = 531 kJ m^{-2} $year^{-1}$.

You can check your answer by making sure the arrows add up. So in this case the 'in arrow' is 598. The 'out arrows' are 531 and 67, which added together do add up to 598.

2 What is the efficiency of energy transfer between the Sun (solar energy) and producers?

To calculate the efficiency of energy transfer you always work out a percentage. This allows you to compare different ecosystems where the initial energy inputs might be different. The percentage is the energy that is transferred divided by the energy that was in the previous trophic level and then multiplied by 100. So in this case the energy transferred to the producers was 72 567 kJ m^{-2} $year^{-1}$ and the energy in the previous trophic level (the Sun) was 1.6×10^6 kJ m^{-2} $year^{-1}$. So the efficiency of transfer is:

$(72\,567 \div 1.6 \times 10^6) \times 100 = 4.53\%$

You may also be given similar information in the form of a pyramid of energy. In this case, just use the figures in the pyramid in your percentage calculation. Always divide the figure in any particular tropic level by the figure for the previous level and then multiply by 100. For example: (energy in primary consumers / energy in producers) × 100.

Questions

1 a Calculate the amount of energy used in respiration (Y) by primary consumers.

b Calculate the efficiency of energy transfer between producers and primary consumers.

2 The pyramid of energy in Figure 3.13 shows the energy in a marine food chain. It is not drawn to scale and the energy is given in arbitrary units.

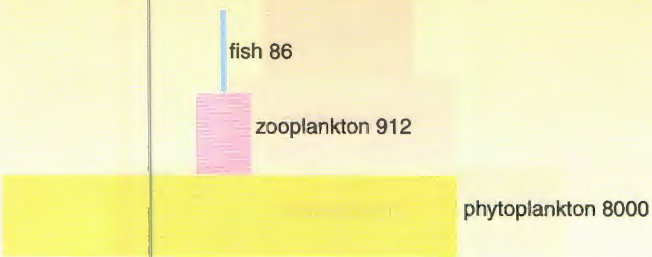


Figure 3.13. Pyramid of energy showing energy in arbitrary units.

a Use the information in Figure 3.13 to calculate the efficiency of energy transfer between the phytoplankton and the zooplankton.

b Use the information in Figure 3.13 to calculate the efficiency of energy transfer between the zooplankton and the fish.

c The average efficiency of transfer between producers and primary consumers is 10%. Suggest why the transfer in this pyramid between phytoplankton and zooplankton is more efficient than this.

3.4 Illustrating feeding relationships

You can show the relationships between the different trophic levels using pyramids of number, biomass and energy. These are like bar charts but are made up of horizontal bars arranged in a pyramid shape to show a particular food chain. They can be drawn to scale or simply sketched to give an idea of the changes as energy is transferred along the food chain. Producers are always at the bottom, followed by primary consumers, secondary consumers and tertiary consumers. Although energy is transferred to decomposers once the producers and consumers die, it is not often shown on the pyramid.

Pyramids of number

A **pyramid of numbers** simply shows the number of organisms present in each trophic level at a particular moment in time. The size of each horizontal bar is proportional to the number of organisms. In theory this should be quite simple but in practice it is actually rather difficult. It is often hard to estimate accurately the number of organisms present, and even once this has been achieved it can be difficult to show them to scale. For example, a typical oceanic food chain is:

phytoplankton → zooplankton → herring → mackerel → mahi mahi → shark

There could be millions of cells of phytoplankton and only one or two sharks. Finding a scale to show this is impossible. For this reason many pyramids of numbers are sketched rather than drawn to scale (Figure 3.14). In addition, much of the phytoplankton is consumed very quickly after it is produced. Thus if the numbers present in an ecosystem are counted after most have been eaten, the pyramid will be inverted (upside down) and it will look as though there are fewer phytoplankton than zooplankton. The number of organisms in an ecosystem will also vary depending on factors such as the time of year or the amount of fishing. This means that the pyramid can only show the numbers in each trophic level at a particular moment in time. Using pyramids of number also does not take into account the size of organisms, which can lead to odd-looking pyramids. For example, if several small parasites feed on one large fish you will see an inverted pyramid.

KEY TERM

Pyramid of numbers: a diagram that shows the number of organisms in each trophic level of a food chain

Pyramids of biomass

Instead of finding the number of each organism you could measure their total biomass. This overcomes the difficulties of having organisms of different sizes, such as the parasites in the last example. It does not, however, solve the issues caused by phytoplankton being eaten before they can be measured. It is possible that the

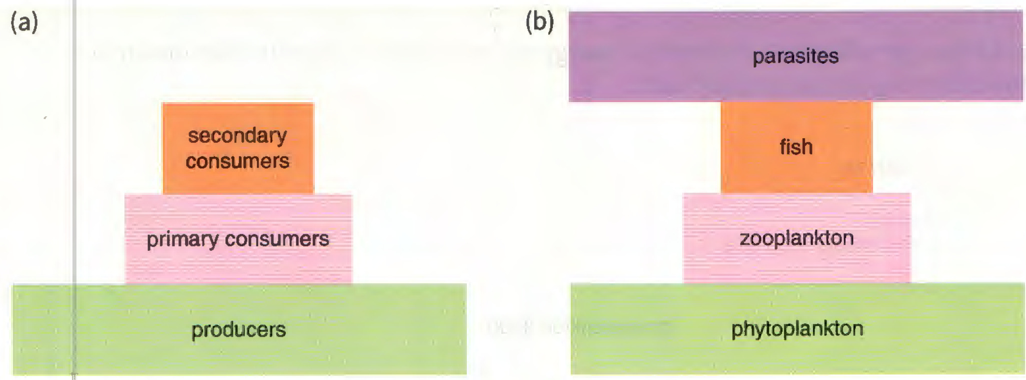


Figure 3.14. (a) A generalised pyramid of numbers; (b) A pyramid of numbers for a marine ecosystem showing small parasites feeding off a large fish.

biomass of organisms within an ecosystem could increase or decrease after measurements are taken which will make the pyramid inaccurate.

It is difficult to find the biomass of each trophic level accurately. Organisms vary in the amount of water they contain, and this water does not contribute to their biomass. For this reason dry mass should be used, with the water removed by evaporation. Clearly to do this the organisms must be killed, and it is therefore undesirable to measure the biomass of the entire food chain. Instead there are conversions available to change the mass of living material into dry mass. This still means that every individual must be found and weighed. Alternatively, the dry mass of a sample can be taken and then multiplied by the total number of organisms to give the total average dry mass. Both of these methods will give an estimate of the total biomass but neither of them will be completely accurate.

A **pyramid of biomass** may still be inverted as the total amount of biomass in phytoplankton at any one time is small because they are eaten very quickly. However, their reproductive rate is very high so they reproduce quickly enough to provide enough biomass to maintain the population of consumers. In other words the amount of biomass is low but the rate of production of biomass is high. This snapshot view of the biomass at a particular moment in time is known as the standing crop (Figure 3.15).

Pyramids of energy

A **pyramid of energy** shows the rate of production of biomass rather than the standing crop, and is therefore always pyramid shaped (Figure 3.16). It involves finding the energy in each trophic level of the food chain, which is a complex procedure. Data is collected over a long period of time, normally a year. Often conversion tables are used that will convert dry biomass into energy production. The units for pyramids of energy are kJ m^{-2} $year^{-1}$ so it will not be a standing crop but a measurement of the energy available over the entire year. Although pyramids of energy are the most difficult to produce, they are probably the most useful in terms of understanding the ecosystem.

KEY TERMS

Pyramid of biomass: a diagram that shows the biomass present in each trophic level of a food chain

Pyramid of energy: a diagram that shows the amount of energy in each trophic level of a food chain

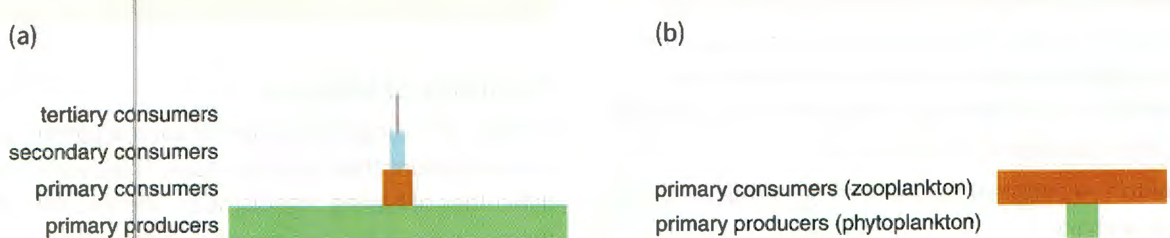


Figure 3.15. (a) Pyramid of biomass showing the decrease in biomass through the food chain; (b) Inverted pyramid of biomass showing the problems caused by the standing crop of rapidly reproducing phytoplankton.

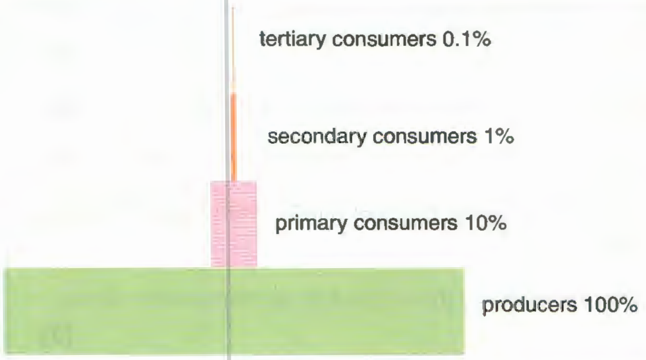


Figure 3.16. A generalised pyramid of energy showing the approximate transfer between tropic levels.

SELF-ASSESSMENT QUESTIONS

11 What are the drawbacks of using pyramids of number?

12 Why is it best to use dry mass to produce pyramids of biomass?

13 Describe what an inverted pyramid is and explain what might cause it.

Summary

- Energy enters marine ecosystems in two main ways: either through photosynthesis or chemosynthesis.
- Photosynthesis is carried out by producers such as phytoplankton, seaweeds and seagrasses.
- In photosynthesis, light energy is used to fix carbon dioxide into carbohydrates.
- Chemosynthesis is carried out by bacteria at hydrothermal vents, which are able to convert energy in chemicals dissolved in the water into carbohydrates.
- Productivity is the rate of production of new biomass by the autotrophs, which depends on various factors including the amount of light and the availability of nutrients.
- Productivity can be measured by measuring the rate of photosynthesis, looking at changes in biomass or by using satellite images that show the amount of chlorophyll in the oceans.
- If productivity is too high this can cause an algal bloom, which reduces the amount of oxygen in the water and damages the ecosystem.
- Not all of the energy from the Sun is fixed by producers, some is reflected by the water, some is the wrong wavelength for chlorophyll to absorb, and some simply does not reach a producer.
- Some of the energy fixed into carbohydrates is used in respiration, or lost through excretion, the rest is available to be passed to the next trophic level.
- The efficiency of this transfer varies but is normally around 10%.
- You can show the transfer of energy by drawing pyramids of number, biomass or energy.
- Pyramids of energy are the most difficult to draw but give us the most information about the food chain.

Exam-style questions

1 **a** **i** Describe what is meant by the term productivity. **[3]**

ii Give three factors that can affect the productivity. **[3]**

iii Briefly describe a simple method to measure productivity. **[3]**

b Explain why productivity is increased during the spring and summer. **[4]**

[Total mark: 13]

2 **a** Describe the process of photosynthesis. **[4]**

b **i** Why does photosynthesis not occur at hydrothermal vents on the ocean floor? **[2]**

ii Describe how energy enters the ecosystem found at the hydrothermal vents. **[4]**

c The solar energy falling on the ocean is 1.7×10^6 kJ m^{-2} year^{-1} and the phytoplankton are able to use 18 754 kJ m^{-2} year^{-1} of this.

i Calculate the percentage of the Sun's energy that is used by phytoplankton. Show your working. **[2]**

ii Explain why 100% of the energy is not used. **[3]**

[Total mark: 15]

3 Study the graph below.

Figure 3.17. Chlorophyll concentrations on the California coast in 2001.

a Describe the shape of the graph. **[3]**

b Explain why the amount of chlorophyll increases in March. **[5]**

c Suggest and explain what will happen to the population of zooplankton in March and April. **[2]**

d Within this ecosystem, herring feed on the zooplankton and mackerel feed on the herring. There are 809 phytoplankton, 37 zooplankton, 11 herring and 1 mackerel. Draw the pyramid of numbers for this food chain. **[3]**

[Total mark: 13]

4 Study the graph below.

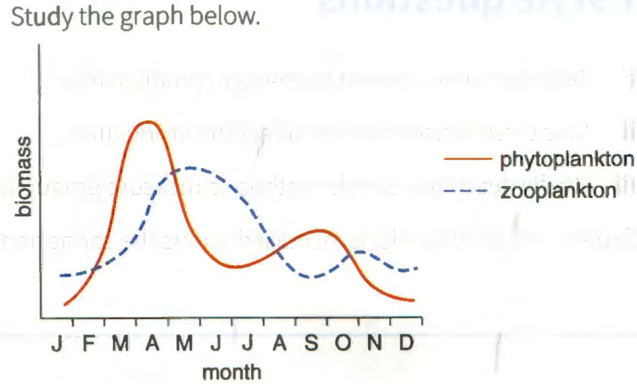


Figure 3.18. The biomass of phytoplankton and zooplankton round the Norwegian coast over the course of a year.

a Sketch a pyramid of biomass to show the phytoplankton and zooplankton in March. **[2]**

b Explain why there is normally more biomass in the producers than in the consumers. **[3]**

c Describe how the pyramid of biomass would be different in July. **[2]**

d Explain why the pyramid of biomass would be different in July. **[1]**

[Total mark: 8]

5 Figure 3.19 shows a food chain from a marine ecosystem. The figures show the energy in each trophic level in winter in arbitrary units.

phytoplankton 5000 → zooplankton 589 → sardine 61 → tuna 4

Figure 3.19. A food chain from a marine ecosystem showing the energy in each trophic level in arbitrary units.

a Calculate the efficiency of the transfer of energy between the phytoplankton and the zooplankton. Show your working. **[2]**

b Explain why there is less energy in the consumers than in the producers. **[3]**

c **i** Suggest what would happen to the energy in each level during summer. **[3]**

ii Suggest what might happen to the food chain if fertilisers from coastal farmland drain as run-off into the water. **[3]**

[Total mark: 11]

6 **a** **i** Explain the difference between gross primary production and net primary production. **[3]**

ii The gross primary production in an ecosystem is 78 935 kJ m^{-2} $year^{-1}$ and the energy lost in respiration is 23 674 kJ m^{-2} $year^{-1}$. Calculate the net primary production. **[2]**

b Explain why measurements of productivity in kJ m^{-2} $year^{-1}$ are a more accurate representation of what is happening in the ecosystem than measurements of biomass. **[2]**

[Total mark: 7]

The Gulf of Mexico dead zone

The Gulf of Mexico is an ocean basin surrounded by the United States, Mexico and Cuba (Figure 3.20). It is approximately 1500 km wide and is connected to both the Atlantic Ocean and the Caribbean Sea.

A dead zone is an area of water where oxygen levels have become very low (hypoxic). This means that there is insufficient oxygen for respiration, and organisms either die or move to a different area where the dissolved oxygen levels are higher. Dead zones occur near coastlines where there are high levels of nutrients washing off agricultural land. The first dead zone was reported in the early 20th century and since then the numbers have increased every year (Figure 3.21).

Figure 3.20. The Gulf of Mexico and surrounding countries.

Formation of dead zones

Dead zones form when excess nutrients such as phosphates and nitrates enter the water. These primarily come from chemical fertilisers and waste such as sewage. Dead zones can also form naturally if changes in wind and currents alter the upwelling of nutrients from deep water.

When the excess nutrients enter the water, they massively increase the growth of algae, leading to an algal bloom. Phosphates and nitrates tend to increase the growth of blue-green cyanobacteria, which are not eaten by many zooplankton. This means that their numbers can build up unchecked. When the organisms die they sink to the bottom, where they provide a food source for the bacteria, which break them down in the process of decomposition. The numbers of bacteria rapidly increase and their respiration uses up the majority of the oxygen dissolved in the water. The water therefore becomes hypoxic and other aquatic organisms die.

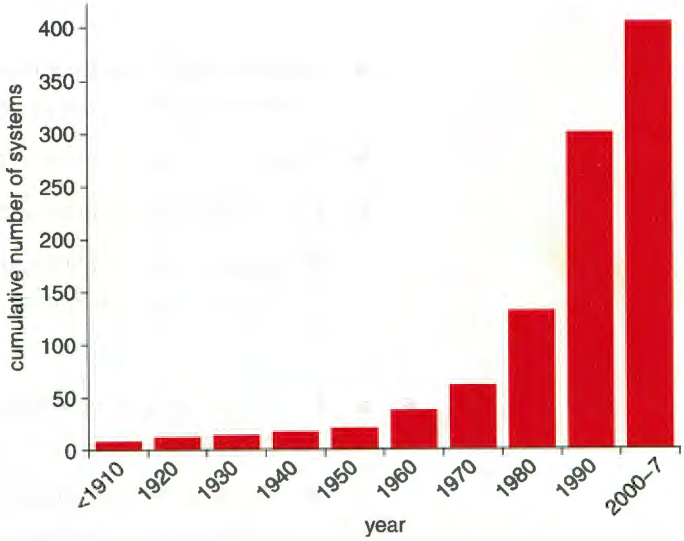


Figure 3.21. Number of dead zones by decade.

The Gulf of Mexico

The Gulf of Mexico dead zone is interesting for two reasons. First, it is the second largest dead zone in the world. Second, it is seasonal and its size fluctuates depending on the weather conditions each year. The Mississippi River drains into the Gulf and has the largest drainage basin of any river in North America. The levels of nutrients it washes into the Gulf are correspondingly large. Twelve million people live in areas that border the Mississippi and that discharge treated sewage into the water. The majority of the land

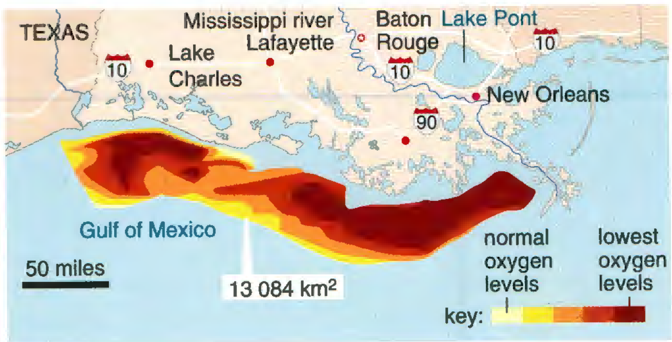


Figure 3.22. An average-sized dead zone in 2014.

near the Mississippi is farmland so rainwater constantly washes fertilisers into the water. About 1.7 million tonnes of nutrients are released into the Gulf of Mexico from the Mississippi every year. In the spring and summer this causes algal blooms and the development of the dead zone. The size of the dead zone varies; on average it is around 13 000 km^2 but it has been as large as 22 000 km^2 (in the summer of 2002). During times of heavy flooding the dead zone tends to be very large. In the late summer of 1998 the dead zone disappeared because there was a severe drought and the amount of water entering the Gulf decreased significantly. Figure 3.22 shows the size of the dead zone in an average year.

The fresh water flowing into the Gulf from the Mississippi is less dense than the seawater and so forms a layer on the top. This means that the deeper water, where the hypoxia occurs, is cut off from a resupply of oxygen from the atmosphere. The dead zone therefore persists until the water mixes again, either because of a hurricane or when cold fronts form in the autumn and winter.

The effects of the dead zone

The seafood industry in the Gulf of Mexico is very important. The Gulf provides the United States with the majority of its farmed oysters and shrimp, as well as being a source for several types of fish. The National Oceanic and Atmospheric Administration (NOAA) has estimated that the dead zone costs the tourism and fishing industries $82 million $year^{-1}$. When fish move out of the dead zone because of the lack of oxygen, fishers have to travel further to catch them. This costs both time and money. Shrimp are often unable to escape the dead zone and instead are simply killed, reducing the population and making them harder to catch in the future.

Reducing the size of the dead zone

The main way to reduce the size of any dead zone is to reduce the level of nutrients entering the water. In 1997 the Gulf of Mexico Watershed Nutrient Task Force was formed with the aim of reducing the average size of the dead zone to 5000 km^2. Strategies that can be used include reducing the use of inorganic fertilisers on farms, as well as altering the timing of their use to avoid leaching by rainwater. Management of flood plains is important because an increased area of flood plains means that less floodwater makes its way into the Gulf and nutrient-rich sediment is captured. Farmers are being encouraged not to drain wetlands but to leave them in their natural state to improve soil quality and reduce erosion. Waste treatment processes are being improved to reduce the discharge of nutrients into the water and to avoid animal waste entering waterways at all.

Questions

1 Describe how a dead zone forms.

2 Suggest why the number of dead zones has increased since they were first discovered.

3 Explain why the Gulf of Mexico dead zone varies in size each year.

4 Explain why the Gulf of Mexico dead zone is seasonal.

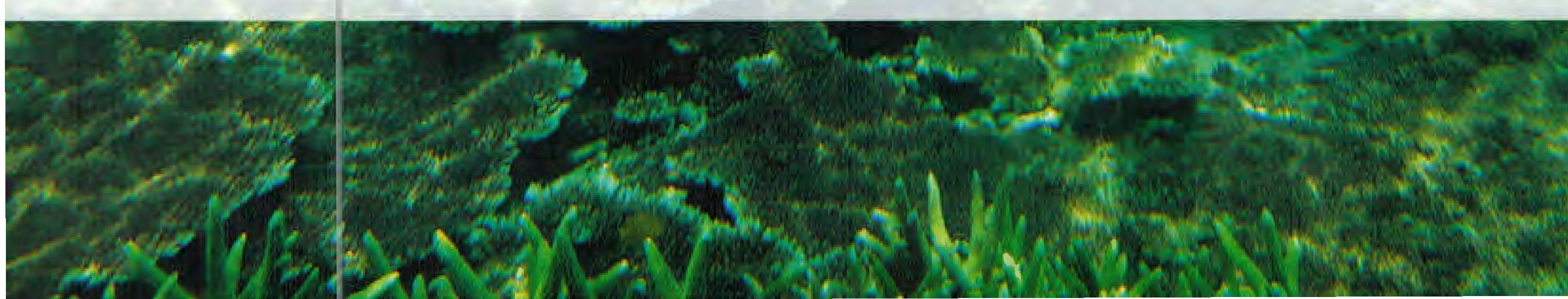
5 Summarise the control measures being taken to reduce the size of the Gulf of Mexico dead zone and explain how each measure works.

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.



4.1 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

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

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

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

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

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

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

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

4.2 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

KEY TERM

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

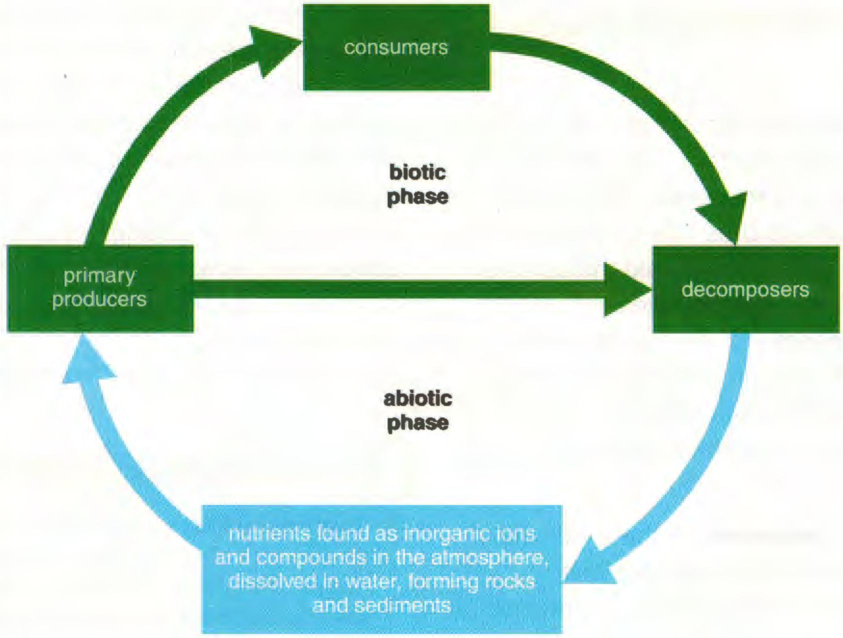


Figure 4.1. A generalised nutrient cycle showing the movement from the biotic to the abiotic phases.

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

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 is much shorter because the nutrients are constantly being used and recycled by the organisms

KEY TERM

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

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.

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.

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 with 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.

4.3 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

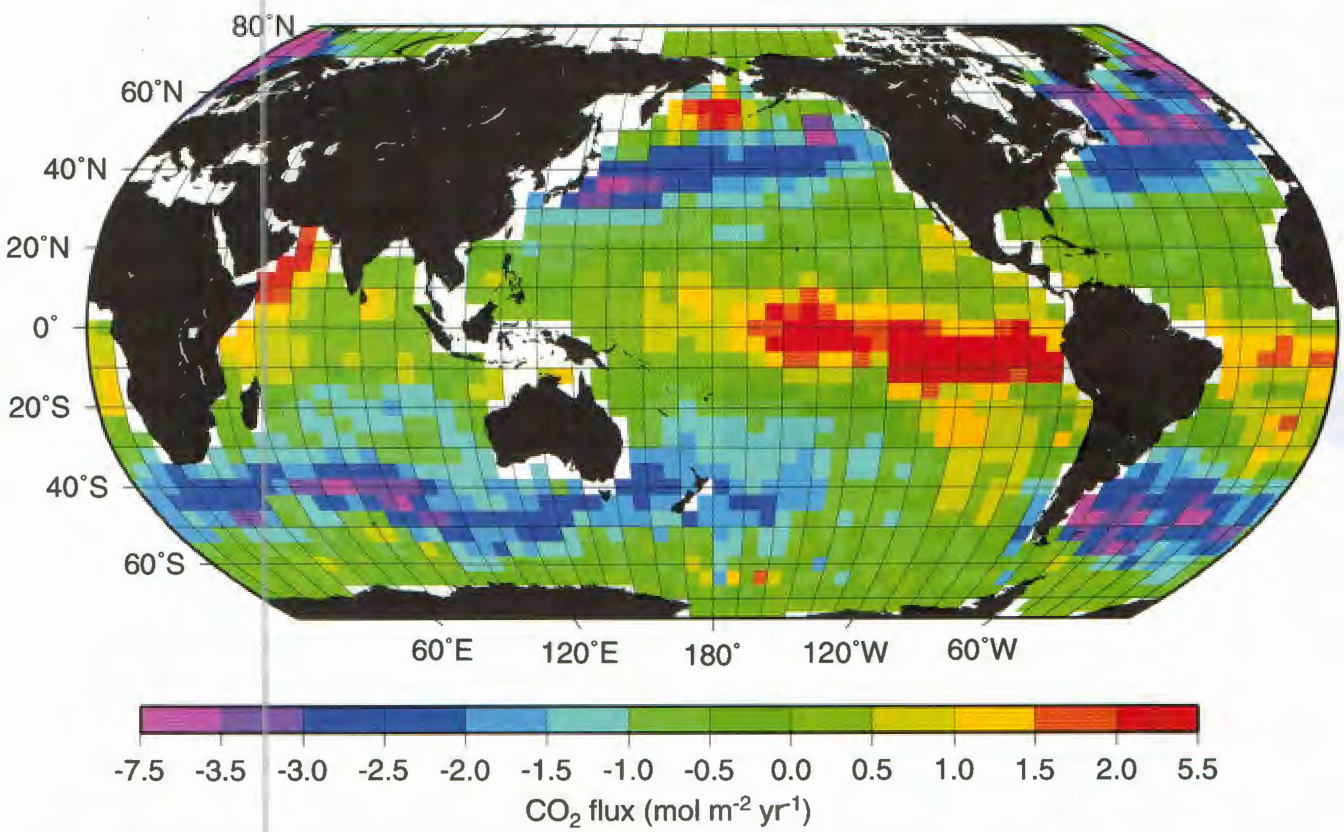


Figure 4.2. Movement (flux) of carbon dioxide into and out of the ocean over the course of a year. Purple and blue areas are carbon sinks; yellow and red areas are carbon sources; green areas are at an equilibrium, with the same amount of carbon dioxide dissolving as being released.

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.

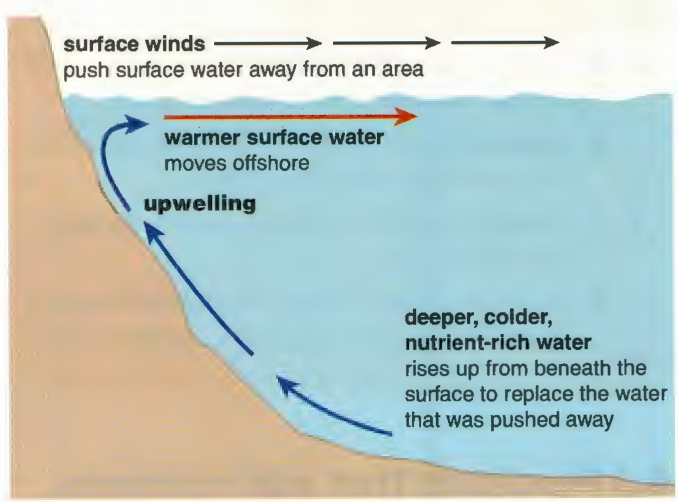


Figure 4.3. Coastal upwelling caused by surface winds.

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

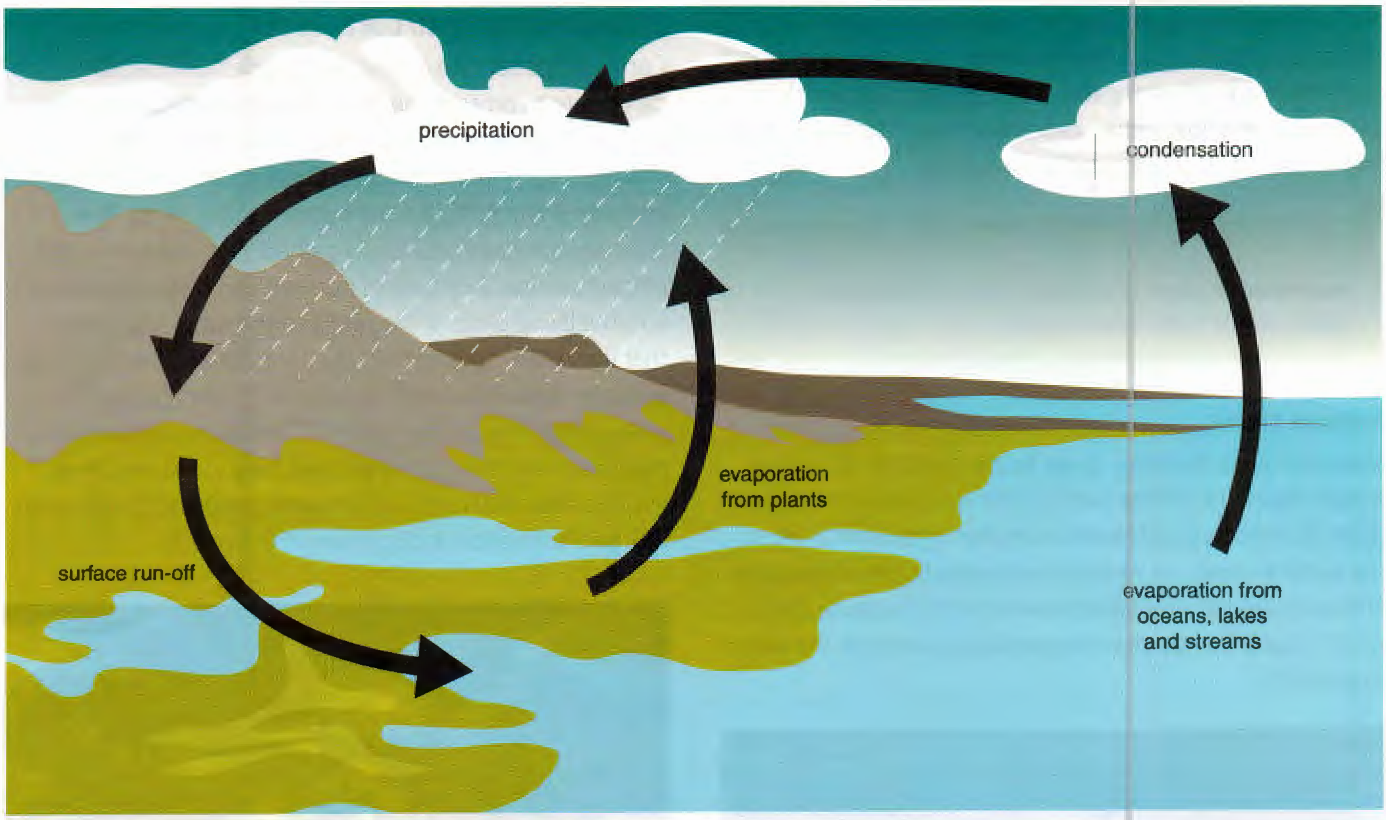


Figure 4.4. Summary of the water cycle.

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.

4.4 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).

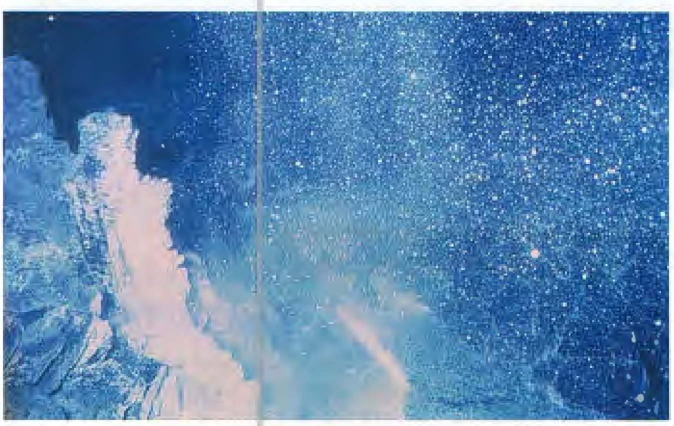


Figure 4.5. Marine snow in the water.

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.

4.5 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.

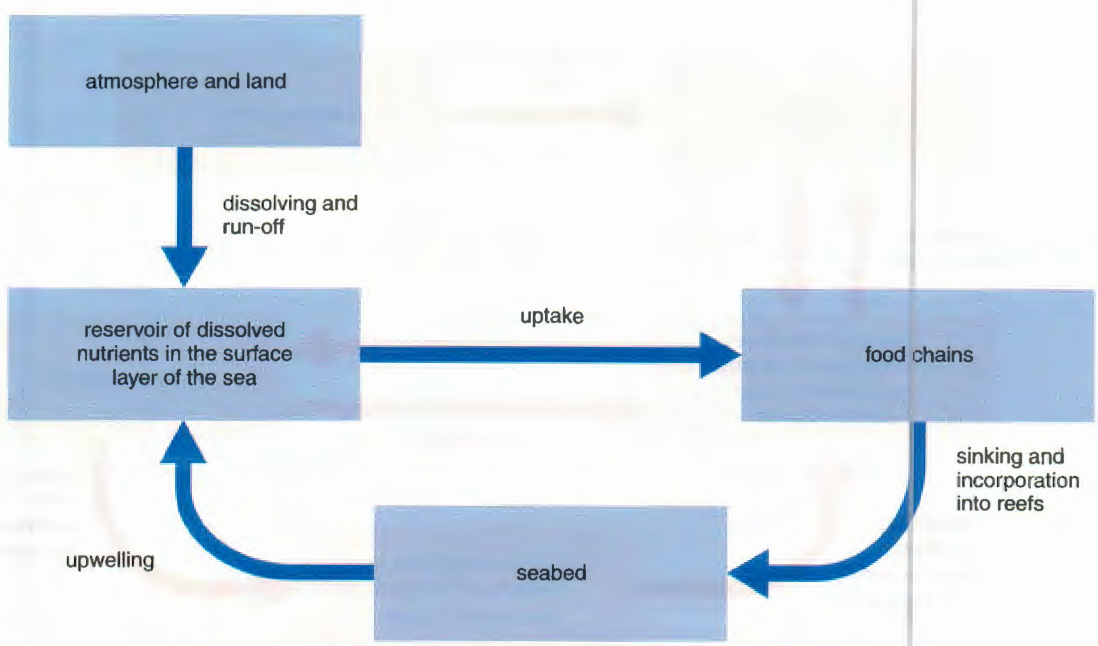


Figure 4.7. A summary of marine nutrient cycles.

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

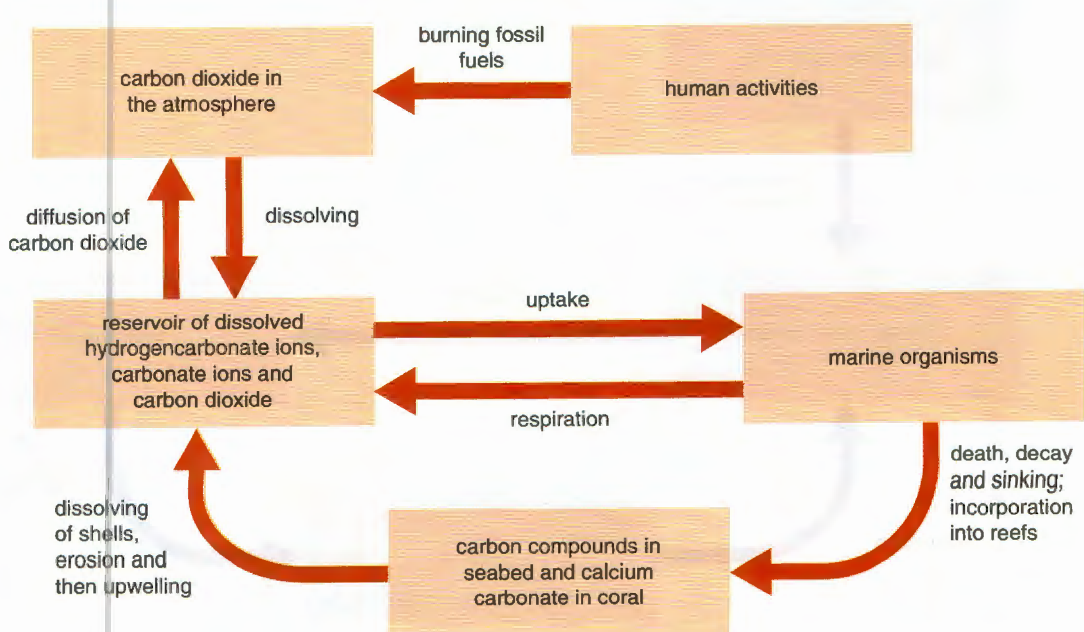


Figure 4.8. Summary of the main processes in the marine carbon cycle.

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 4.1

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. As 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 such as 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 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.

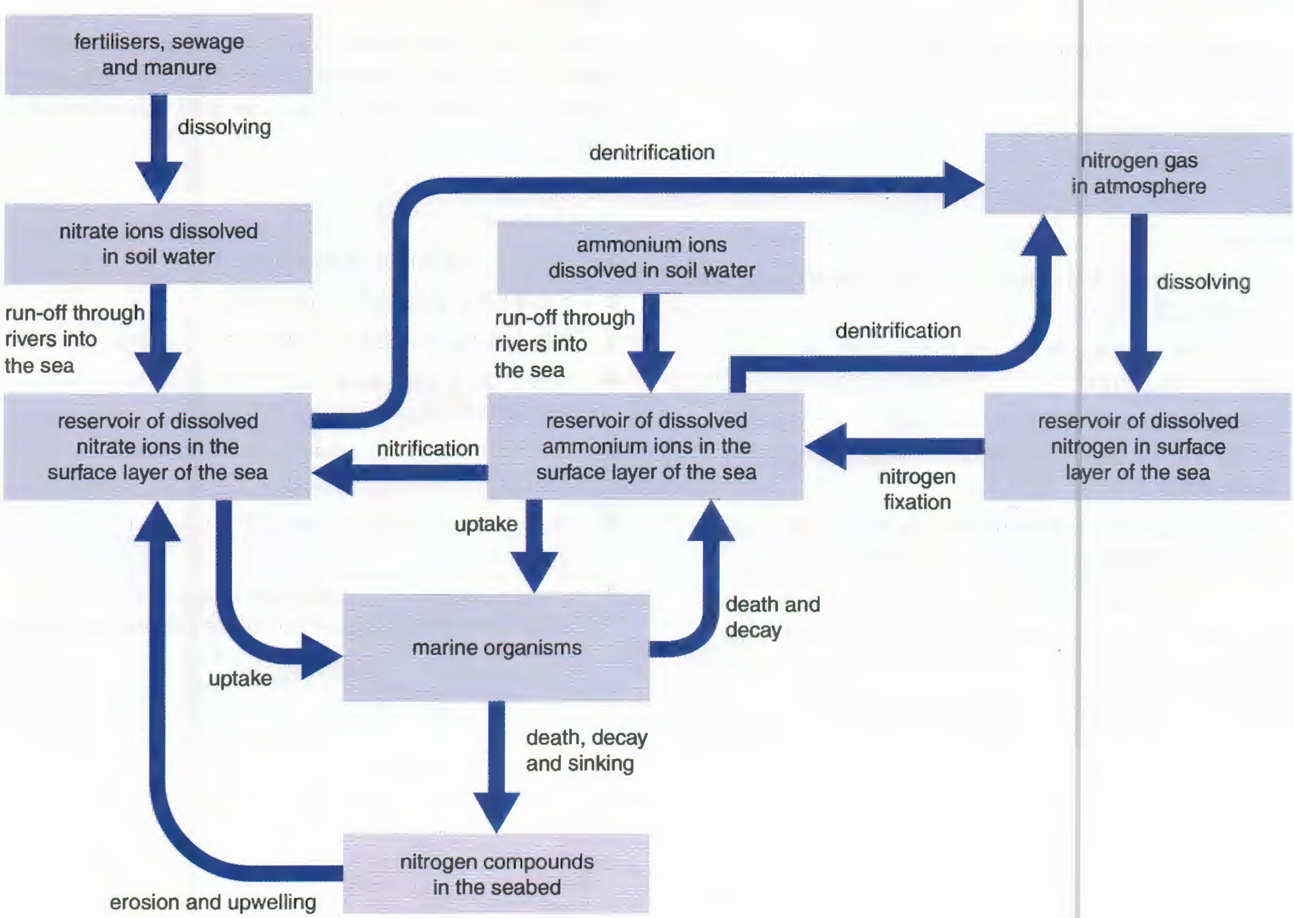


Figure 4.10. Summary of the main processes in the marine nitrogen cycle.

PRACTICAL ACTIVITY 4.2

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 before fish are introduced.

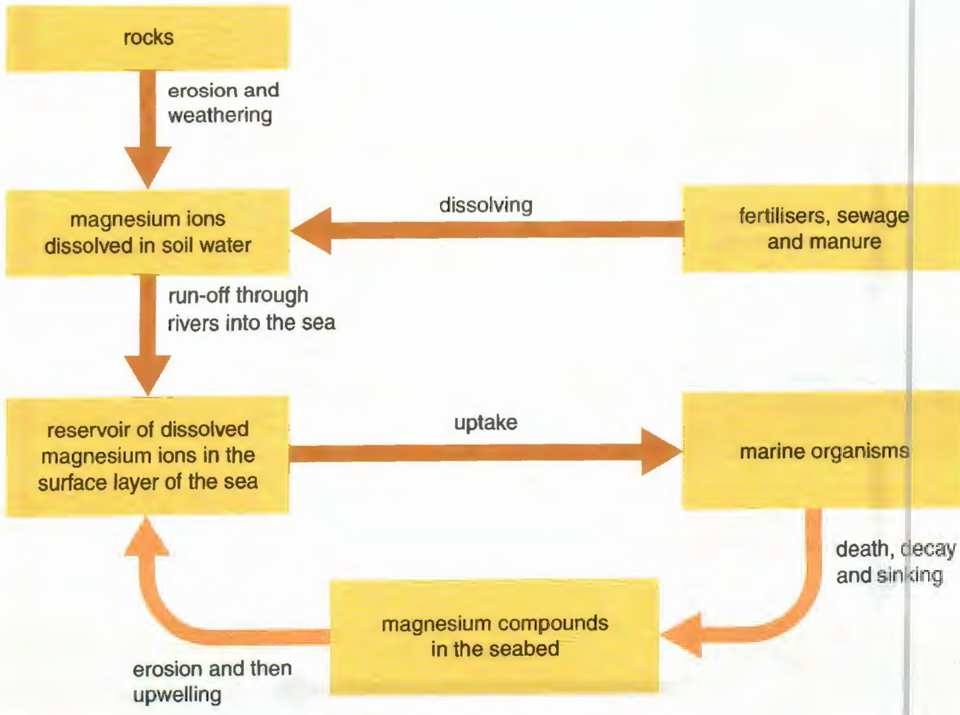


Figure 4.11. Summary of the main processes in the marine magnesium cycle.

The calcium cycle

Calcium is necessary to build healthy bones, coral and teeth 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 Dover in England are a famous example of chalk produced in this way from coccolithophores (Figure 4.14).

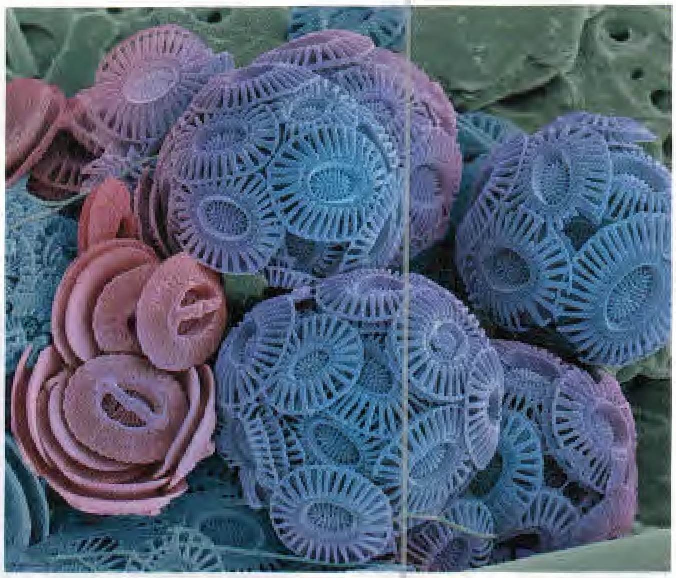


Figure 4.12. Magnified picture of a coccolithophore.

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 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.

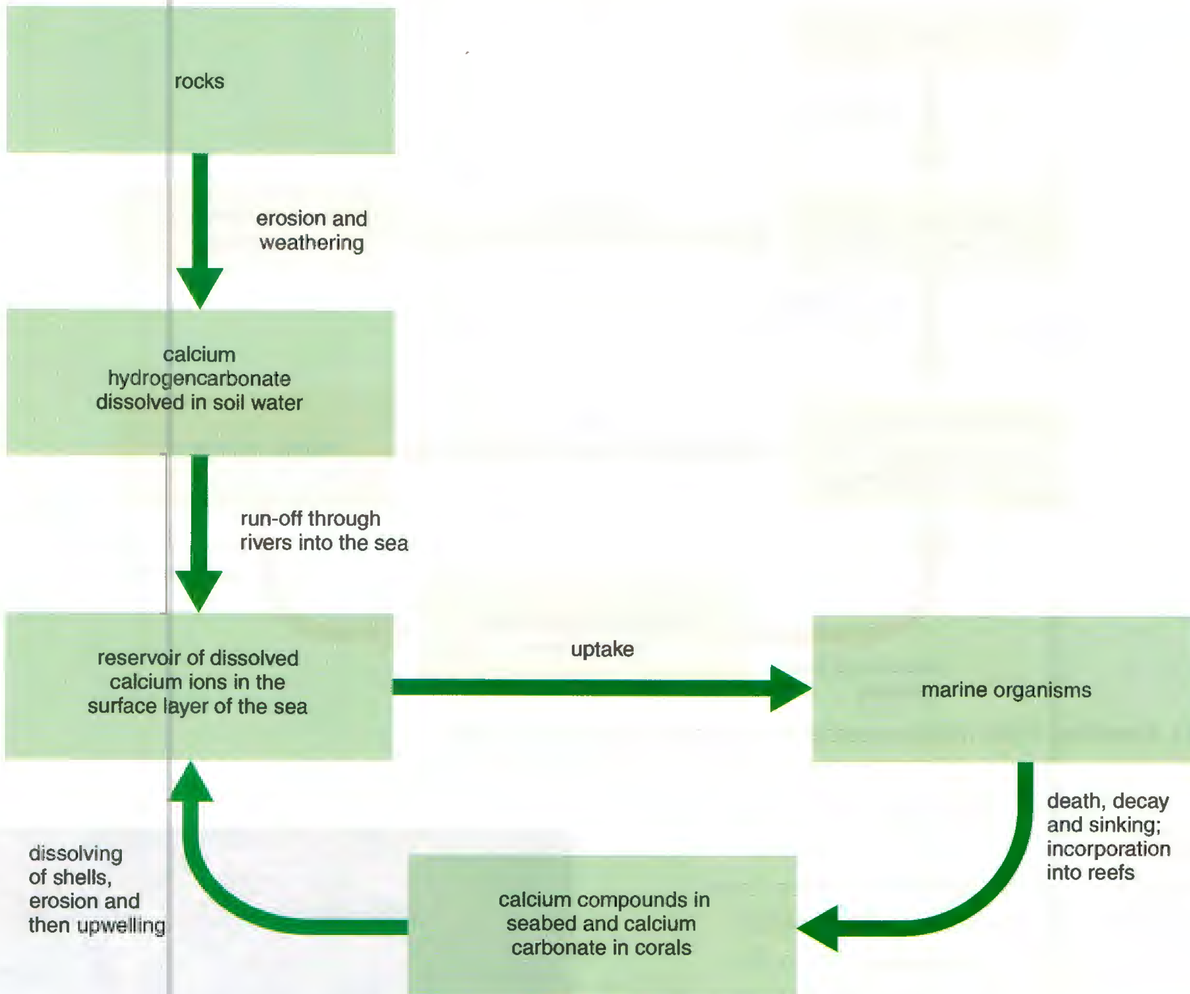


Figure 4.13. Summary of the main processes in the marine calcium cycle.

Figure 4.14. The white cliffs of Dover in England.

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.

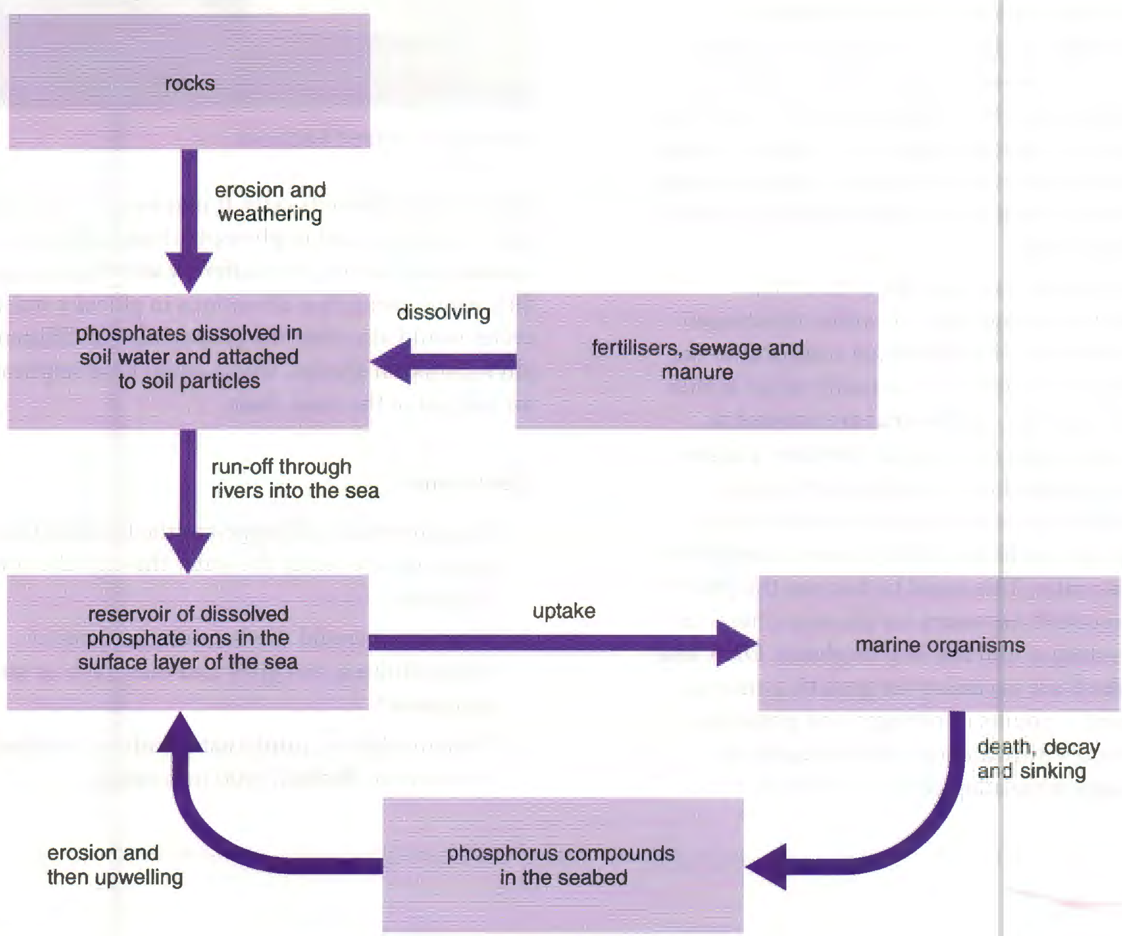


Figure 4.15. Summary of the main processes in the marine phosphorus cycle.

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

Figure 4.16. Alfred Redfield.

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.

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.

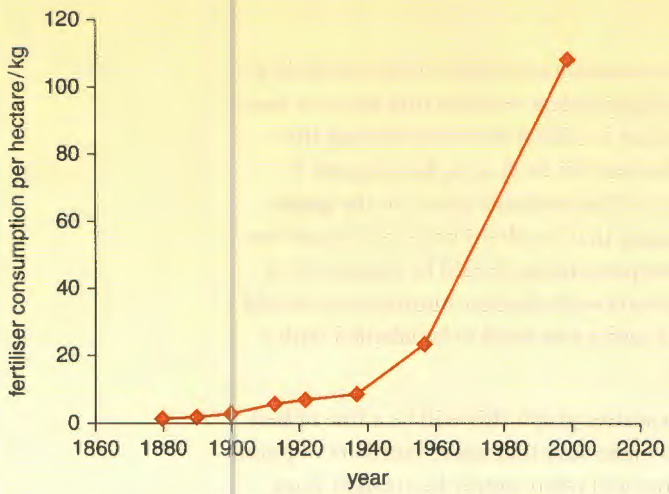


Figure 4.17. Fertiliser consumption in the USA from 1880 to 1999.

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.

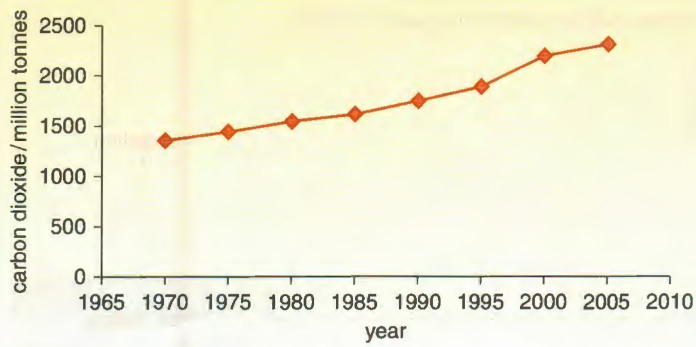


Figure 4.18. Changes in carbon dioxide concentration in America between 1970 and 2005.

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.

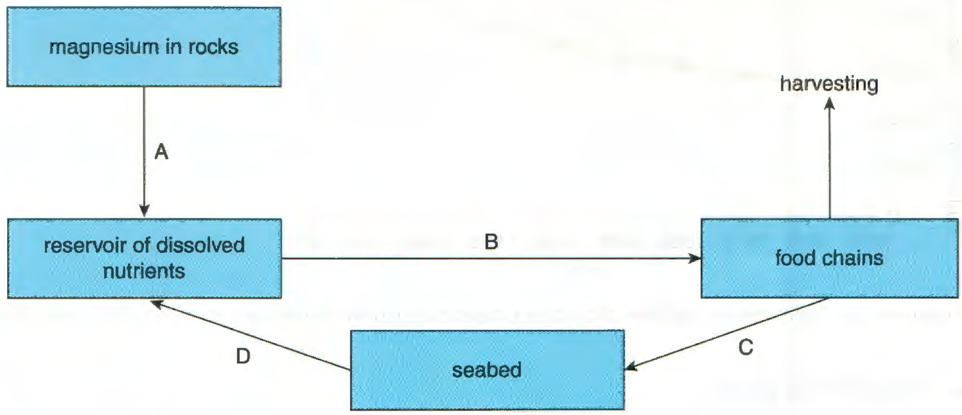


Figure 4.19. The marine magnesium cycle.

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.

→

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.

Figure 4.21. Spawning Pacific salmon moving upstream.

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.

Figure 4.22. Bear catching salmon.

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?

Chapter 5
Coral reefs and lagoons

Learning outcomes

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

- explain and provide evidence supporting the Darwin–Dana–Daly theory of atoll formation
- connect how coral grows and survives with the Darwin–Dana–Daly theory
- explain what can cause a change from reef growth to reef erosion
- explain how reefs can reduce the energy of waves and help protect shores and anchorages, and the negative effects of reef erosion
- discuss the effects of artificial reefs on shores and anchorages
- describe and differentiate between the methods used to discover the history of reefs and the effects of sea-level changes on reefs
- apply what you have learnt to new, unfamiliar contexts.

5.1 Coral seas

Clear, blue waters surround the world's 284 300 km^2 of coral reef ecosystems. Reef structures are, arguably, one of the greatest intersections between the physical structure of an environment and the organisms that live there. Just as in tropical rainforests, in coral reef communities the living organisms in the environment actually provide the structure necessary for the many microhabitats of the community to exist. These microhabitats provide homes to thousands of marine species. The species surviving on a coral reef, as well as the coral itself, create one of the most beautiful and biodiverse communities on our planet: a community that is reliant on the physiology of the coral animal for health and survival.

One of the most well-known coral reef systems is the Great Barrier Reef off the coast of Queensland, Australia. This reef system is home to over 2900 individual coral reefs housing more than 2000 species of animals, from corals to whales.

Unfortunately, this beautifully biodiverse community, like other coral reefs worldwide, is under attack.

Climate change, pollution and reef erosion are happening at rates that are dangerous for the world's coral reefs. Over 90% of the corals living on the Great Barrier Reef are suffering from a disease called **coral bleaching**. More than 20% of those corals affected have already died because of the loss of nutrients caused by the bleaching. Coral bleaching tends to happen in areas with rising water temperatures and increased levels of pollution. Recovering from the disease is possible but not easy. It is vital that we begin the process of cleaning up our oceans and reducing our ecological impact in order to give the coral communities their best chance at survival.

KEY TERM

Coral bleaching: the loss of symbiotic algae from the tissues of corals as a result of environmental factors

5.2 Coral physiology

All corals belong to a special phylum of organisms called cnidarians. Animals in this phylum are found in aquatic ecosystems, primarily marine, and all capture food using stinging cells called cnidocytes. The presence of these stinging cells in coral polyps indicates a close relationship with sea anemones and jellyfish.

Like anemones, corals live their entire adult life as polyps. Polyps are the sessile (non-moving) life stage of coral animals. Polyps tend to be simple in appearance, just a cylinder of epidermal tissue with tentacles surrounding a mouth. This mouth leads to a simple, sac-like stomach, or gastrovascular cavity, made of tissue designed to secrete enzymes for digestion. Polyps may live individually or in giant colonies capable of building reefs. There are two major categories of corals: those that build reefs, **hermatypic** corals, and those that do not build reefs, **ahermatypic** corals.

KEY TERMS

Ahermatypic: soft corals that do not build reefs

Hermatypic: hard corals capable of reef-building

Zooxanthellae: symbiotic, photosynthetic dinoflagellates living within the tissues of many invertebrates

Ahermatypic corals are routinely referred to as soft corals because they are flexible and do not create stony skeletons, using proteins for support instead. Soft corals resemble plants, trees or fans, and generally do not maintain a symbiotic relationship with **zooxanthellae**, photosynthetic dinoflagellates that can be found in the tissues of corals and many other marine invertebrates. Some examples of soft corals are sea whips, sea fans and gorgonians.

Hermatypic corals, or hard corals, are the reef-building group of corals. Within this group, the coral polyps always live in colonies and always include zooxanthellae (Figure 5.1). These colonies begin when a single planktonic coral larvae settles on a hard substrate. Once the larvae has attached, it goes through metamorphosis to become a coral polyp. If this original polyp survives and thrives, it will reproduce asexually through a process called budding. Budding happens when the initial polyp grows a clone of itself. As a result of this process, typically all polyps in a coral colony are genetically identical to the founder polyp. In order to cement themselves to the substrate, each polyp secretes calcium carbonate ($CaCO_3$) onto the substrate. When an older polyp dies, a new polyp will grow in its place, adding another layer of calcium carbonate to the structure. Eventually, this process creates a limestone skeleton that can form many different shapes and provides the framework of the coral reef. Because coral polyps are so tiny, it can take billions of polyps to form a reef.

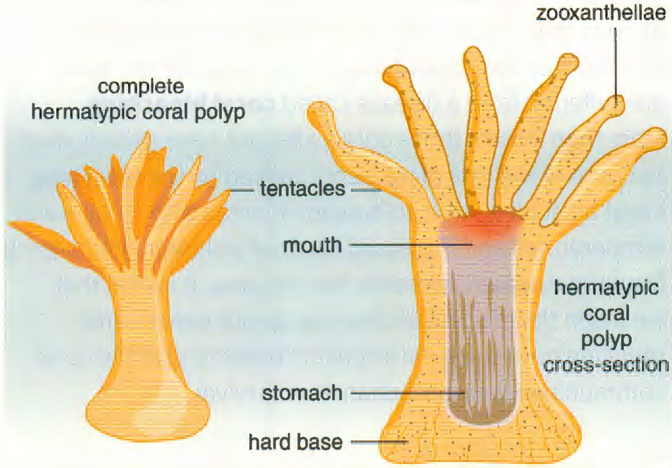


Figure 5.1. Hermatypic coral polyp with symbiotic zooxanthellae.

It is important to note that hermatypic corals would probably be unable to build reefs without the symbiotic relationship they maintain with zooxanthellae. Zooxanthellae are microscopic, single-celled dinoflagellates that live within the tissue of hard corals (Figure 5.1). Using the carbon provided by the coral host, zooxanthellae perform photosynthesis to generate organic material that can then be passed on to the coral. Without the extra nutrition provided by zooxanthellae, corals would be unable to secrete enough calcium carbonate to build the skeleton of the reef. The zooxanthellae provide enough food for the coral in clear, sunny waters so that often the coral can survive without eating. Coral are predators, however, even if zooxanthellae support them. Coral polyps use their tentacles filled with cnidocytes to prey on microscopic zooplankton floating in the water near them.

5.3 Physical factors necessary for coral growth

In 1842 Charles Darwin published a book called *Coral Reefs* based on his observations aboard the HMS *Beagle* between November 1835 and April 1836. This book would become central to the discussion of how coral reefs form and the environment necessary for their unimpeded growth. In the book, Darwin included a map of all the known coral reefs. This map showed where in the world coral reefs are most likely to be found: between 30° north and 30° south of the equator. It is interesting to note that, despite a lack of modern equipment, Darwin's map, and the observations that formed it, are still largely accurate today. Darwin also distinguished between three major types of reef (fringing, barrier and atoll) and how each is formed, which you will find out about in the following section.

Coral reefs are reliant on several physical factors for healthy growth and colonisation, particularly an appropriate temperature, water clarity and suitable depth. When mapping out coral reef distribution (Figure 5.2), scientists can hypothesise which reefs will have the highest growth rates by evaluating the presence, or lack, of these vital physical factors. As the combination of these factors is prevalent within an area referred to as the 'tropics', this is where coral reefs are most likely to be found.

The most important physical factor for corals is temperature. Hard corals are limited to waters with temperatures ranging between 16 °C and 35 °C (61–95 °F). Corals growing in water with temperatures at either end of this range tend to be less healthy and grow less quickly than those in water of the preferred range of 23–25 °C (73–77 °F). Because of the warm temperatures needed for successful coral growth, you would expect to find coral reefs located exclusively in the tropics between 30 °N and 30 °S of the equator. However, some areas outside this zone, such as Florida and southern Japan, are also able to support healthy coral reefs. This is because there are warm water currents flowing along the continental shelf in those areas.

A suitable depth of water is needed for healthy coral growth. While all corals grow in the subtidal zone, those present in areas within 20 m of the surface tend to have the fastest growth rate. Because of the symbiotic nature of coral's relationship with photosynthetic zooxanthellae, you do not find coral reefs in deeper water because there is insufficient light. Those corals that do not use zooxanthellae may be found in deeper waters with warm enough temperatures.

In order for zooxanthellae to photosynthesise efficiently, sunlight must be able to reach the coral polyps at sufficient levels. Therefore, water clarity is also vital to the health and growth of coral reefs. If the light is unable to reach the coral polyps, the zooxanthellae cannot produce the organic material necessary for the coral to build up the reef. This reduces overall growth and potentially stresses the coral, which is why clear water without silt or an excess of nutrients is needed for rapid coral growth. An abundance of nutrients may lead to an algal bloom that can cloud the surrounding water and reduce light penetration. An excess of small sediments, like silt, also causes turbidity, or cloudiness, within the water.

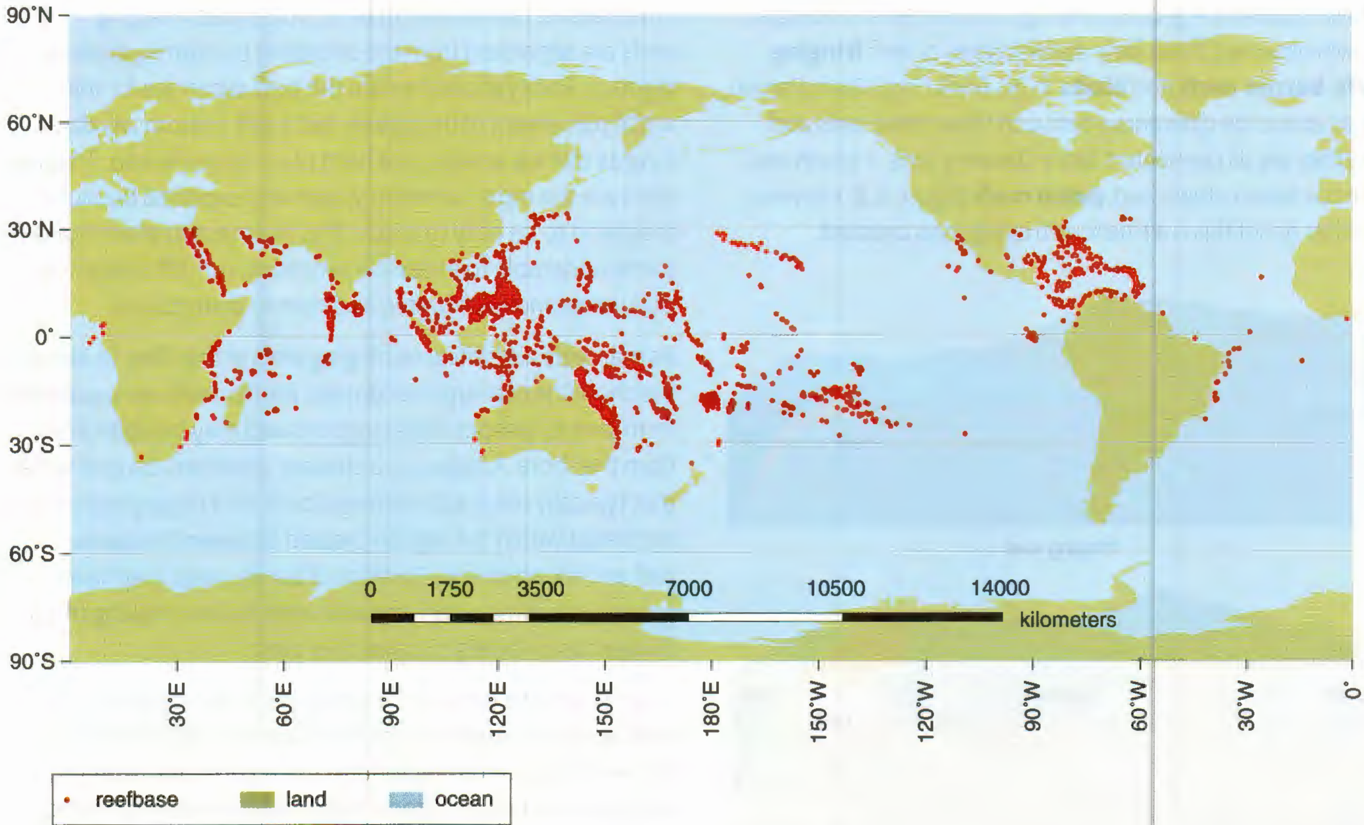


Figure 5.2. A map of the world's coral reefs.

Salinity and substrate are determining factors in the success of a coral reef. Corals must have an appropriate rocky surface for attachment. Coral larvae cannot attach to sand or other unstable materials, so the larvae tend to attach to denser materials. The basaltic rocks of undersea mountains and other hard surfaces along the continental shelf provide excellent attachment sites for the larvae. Corals are not adapted to freshwater or brackish conditions. For this reason, they do not do well near river mouths or other areas linked with fresh water or run-off flowing into the sea.

A final physical factor determining coral health is pH. Scientists use pH to determine how acidic or basic a substance is on a logarithmic scale of 0–14. Acidic substances have a pH below 7; neutral substances have a pH around 7; basic substances have a pH above 7. For healthy growth in coral reefs to occur, the ocean should be slightly basic, with a pH between 8.1 and 8.5. Waters with lower pH levels stress the corals and cause bleaching.

If a coral larva has found a location that meets all of these requirements, it will thrive and begin the process of reef-forming. Coral polyps will continue to add to existing coral skeletons, growing outwards for thousands of years. If the seabed subsides, or sinks, the coral polyps will tend to grow vertically to maintain the appropriate depth for photosynthesis. This will also occur if there is sea-level rise, as when polar ice caps melt adding water to the ocean.

SELF-ASSESSMENT QUESTIONS

1 Explain why coral reefs are most commonly found within 30 °N and 30 °S of the equator.

2 Suggest which physical factors are linked most closely with the symbiotic relationship coral has with zooxanthellae. Support your answer with evidence.

5.4 Types of reef

Geomorphology is a term used to describe the scientific study of landforms and the processes involved in creating those landforms. While aboard the HMS *Beagle*, Charles

KEY TERM

Geomorphology: the study of the characteristics, origin and development of landforms

Darwin studied the geomorphology of coral reefs. In doing so, Darwin observed three fairly distinct types of reef: **fringing reefs**, **barrier reefs** and **atolls**. In his book *Coral Reefs*, Darwin writes about the differences between these three reefs and how they are all connected. Since Darwin's time, a fourth reef type has been categorised: **patch reefs** (Figure 5.3). However, whether or not this is a true fourth category is debated.

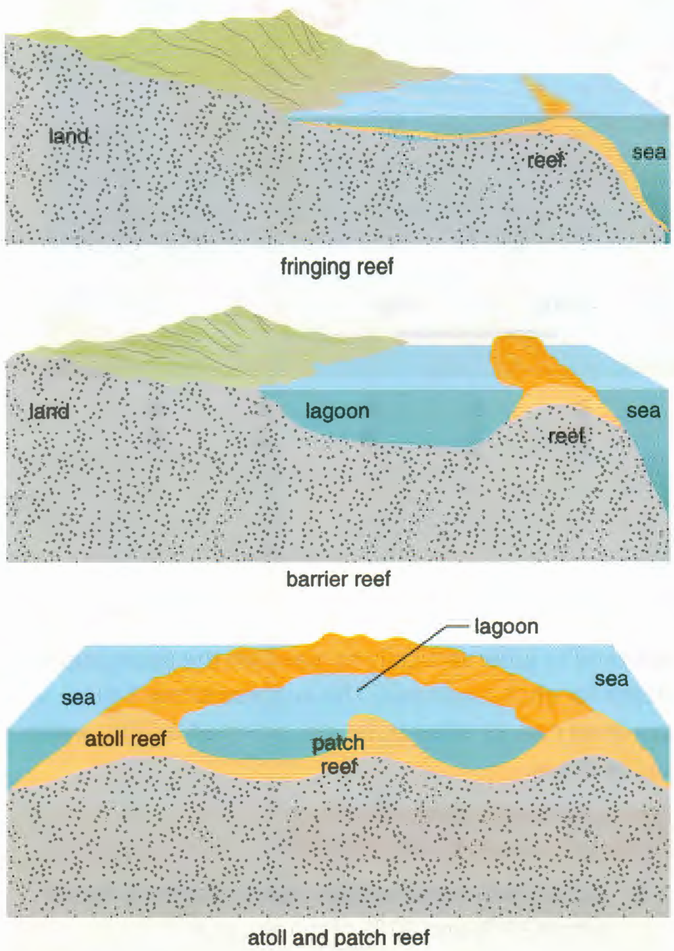


Figure 5.3. Different reef formations.

KEY TERMS

Fringing reef: a reef close to and surrounding newer volcanic islands or that borders continental landmasses

Barrier reef: a reef separated by a lagoon from the land mass with which it is associated

Atoll: a coral reef somewhat circular in shape with a central lagoon

Patch reef: small, isolated reef usually located within the lagoon of a barrier reef

Darwin hypothesised that all reefs begin as fringing reefs. Fringing reefs form along the edges of continental landmasses, islands and oceanic volcanoes. Fringing reefs are separated from the shoreline by narrow, shallow lagoons. Rocky shorelines are the best substrate for the initial placement of the larvae, but a soft bottom will do as long as there is at least one hard place to cement to. Fringing reefs are the most commonly seen and explored because they tend to be easy to reach. This nearness to shore makes them vulnerable to excessive sediment, run-off containing pollutants and fresh water, and human disturbance.

Barrier reefs are similar to fringing reefs in that they lie along the shoreline of a larger landmass. Barrier reefs are separated from land by deeper, wider lagoons and may be up to 97 km from the shore. A lagoon is a shallow, sheltered body of water that typically has a soft sediment bottom. Fringing reefs may even exist within the lagoon created between the barrier reef and the shoreline. Portions of barrier reefs may have grown so that the water above is very shallow, making them dangerous for boats to travel over them.

Typically found between fringing reefs and barrier reefs are patch reefs. Patch reefs are the smallest of the reef types and they tend to grow vertically from the continental shelf or lagoon floor as an isolated formation within the lagoons formed by barrier reefs. The size of patch reefs can vary based on age and location, but they rarely have the vertical height needed to reach the water's surface. It has been argued that patch reefs are actually just a formation within a barrier reef and should not be placed in a separate category.

The final category of reefs are atolls. An atoll is a coral reef that develops as a ring around a central lagoon. Atolls vary in size from 1 to 32 km in diameter. Most atolls can be found in the tropical Indian Ocean and the west and central Pacific Ocean; they are rare in Caribbean and Atlantic oceans. Atolls vary drastically from fringing and barrier reefs in their location. Typically, atolls are found kilometres from any visible land in incredibly deep water. This enormous distance provided a challenge to the scientists of Darwin's day. These scientists, including Darwin, wanted to be the first to determine how atolls formed.

Darwin–Dana–Daly theory of atoll formation

After much observation and consideration on his HMS *Beagle* voyage, Darwin was certain he had worked out how atolls were formed. According to Darwin, the type of reef seen was dependent on time. He described a fringing reef as the first, which would lead to a barrier reef and subsequently end up as an atoll. After Darwin released his hypothesis of atoll formation, it was supported and modified by two leading geologists of the day: James Daly and Reginald Dana.

The Darwin–Dana–Daly theory of atoll formation can be summarised as follows. Coral larvae begin to colonise the basaltic rocks along the coastline of a recently emerged oceanic volcano (sea mount). The corals continue to grow and colonise, creating a fringing reef around this island. The island then begins to erode at the top and sinks slowly beneath the sea. (It has since been discovered that tectonic activity is responsible for this sinking.) As the island sinks and erodes, a lagoon begins to form and grow between the reef and the island. Once the lagoon has grown sufficiently, the reef is classified as a barrier reef. This reef continues to grow around the area where the island had been, despite the continuous sinking of the island. Eventually, the island sinks entirely below the surface of the water, leaving behind a ring of coral, an atoll, with a relatively shallow lagoon in the centre (Figure 5.4).

This theory has since been supported by data from multiple sources. As an example, when scientists took drilling cores of the Bikini Atoll in the Pacific Ocean, the data showed that coral age increased with depth. Those corals located at the base of the atoll, nearly 1200 m deep, were 50 million-year-old fossilised coral species, while those at the surface were living modern species. After testing the substrate under the fossilised corals, scientists found volcanic rock, supporting the idea that the original corals settled along the edges of a recently emerged volcanic island. As these fossil corals, now located more than 1000 m below the surface, could only have grown in shallow waters, this provides even more evidence supporting the idea that the island sank over time.

SELF-ASSESSMENT QUESTIONS

3 Compare and contrast the three major types of reefs: fringing reefs, barrier reefs and atolls, paying particular attention to formation and age.

4 Summarise the evidence used to support the Darwin–Dana–Daly theory of atoll formation.

5.5 Reef erosion

A healthy coral reef in a location where all physical factors are being met can expect to accumulate between 3 and 15 m of calcium carbonate every 1000 years. The largest of the coral species are the slowest growing, often only adding between 5 and 25 mm of calcium carbonate a year. The faster growing corals, such as staghorn corals, can add as much as 20 cm to their branches per year. According to current geological estimates, most modern coral reef systems are between 5000 and 10 000 years old. This slow growth rate of healthy corals is one reason why **reef erosion** can be so detrimental.

When a coral reef begins to lose more calcium carbonate each year than it accumulates, it is undergoing reef erosion. There are many causes of reef erosion, both biological and

KEY TERM

Reef erosion: the gradual wearing away of a coral reef by the action of living organisms (bioerosion) and physical factors, such as storms

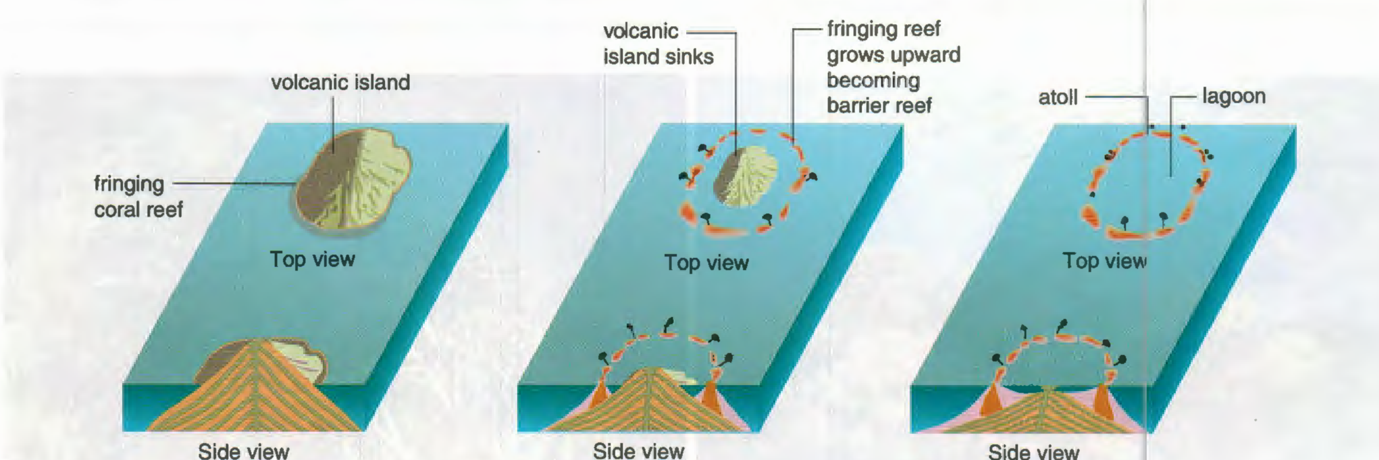


Figure 5.4. An aerial and side view of atoll formation.

physical. Biological causes of reef erosion, often referred to as bioerosion, include the predation of coral by organisms such as the parrotfish, butterflyfish and the crown-of-thorns starfish. Physical causes of reef erosion include storms, exposure to air and ocean acidification.

Both parrotfish and butterfly fish are avid predators of coral polyps among coral reefs. Butterfly fish tend to be specialists, eating only a few particular species of polyps. Parrotfish, on the other hand, are grazers that eat coral polyps in order to get to the algae living within them. Parrotfish will use their beak-like teeth to bite off portions of rock or coral reef, which they swallow whole. Their bodies then digest all of the organic material (i.e. the algae) located within the coral polyps and release the indigestible calcium carbonate as faeces. This process leads to an overall loss of calcium carbonate present on the reef, causing reef erosion.

The crown-of-thorns starfish (*Acanthaster planci*) has been a serious threat to corals in the Indo-Pacific region for the last 50 years. These coral predators have seen multiple population booms and are considered to be the greatest cause of coral mortality on the Great Barrier Reef. There are several hypotheses about what causes an outbreak of crown-of-thorns starfish, but the most likely is nutrient-rich run-off as a result of the overuse of fertilisers combined with the removal of predators. These nutrients, primarily nitrogen and phosphorus, tend to cause plankton blooms where crown-of-thorns starfish larvae thrive. Without predatory fish to control the population of larvae, the larvae metamorphose into adult starfish and devour the reef.

Physical damage to reefs during low tide can also be extensive. Because corals need to be in subtidal regions, any exposure to air can be dangerous. During spring tides, the lowest of the tides can leave coral reefs exposed to the air, causing the corals to desiccate or overheat. When the coral polyps die, they may be replaced with algae or slowly eroded.

Storms are another major source of reef erosion. The turbulence caused by hurricanes, typhoons and tropical storms can be extensive. Typically, the damage is caused by breakage of the coral itself or a scouring of the coral by abrasive sediments that are being swirled through the normally calm waters. Evidence of the damage to the Great Barrier Reef caused during cyclone Ita is shown in Figure 5.5.

Corals can generally recover from hurricane damage but the time the recovery takes is influenced by several factors, including:

- the amount of coral rubble remaining after the storm
- the sediment stirred up by turbulence
- the growth of algae competing for attachment surfaces within the reef
- run-off, which may bring toxins, lower the salinity of the water and increase nutrients, encouraging an algal bloom.

For example, Hurricane Hattie destroyed a 43 km stretch of barrier reef off the coast of British Honduras in 1961. At the time it was estimated that 80% of the Belize Barrier Reef was damaged by this storm. While the reef has since recovered, scientists at the time believed it would take between 25 and 100 years for the ecosystem to repair itself.

Over the last 300 million years the pH of the world's oceans has been slightly basic, at an average pH of 8.2. However, within the last 200 years, since the Industrial Revolution, it has dropped to 8.1. This drop seems tiny, but the pH scale is logarithmic, so a 0.1 drop represents a 25% increase in acidity. This process is called **ocean acidification**. The gases in our atmosphere (especially carbon dioxide) dissolve at the ocean surface (see Chapter 7). This creates higher levels of carbonic acid (H_2CO_3), lowering the overall pH of the

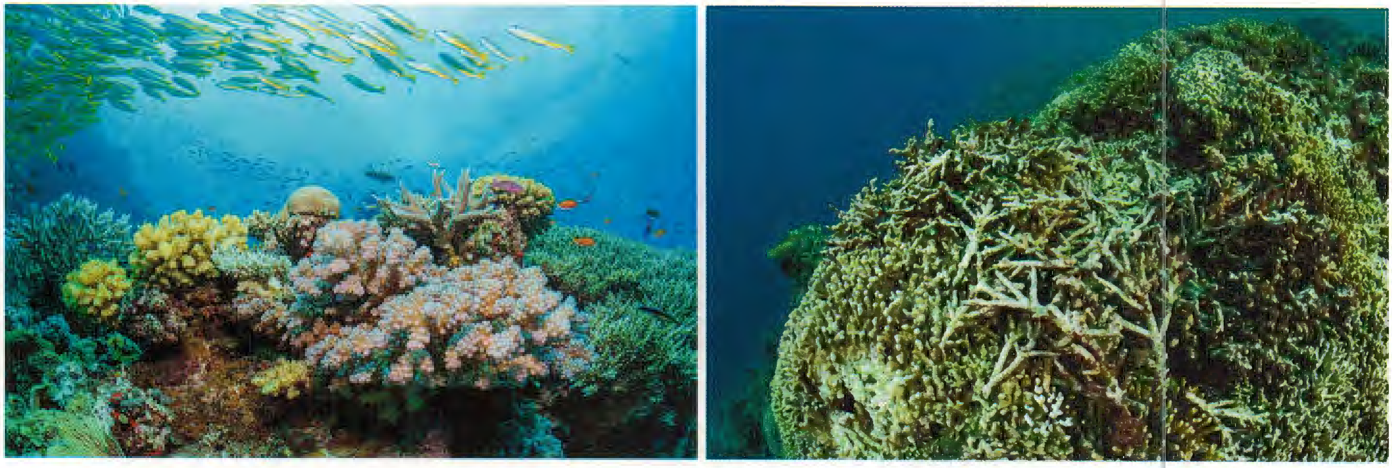


Figure 5.5. A portion of the Great Barrier Reef before and after the category five tropical cyclone Ita passed through in 2014.

ocean. This acidity is having an abnormally large impact on coral reefs that use calcium carbonate in the manufacture of their skeletons. Ocean acidification prevents corals from absorbing all of the calcium carbonate they need to build their skeletal structures. This can lead to the skeletons themselves dissolving in the more acidic water.

KEY TERM

Ocean acidification: a reduction in the pH of the ocean over an extended period time, caused primarily by uptake of carbon dioxide from the atmosphere

CASE STUDY

Reef destruction through human interference

While most reef erosion happens naturally through bioerosion and physical factors such as storms, quite a bit is also caused by human interference. Human interference can take many forms. Fishing, tourism and coral harvesting are probably the most well-known causes of destruction of coral reefs worldwide.

Fishing near a coral reef makes sense economically considering the vast biodiversity of a healthy reef system. However, this can pose several problems. If the fishermen are not careful, they can easily anchor their boats on a portion of the reef or run their boat over the top of the shallower portions of the reef. This also applies to boats chartered for tourists and cruise liners. For example, a single cruise ship destroyed 3150 km^2 of reef in Fiji in 2006.

Additionally, fishing methods and practices, such as dynamite and cyanide, can be especially dangerous for coral reefs. These methods are used to stun fish so that they are easy to catch at the surface in handheld nets (Figure 5.6). The blast of the dynamite will explode portions of the reef, causing permanent damage. Cyanide fishing is only meant to stun larger fish for easier catching, but actually kills smaller organisms like coral polyps. Over-fishing of large predatory fish on the reef has also led to an average decrease in fish size on most of the world's reefs and large-scale ecosystem change on some reefs. When the larger predatory fish or herbivorous fish are removed from the coral reef system, there is nothing to keep algae or coral predators, like crown-of-thorns starfish, from overtaking the reef.

Figure 5.6. A young man dynamite fishing in the Philippines.

The harvesting of coral is one human interference that is not accidental. Many uninformed tourists break off pieces of the reef to take home as souvenirs, but damage is also often caused by local businesses. Black coral can be polished and is sold as jewellery in many parts of the world. Other pieces of coral are dried out and sold to people as decorative items for their homes. On a large-scale, this harvesting causes a lot of damage to reefs over time.

Questions

1 Using your knowledge of average coral growth, describe the damage the cruise ship mentioned previously caused in ecological terms.

2 Suggest a possible reason why over-fishing can lead to erosion on coral reefs.

3 With specific reference to hermatypic and ahermatypic corals, explain which type you think is most commonly harvested and why.

Coral bleaching and climate change

The term **climate change** refers to changes in global or regional climate patterns and more specifically to the changes that have been seen since the late 20th century. Many studies have found a correlation between the rate of climate change and rising levels of carbon dioxide in our atmosphere as a result of fossil fuel use. Climate change has two primary impacts on ocean ecosystems: a rise in sea surface temperatures and a lowering of pH levels.

KEY TERM

Climate change: changes in global or regional climate patterns, especially changes that have been seen since the late 20th century

Coral bleaching occurs when hard corals become stressed by environmental factors, particularly rising water temperature and acidity. This stress causes the coral polyps to reject their symbiotic zooxanthellae. Because the zooxanthellae contain all the pigments that give the coral polyps their colour, the bright white calcium carbonate skeleton of the reef becomes visible (Figure 5.7). This change from yellows and browns to white is called bleaching. While bleached, corals are not adding to their calcium carbonate skeletons, so reef growth stops. If the bleaching event lasts too long the corals will die as a result of lack of nutrients and poor conditions. There have been multiple mass bleaching events around the world since the mid-1990s.

Figure 5.7. A healthy coral and a bleached coral in the Florida Keys.

Impacts of reef erosion and artificial reefs

While many people see coral reefs as beneficial only in terms of biodiversity in the ocean, they are also of benefit to onshore habitats. Coral reefs absorb on average 97% of the energy of waves coming into shore. Wave height is also reduced, on average by 84%. These reductions in wave energy and height have important implications for the shoreline. By reducing the oncoming wave energy, coral reefs are able to protect the shoreline from erosion caused by strong waves. Preventing erosion of the shoreline and reducing wave height helps to protect anything on the shore from being damaged during storms and being lost to the sea as a result of erosion. Those ecosystems that exist along the shoreline, for example mangroves, also benefit from reduced wave action and serve as nurseries for marine organisms.

Healthy coral reefs also help protect boats and **anchorages**. Many coastal communities provide breakwaters to create anchorages, areas where people anchor their boats. These breakwaters can be expensive. However, where there is a healthy coral reef, the reduced wave action means there is less need for a breakwater, reducing the cost to the community. Additionally, the anchorage itself is safer for boats because the coral reduces turbulence in the area, calming the waters. The reduction in erosion and cost of breakwaters means areas with healthy coral reefs have a significant economic advantage over those areas without.

Those areas with coral reefs suffering from reef erosion are therefore at an economic disadvantage. Coastal properties and shores are at a greater risk of exposure to the damaging effects of waves, particularly during tropical cyclones. The loss of shoreline and greater damage by storm surges can cost human communities millions of dollars to repair. This is why many communities are creating **artificial reefs**. In addition to increasing biodiversity and ecological stability, artificial reefs provide many of the other benefits of healthy coral reefs. Artificial reefs help reduce wave energy and height, behaving as a submerged breakwater. This protects anchorages and boats from damage, and shorelines from erosion.

Artificial reefs are human-made structures designed to recreate a coral ecosystem. Typically these reefs are placed in areas that do not have an appropriate substrate for larval attachment. Many different materials have been used to create artificial reefs, including specially designed non-toxic concrete, sacks filled with sand, stone blocks and even sunken ships. Figure 5.8 illustrates one type of artificial reef: the reef ball. The USS *Oriskany*, a retired aircraft carrier, was sunk off the Panhandle of Florida with the intention of creating an artificial reef in 2006. The ship was overhauled to ensure no toxins (for example paints or oils) would seep from it into the marine environment. Since its sinking, the *Oriskany* has become a popular diving location to see reef fish.

KEY TERMS

Anchorage: [boats] the portion of a harbour or estuary used for ships to anchor; [organisms] location on a substrate where a sessile organism attaches and lives

Artificial reef: an artificial underwater structure built to mimic the characteristics of a natural reef

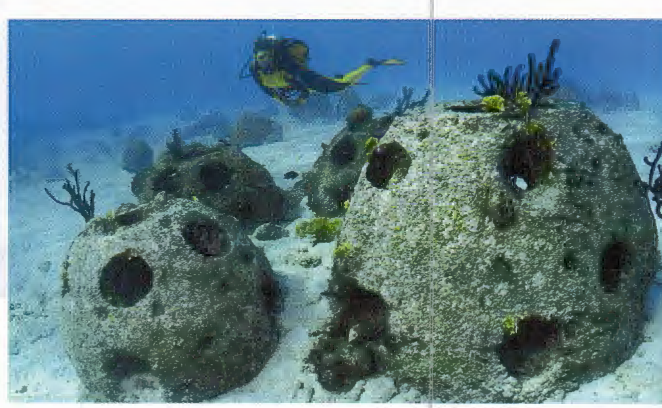


Figure 5.8. Commercially available artificial reef balls.

Artificial reefs provide a physical structure for coral, sponges and algae to colonise. Once these sessile animals have become attached and begun to colonise, many different species of fish are attracted to the area. After several years, it should be impossible to tell that the reef was once an artificial construct, it will so closely resemble a genuine coral reef. At the Cancun Underwater Museum in Mexico, British artist Jason de Caires Taylor has created an art installation with more than 400 sculptures of humans designed to become artificial reefs. Even as these artificial reef sculptures are colonised, they may retain some of their original identity.

PRACTICAL ACTIVITY 5.1

The effect of acidity on calcium carbonate

Apparatus

- 12 small limestone rocks per group
- 3 × 500 cm^3 beakers
- pH paper or other pH testing device
- Water, preferably distilled water
- Acetic acid (vinegar)
- Sodium hydrogencarbonate (baking soda)
- Scale

Method

- Rinse all the rocks until all dust is removed. Allow to dry.
- Place 240 cm^3 of vinegar in one 500 cm^3 beaker.
- Test the acidity of the solution using pH paper. Record the acidity level.
- Add water to the vinegar until the pH is between 4 and 5.
- Place 240 cm^3 of vinegar in a second 500 cm^3 beaker.
- Add small amounts of sodium hydrogencarbonate until the pH is between 8 and 9.
- Place 400 cm^3 of water in the third 500 cm^3 beaker.
- Divide the dried limestone rocks into three groups.
- Weigh the total mass of each group and record the results.
- Place one group of weighed rocks into each beaker.
- Leave the mixtures overnight.
- After 24 h, remove the rocks from each solution, rinse and dry them but keep the three groups separated. Weigh each group again.

Results and analysis

Copy Table 5.1 and enter your data. Calculate the percentage difference between the initial mass and the second mass for each group of rocks.

$$\frac{\text{final} - \text{initial}}{\text{initial}} \times 100 = \text{percent difference}$$

Generate an appropriate graph of the results. Decide whether you should have a bar graph or a line graph.

Conclusions

1 What is the independent variable in this study? What is the dependent variable?

2 Is there a control present? If so, which mixture represents the control?

3 Compare your data with other people's data. Are there similarities or trends in the data? What are they?

4 How does this information relate to coral reefs?

mixture	pH	initial mass / g	mass after 24 h / g	% difference
water				
vinegar				
sodium hydrogencarbonate				

Table 5.1. Results table for effect of pH on calcium carbonate.

5.6 Reconstructing the history of coral reefs

Using what we now know about the geomorphology of coral reef structures, scientists are able to determine a reef's age and history with modern techniques. Of primary interest to these scientists are changes in species composition and growth patterns of the reef. The evidence gained from these techniques helps us understand the Earth's geological and climatological history in order to better predict the results of modern-day climate change through modelling.

Deep drilling of coral reefs is designed to provide cylindrical cores of calcium carbonate and biological material. Scientists use specialised equipment to drill into the cores and remove long cylinders of the coral skeleton intact (Figure 5.9), making these cores an excellent timeline of coral growth. The cores are analysed to determine the history of species that existed on a reef and estimate

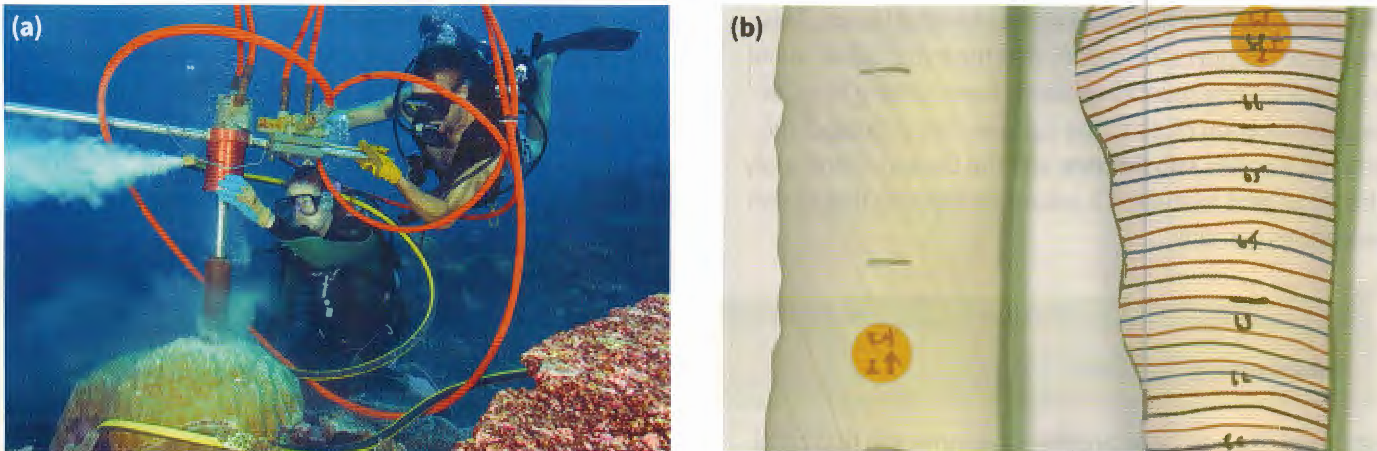


Figure 5.9. (a) Coral scientists use a pneumatic drill to remove a cylinder of past coral; (b) a drawing of a core sample labelled to show the horizontal growth lines.

the reef's approximate growth rate. Like a tree, corals continually grow outwards, so when a core of a coral reef is taken, scientists can see 'bands' of growth: layers of calcium carbonate laid down by the different generations of polyps through time. The width of these bands is dependent on water temperature, nutrient availability and other environmental conditions. Using information from deep drilling, scientists can generate hypotheses and correlations relating growth and environmental conditions of the past.

KEY TERM

Radiocarbon dating: a process used to estimate the age of organic material by measuring the radioactivity of its carbon content (also called carbon dating)

Radiocarbon dating, also referred to as carbon dating or carbon-14 dating, is another method used to analyse the history of coral reefs. Carbon dating determines the age of organic materials by comparing the proportions of the radioactive isotope of carbon (^{14}C) with the non-radioactive form of the carbon element (^{12}C). The technique relies on biomass being passed through food webs.

Radiocarbon (^{14}C) is being continuously created within our atmosphere when ultraviolet (UV) rays interact with atmospheric nitrogen. Once created, the ^{14}C joins with oxygen to create a radioactive form of carbon dioxide capable of diffusing into the ocean. When producers (for example zooxanthellae) photosynthesise, they take up carbon from the surrounding environment, including the radioactive carbon. After photosynthesis, the zooxanthellae pass the newly made organic materials containing ^{14}C to the coral host. The coral polyps can then use this ^{14}C to create calcium carbonate in order to build their skeleton framework. Once the carbon has been deposited, it begins to go through radioactive decay, reducing the amount of ^{14}C present in the sample. The half-life of ^{14}C is 5730 years, which means that every 5730 years half of the ^{14}C in the sample will have decayed. Using this information, it has been determined that carbon dating can be successfully used on samples 50 000 years old or younger (Figure 5.10).

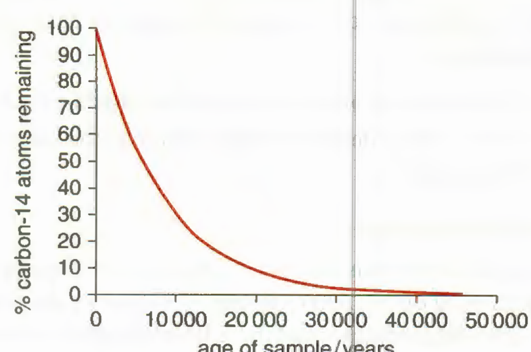


Figure 5.10. Graph of the decay of carbon-14.

Carbon dating allows coral scientists to judge accurately the age of a particular reef or place on a reef. Because the growth of coral is particularly dependent on the availability of light for rapid growth, scientists know that most hard corals prefer to be within 20 m of the ocean surface. However, in places like Bikini Atoll, fossil corals have been found in waters more than 1200 m deep. Using carbon dating and deep drilling, scientists have been able to show that the coral polyps grow slowly in layer after layer on top of older pieces of the reef, continuously growing vertically over the course of hundreds of thousands of years. This evidence supports the theory that the initial substrate of the coral colony must have slowly been sinking from its original location close to the surface. This sinking of the seabed is called **subsidence** and the Darwin–Dana–Daly theory of atoll formation is reliant on the idea that ocean volcanoes can sink.

KEY TERM

Subsidence: sinking of land

Sea-level rise and fall is another phenomenon that coral reefs have to survive. During interglacial periods, when the ice caps are melting, sea-levels tend to be higher than during ice ages. This is because, during an ice age, the cold weather freezes the ocean water, locking it in ice and reducing the overall depth of the ocean. When sea-levels are high, coral reefs must grow vertically to remain within 20 m of the surface for the best light. When sea-levels drop, however, the coral reef is exposed to air and dies. The best evidence of these changes in sea-level is present in fossilised corals that occur above sea-level. Several fossilised corals have been examined recently in Mexico. Scientists were able to correlate the growth and death of these corals with the sea-level changes between ice ages.

SELF-ASSESSMENT QUESTIONS

5 Describe the major factors leading to reef erosion.

6 Explain the role of artificial reefs in the preservation of shorelines.

7 Suggest a reason why surfers at popular surfing locations may protest against the installation of an artificial reef designed to protect the shoreline.

8 How are modern scientists using carbon dating and deep drilling to support early theories like the Darwin–Dana–Daly theory of atoll formation?

Maths skills

Radiocarbon dating

As discussed in this chapter, scientists routinely use carbon dating to determine the age of coral reefs and other organic materials. This information can then be analysed to estimate changes in sea-level or subsidence of the seabed. In order to begin this process, scientists need a few key pieces of information:

- ^{14}C decays at a constant rate once the organism has died
- ^{14}C has a half-life of 5730 years, meaning that for every 5730 years, half of the remaining sample of ^{14}C has decayed.

Worked example

If a coral sample has 100 g of ^{14}C when the organism dies, then after 5730 years the sample will only contain 50 g of ^{14}C. After another 5730 years pass, there will only be 25 g of ^{14}C remaining. This pattern will continue until there is only a tiny amount of ^{14}C remaining in the sample. So, using N_0 to represent the original amount of ^{14}C within a sample, you can determine the amount left after multiple half-lives have passed.

To determine one half-life: $\frac{1}{2} \times N_0 = \frac{N_0}{2}$

Assuming 5000 g for N_0, that means: $\frac{1}{2} \times 5000 = \frac{5000}{2} = 2500\,g$

To determine two half-lives: $\frac{1}{2} \times \frac{1}{2} \times N_0 = \left(\frac{1}{2}\right)^2 \times N_0 = \frac{N_0}{4}$

Assuming 5000 g for N_0, that means: $\frac{1}{2} \times \frac{1}{2} \times 5000 = \left(\frac{1}{2}\right)^2 \times 5000 = \frac{5000}{4} = 1250\,g$

half-lives that have passed	years from present	percentage of original ^{14}C remaining	amount of original ^{14}C remaining / g
0	0	100	5000
1	5730	50	2500
2		25	1250
3			
4			
5			
6			

Table 5.2. Half-life of ^{14}C.

Questions

1 Using the information, complete Table 5.2.

2 Generate a line graph with an appropriate scale showing the relationship between 'years from present' and 'percentage of original ^{14}C remaining'. Make sure to place your data on the appropriate axes.

3 As a coral scientist, you have recently been sent a core sample from the Great Barrier Reef in Australia. Comparing the oldest portion of the coral sample with the newest, you discover that the oldest pieces of coral contain only 60% of the ^{14}C contained in the modern sample. Using that information, estimate how old this portion of the reef is and discuss your reasoning.

Summary

- The coral animal is unique in its ability to create colonies that span thousands of years and generations, and create geological structures inhabited by thousands of other organisms.
- These structures can take the form of a fringing reef, barrier reef or atoll.
- Regardless of type, coral reefs increase the biodiversity on our planet and health of our oceans.
- Coral reefs provide many benefits to our coastlines, which are easily disturbed when the reef begins to suffer from erosion.
- Using technology, scientists are now able to study coral reefs as historical records of climate change and sea-level rise.
- These characteristics make coral reef ecosystems vital to our planet's future.

Exam-style questions

1 a Describe each of the following reef types:

i Fringing reef **[2]**

ii Barrier reef **[2]**

iii Atoll **[2]**

b Outline the Darwin–Dana–Daly theory of atoll formation. **[4]**

[Total mark: 10]

2 a List and describe three reasons why artificial reefs are beneficial to shorelines. **[6]**

b In order to determine the best placement for artificial reefs, developers must take certain physical factors into consideration. Explain which factors are most important when determining placement of a coral reef for healthy growth. **[6]**

c Most artificial reefs are now constructed from a pH neutral cement material. Explain why scientists prefer this material to old truck tyres, abandoned planes and ships. **[4]**

[Total mark: 16]

3 A survey was taken in 2000 of the percentage of coral cover in the Florida Keys of Islamorada and Key West. Another survey was taken in 2005 to determine coral cover after the 2004 hurricane season, and again in 2010. The results of these studies are shown in Table 5.3.

year	percentage cover of corals	
	Islamorada	Key West
2000	62	60
2005	43	35
2010	57	42

Table 5.3. Percentage of coral cover in the Florida Keys of Islamorada and Key West.

a Using the data in Table 5.3, compare the coral cover of both locations between 2000 and 2010. **[2]**

b Calculate the percentage increase in coral coverage between 2005 and 2010. Show your working. **[2]**

c Suggest two reasons why the corals in Key West are not recovering as quickly as those in Islamorada. **[2]**

[Total mark: 6]

4 **a** Describe the relationships shared by the following pairs of organisms:

i Coral polyps and zooxanthellae. **[2]**

ii Butterflyfish and coral polyps **[2]**

b Explain how parrotfish lead to reef erosion. **[3]**

[Total mark: 7]

5 **a** Describe how increased carbon dioxide in our atmosphere is related to ocean acidification. **[3]**

b Explain how limiting nutrients, such as nitrogen and phosphorus, can have both *positive* and *negative* impacts on coral growth. **[4]**

c Suggest one reason why coral reefs are not usually found in upwelling areas. **[1]**

[Total mark: 8]

EXTENDED CASE STUDY

Crown-of-thorns starfish on Indo-Pacific reefs

The crown-of-thorns starfish (*Acanthaster planci*) is a naturally occurring venomous predator found on coral reefs in the Indo-Pacific Ocean. This predator is an important part of the food web on these reefs. On healthy reefs, it tends to feed on only the fastest growing corals, such as staghorn and plate corals. It may seem that any coral predation is negative, but by feeding on these fast-growing corals, the crown-of-thorns starfish provides a mechanism for the slower growing coral species to develop into well-established colonies. This increases the coral biodiversity on the reef, which in turn provides more niches for other organisms to occupy, increasing the overall biodiversity of a reef.

However, the crown-of-thorns starfish has got a bad reputation as a destroyer of reefs because of several 'outbreaks' that have occurred in the last 50 years. Not everyone agrees on how to define an 'outbreak' of crown-of-thorns starfish. Although, one easy-to-use definition comes from the Great Barrier Reef Marine Park Authority. According to them, when there is a high level of coral cover, 'an outbreak is considered to have occurred when there is roughly more than 15 starfish per hectare'. Outbreaks of crown-of-thorns starfish have been cited as one of the most significant threats to the Great Barrier Reef. An outbreak may last over a decade as the crown-of-thorns starfish spread along the reef southwards.

Causes of outbreaks

Many studies have been conducted to determine what causes these outbreaks and it seems that multiple factors are involved before an outbreak occurs. Large female crown-of-thorns starfish are capable of producing up to 65 million eggs during the spawning season, but this is not unusual for invertebrates. Therefore, other causes must have a role in an outbreak. Initially, there needs to be an overall increase in certain limiting nutrients, particularly nitrogen and phosphorus, in the ecosystem. Generally, an increase in these nutrients is seen when fertiliser used on land is washed into the sea as run-off. When these nutrient levels are high, phytoplankton blooms provide more food for crown-of-thorns starfish larvae. As more larvae are well-sustained in this juvenile stage, an unusual number of larvae settle and metamorphose to become adult crown-of-thorns starfish.

However, as larvae and adults, crown-of-thorns starfish have natural predators. So, a second factor that must come into play for an outbreak to occur is a reduction in crown-of-thorns starfish predators. Not much is known about the larval predators, although many scientists hypothesise that corals themselves are the best predators of larval crown-of-thorns starfish. Adults are preyed on by giant triton snails (Figure 5.11), humphead Maori wrasse, starry pufferfish and titan triggerfish. When these animals are over-fished for either food or aquaria, then the reef can easily become overwhelmed by too many starfish.

Figure 5.11. A giant triton snail attacks while a crown-of-thorns starfish tries to dine on a piece of the coral reef.

On the Great Barrier Reef, and elsewhere, it appears that outbreaks of crown-of-thorns starfish happen cyclically. According to the Great Barrier Reef Marine Park Authority, outbreaks happen approximately every 15–17 years, with the latest outbreak occurring in 2010. There have been four major outbreaks on the Great Barrier Reef since the 1960s, and the crown-of-thorns starfish are probably responsible for up to 36% of the coral damage, making the crown-of-thorns starfish the greatest cause of coral damage on the Great Barrier Reef.

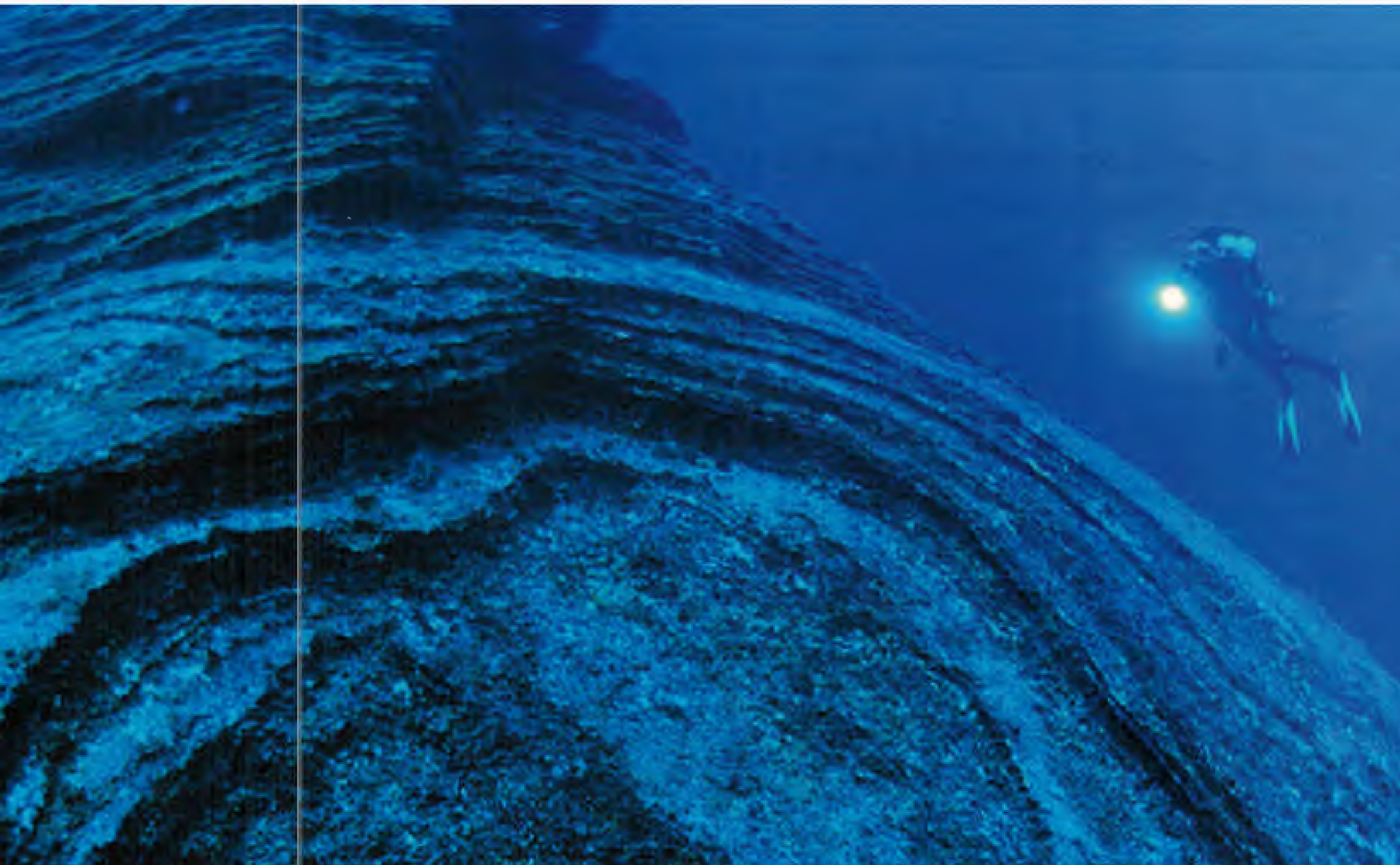
Questions

1 Outline the causes of crown-of-thorns starfish outbreaks.

2 Describe how a loss of coral through reef erosion during a tropical cyclone may lead to an outbreak of crown-of-thorns starfish.

3 Explain how poor fishing practices and waste management are contributing factors to outbreaks of these starfish.

4 Explain when and how crown-of-thorns starfish can be beneficial to the coral reef ecosystem.



Chapter 6
The ocean floor and the coast

Learning outcomes

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

- explain and provide evidence supporting the theory of plate tectonics
- demonstrate how tectonic processes produce features along the ocean floor, such as trenches, mid-ocean ridges, hydrothermal vents, abyssal plains and volcanoes
- demonstrate how tectonic processes create natural disasters such as volcanic eruptions, earthquakes and tsunamis
- explain why pressurised, hot, nutrient-rich water arises from hydrothermal vents
- explain the process and effects of isostasy
- describe how erosion and sedimentation create the different habitats found within the littoral zone, including estuaries, deltas, and rocky, sandy and muddy shores
- explain how the physical environment influences littoral communities, including mangrove forests
- apply what you have learnt to new, unfamiliar contexts.

6.1 How the Second World War changed marine science

The shore is where people first fall in love with the sea. Coastal environments are some of the most studied marine environments worldwide, because they are easily accessible for scientists interested in the biodiversity of our oceans. Conducting studies and experiments on the coast is easy because you need no special equipment to get there and it is easy to return to the same spot to repeat surveys. A love of the coast is not restricted to scientists, however: whenever you spend a sunny day relaxing at the beach, you are enjoying a small piece of the littoral zone.

While scientists may have started by studying the sea from dry land, they soon wanted to know what lies below the large bodies of water that dominate our planet. Images of the Kraken and other sea monsters swam through the minds of many sailors for thousands of years, as they wondered what really lay below the keels of their ships.

Unfortunately for those seafarers; it was not until the 20th century that technology became advanced enough to allow us to see what lies on the seabed, even though the technology used to explore the seabed was actually designed with another purpose in mind.

During the Second World War, many countries needed to be able to detect enemy submarines in the ocean. New technology was needed to make this possible, and that is why SONAR (an acronym for **so**und **n**avigation **a**nd **r**anging) was invented. SONAR enables scientists to map the ocean floor, and some amazing discoveries have been made using SONAR data. Instead of flat, barren plains stretching from shore to shore, scientists found mountain ranges dividing oceans in half and trenches sinking deeper than the highest mountains. This technology, followed quickly by SCUBA (**s**elf-**c**ontained **u**nderwater **b**reathing **a**pparatus), has been used for studies throughout the oceans, changing preconceived notions and providing evidence for new theories about the geology of our planet.

6.2 Plate tectonics

The history behind the theory of plate tectonics

In 1912, a German scientist named Alfred Wegener proposed an unusual theory regarding our planet to the geologists of his day. Wegener based his theory on evidence from multiple disciplines of science, such as geology and palaeontology. While looking at studies performed by other scientists, Wegener realised that identical fossilised plants and animals had been found on the coasts of different continents separated by oceans. When comparing geological structures (for example mountains) between continents, he found evidence that the rock layers in South Africa match those in Brazil. Between Europe and North America, he discovered that the structure of the Appalachian Mountains in the United States closely matches that of the mountains in the West Highlands of Scotland. Wegener then argued that the shape of the coastlines with matching geological features – South America and Africa, North America and Europe – fit together like pieces of a jigsaw puzzle. Using these observations, Wegener developed his theory of **continental drift**. This theory claims that, more than 300 million years ago, all the continents on Earth were joined as a single landmass Wegener named Pangea. Over the course of millions of years, Pangea began to split and its pieces have been slowly moving further and further away from each other since then.

Unfortunately for Wegener, his theory was not well received. In spite of the evidence he presented, his peers were not convinced that continental drift was happening or had ever happened. This was partly because Wegener did not suggest a clear mechanism by which continents moved. He proposed continents ploughed through the oceanic crust as an iceberg moves through water. Other scientists pointed out that this would change the shape of the continents, refuting the evidence Wegener was relying on to support his theory. Scientists at the time insisted on the idea of non-moving continents with long-gone land bridges for animals and plants to cross. It was another 50 years before other scientists were able to discover enough evidence to determine what was really happening. This evidence led them to new discoveries in the fields of geology, morphology and ecology of the oceans.

KEY TERM

Continental drift: a theory supporting the possibility that continents are able to move over Earth's surface

KEY TERMS

Plate tectonics: the process where large sections ('plates') of the Earth's crust are in constant movement over the fluid mantle, causing earthquakes and volcanoes at the borders between the plates

Lithosphere: the outermost layer of the Earth's crust

Asthenosphere: a nearly liquid layer made of the uppermost part of the mantle

Mantle: a region of molten rock within the interior of the Earth, between the core and the crust

The theory of plate tectonics

In the 1960s, the continental drift theory was revised as new evidence came to light. The revised theory included a mechanism for how the continents were actually moving across the surface of our planet, a factor missing from Wegener's original theory. The new theory – the theory of **plate tectonics** – suggests that the outermost layer of the Earth's crust, the **lithosphere**, is made up of many different plates called tectonic plates. Each of these plates floats independently on the nearly liquid **asthenosphere**, a layer made of the uppermost part of the **mantle** (Figure 6.1).

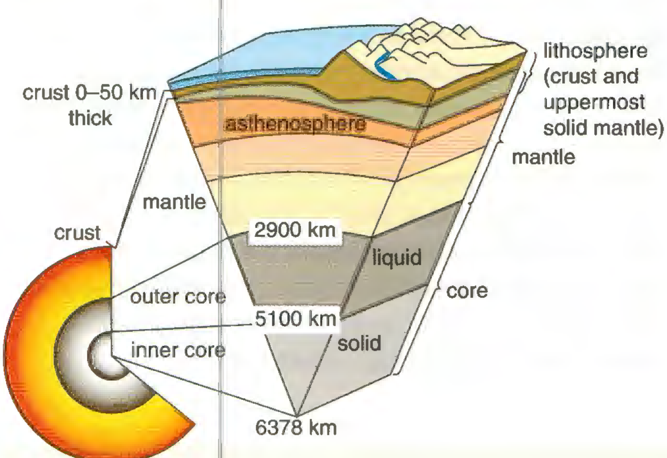


Figure 6.1. A diagram of the Earth's interior.

Evidence supporting the theory of plate tectonics

Seabed spreading

Many lines of evidence supporting plate tectonics have been discovered by scientists since the theory was first proposed. The concepts used by Wegener to support continental drift, of coastlines 'fitting' together and fossils being spread over multiple continents, also support the theory of plate tectonics. However, after the invention of SONAR, new evidence of plate boundaries came to light on the bottom of the ocean.

The data collected while looking for submarines showed mountains and trenches lining the edges of plate boundaries. These geological features created a clear map of where the tectonic plates line up. Marie Tharp, a geologist and oceanic cartographer, and her partner Bruce Heezen, a geologist, collaborated for 20 years to collect ocean floor mapping data in order to create an accurate, scientific map of the seabed. This map (Figure 6.2), called the World Ocean Floor, revolutionised Earth science after its publication in 1977, because of the prominent presence of the mid-ocean ridge. This map is responsible for convincing many scientists to accept the theory of plate tectonics and seabed spreading.

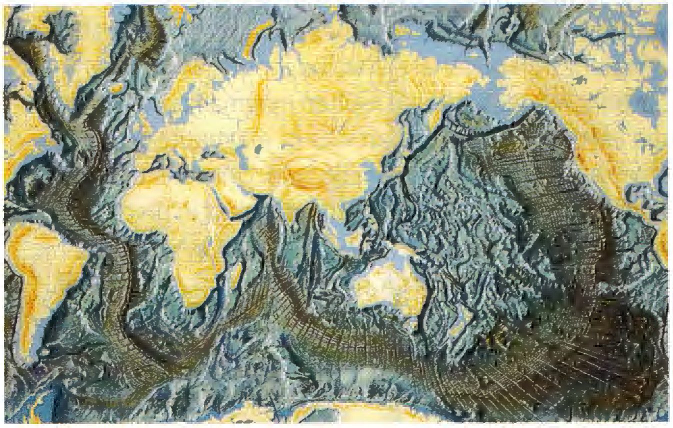


Figure 6.2. The World Ocean Floor by Marie Tharp and Bruce C. Heezen.

Magnetic polarity reversal

More evidence supporting the theory of plate tectonics was discovered after the Second World War had ended. Scientists began studying magnetism on the ocean floor using magnetometers created to locate submarines during the war, as SONAR had been. The evidence they found surprised them. The magnetic field of the ocean floor was laid out in alternating stripes of normal polarity and reversed polarity.

The fact that the ocean floor was magnetic was not the surprise. Sailors had known for more than 100 years that the basaltic rocks lining the ocean floor were magnetic. It was the striped pattern that was unexpected. Further research showed that the striped pattern had an origin around the mid-ocean ridges, where the crust is weakest and magma often pushes through (Figure 6.3). This magma held the explanation.

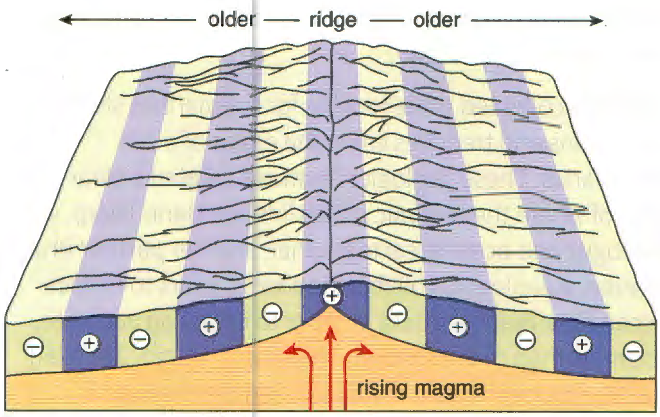


Figure 6.3. Seabed spreading and magnetic reversal.

Basaltic rocks, the type commonly found on the seabed, are an example of an igneous rock. Igneous rocks are created when molten magma from a volcanic eruption cools and hardens. Within igneous rocks is a naturally magnetic iron material called magnetite, which is why basalt is magnetic. When molten magma first reaches the Earth's surface, the particles of magnetite within it align with the Earth's magnetic field. Once the magma begins to harden, the magnetite is locked in place, holding information about the Earth's magnetic field at the time the rock was formed. Scientists have found that the Earth's magnetic field reverses on average every 250 000 years, changing magnetic north to magnetic south. This information, when applied to the ocean floor, provides unique evidence in support of the theory of plate tectonics.

At divergent boundaries, where mid-ocean ridges form, scientists now know the seabed is spreading because of magma rising from the mantle and hardening into igneous rocks. When the magnetic properties of the rocks at these boundaries were measured, scientists confirmed that the rocks lay in alternating stripes of magnetic polarity radiating away from the boundary in parallel lines. These stripes differed in width based on the length of time between each reversal, providing the strongest evidence in support of seabed spreading and plate tectonics.

SELF-ASSESSMENT QUESTIONS

1 Compare the theory of continental drift with the theory of plate tectonics.

2 List the major lines of evidence for the theory of plate tectonics.

6.3 Plate boundaries

In order for lithospheric (tectonic) plates to move, the asthenosphere must be moving as well. This movement is caused by **convection currents** within the mantle. Convection currents happen when the molten rock of the mantle moves because of density changes in the rock caused by temperature differences. In other words, as the molten rock is heated, it becomes less dense as the molecules spread out. The less dense rock moves upwards in the mantle towards the crust in order to float on top of the denser rock. Then, as the rock begins to cool, it begins to sink towards the warmer core. This forms a circular cell of flowing molten rock capable of moving the lithospheric plate lying on top of it. Because the plates are heavy and the convection currents in the asthenosphere move so slowly, the plates move only 2–5 cm $year^{-1}$. However, even this small movement causes the plates to meet and form three types of boundary: convergent, divergent and transform. Each boundary type has identifiable characteristics and geological features (Figure 6.4).

KEY TERMS

Convection current: the movement of fluids or air based on density differences caused by differing temperature

Convergent boundary: when two or more tectonic plates come together

Subduction: the process where one lithospheric plate slides below another at a convergent plate boundary

Trench: a long, narrow and deep depression on the ocean floor with relatively steep sides, caused by convergent plate boundaries

Volcano: a mountain or hill with a crater or vent through which lava, rock fragments, hot vapour and gas are being forced from the Earth's crust

Earthquake: a sudden release of energy inside the Earth that creates seismic waves usually caused by movement of tectonic plates or volcanic activity

Tsunami: a seismic sea wave created by an underwater earthquake or volcanic event, not noticeable in the open ocean but building to great heights in shallow water

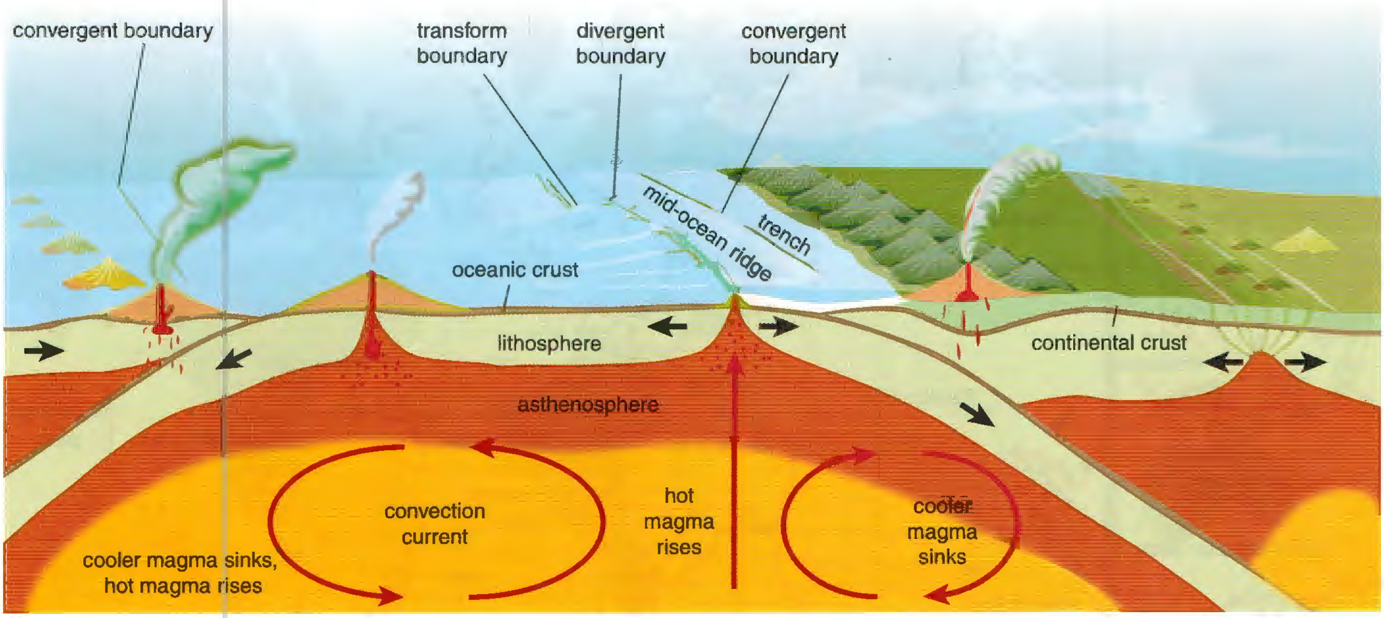


Figure 6.4. Visual representation of plate boundaries and their features.

Convergent boundaries and their features

Convergent boundaries form when two tectonic plates are moving towards each other. These boundaries form **subduction** zones where one plate, typically a denser oceanic plate, slides underneath the other, less dense, continental plate. These areas are known as destructive zones. This is because, as the denser oceanic plate slides below the continental plate, it is destroyed by the heat of the asthenosphere and returns to the molten mantle. Common features along subduction zones are **trenches**, **volcanoes**, **earthquakes** and **tsunamis**.

Trenches are long, narrow, deep canyons in the seabed. Trenches only occur at subduction zones within convergent boundaries. The deepest part of the ocean, Challenger Deep, exists within the Marianas Trench in the western Pacific Ocean. Challenger Deep is 11 033 m deep, which is deeper than Mount Everest is tall (8848 m).

A volcano is formed when an opening in the Earth's crust allows gases and molten rock to escape from the mantle. Volcanoes that rise above sea-level form new islands like those in the Hawaiian and Philippines archipelagos. However, many volcanoes are located under the ocean's surface, creating new seabed when the magma cools after erupting. Of these underwater volcanoes, most lie along the convergent plate boundaries surrounding the Pacific Ocean. Together, they create what is known as the Ring of Fire (Figure 6.5). The areas that border the Ring of Fire are hotspots for volcanic and seismic activity. Volcanoes can also be found at divergent boundaries and areas where the crust is very thin.

Earthquakes occur after there has been a sudden release of energy from the movement of the Earth's crust. When two plates are moving past each other, at either a convergent or transform boundary, they may get stuck. When this happens, the pressure for them to move builds and builds until movement finally happens, releasing stored potential energy in a sudden burst. This burst of energy releases seismic waves that move through the lithosphere making everything on top of the crust shake. Volcanoes are also capable of causing an earthquake when they release enormous amounts of energy during an eruption.

Sudden releases of energy on the seabed, either through an earthquake or a volcanic eruption, can lead to tsunamis. Tsunamis are long-wavelength, high-energy waves created by seismic activity. When an earthquake releases its stored energy on the seabed, it moves all the water lying above. The water holds on to this energy and moves very quickly but unnoticeably through deep ocean water. However, as the tsunami reaches shallow, coastal waters, the wave slows down and grows exponentially in height. These large, high-energy waves can be incredibly destructive. Tsunamis are sometimes called 'tidal waves' but this is inaccurate because the tides have nothing to do with the creation of tsunamis.

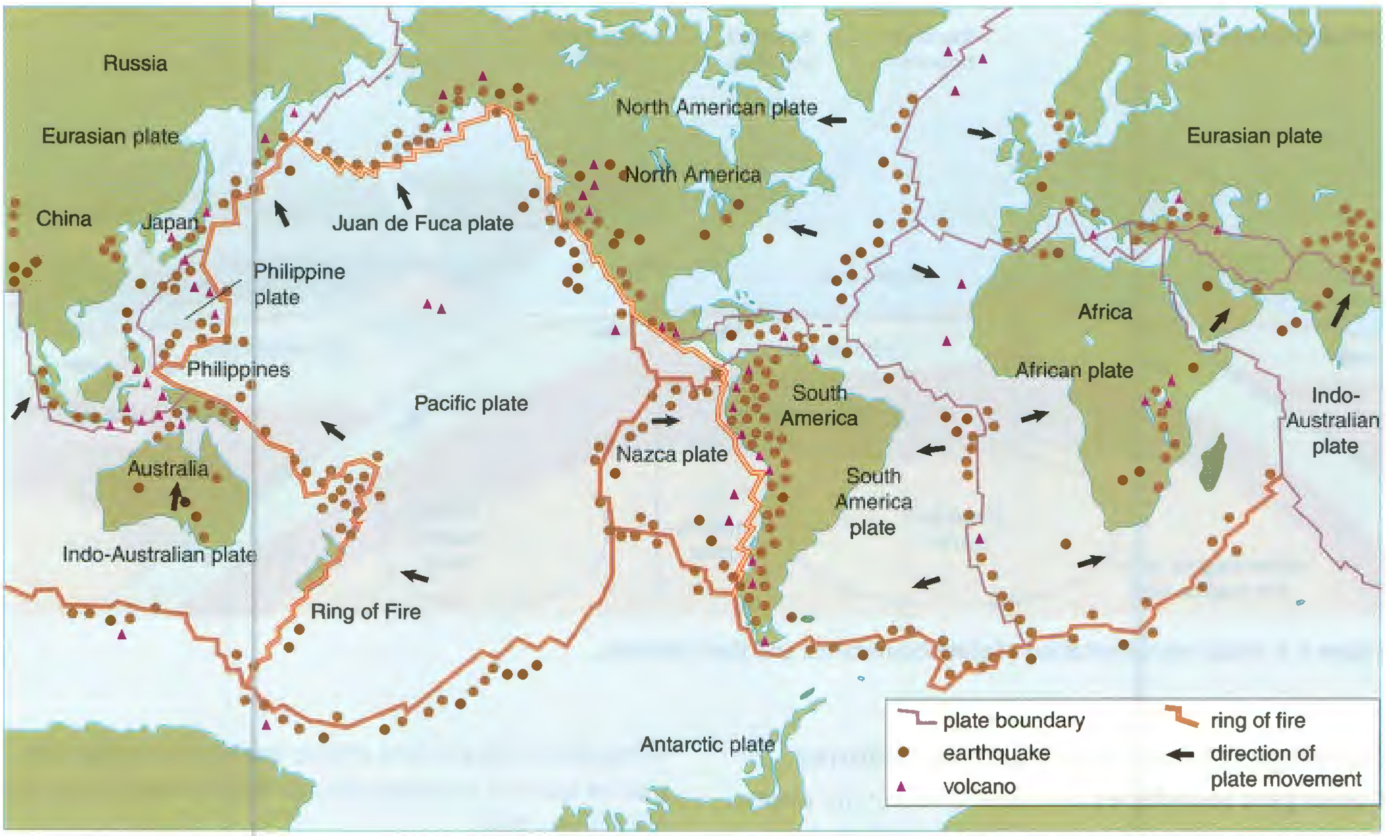


Figure 6.5. The Pacific Ring of Fire with tectonic plate movement.

Divergent boundaries and their features

Divergent boundaries are areas where the tectonic plates are moving away from each other and allowing molten magma from the mantle to push through to the crust. These areas are considered to be constructive zones. As the magma, driven by convection currents, pushes through the opening in the crust, it spreads out and solidifies in the cold ocean waters at the bottom of the sea. The new rocks created through this process eventually build up and form underwater mountain ranges called **mid-ocean ridges**. As these mid-ocean ridges continue to build new crust, there is an eventual movement away from the divergent boundary, causing seabed spreading. Seabed spreading helps to move tectonic plates towards convergent boundaries on the opposite side of the planet. This process, over the course of millions of years, is responsible for a shrinking Pacific Ocean and growing Atlantic Ocean. Located within these mid-ocean ridges are volcanoes and hydrothermal vents, which are discussed in further detail later in this chapter.

KEY TERMS

Divergent boundary: where two tectonic plates are moving away from each other

Mid-ocean ridge: a mountain range with a central valley on an ocean floor at the boundary between two diverging tectonic plates, where new crust forms from upwelling magma

Transform boundary: when two plates are moving in an antiparallel direction, creating friction between them

Abyssal plain: a flat, sandy region of the ocean floor found between trenches and the continental rise

Transform boundaries and their features

Transform boundaries are areas where two plates slide laterally next to each other. No crust is created or destroyed at transform boundaries. However, transform boundaries are areas of great seismic activity. The increased friction between plates at these boundaries causes small cracks called faults to form. The pressure that builds up in these fault lines can lead to earthquakes and tsunamis. The most common ocean feature found along transform boundaries are **abyssal plains**, which are discussed in the section on the seabed.

SELF-ASSESSMENT QUESTIONS

3 Describe how tsunamis are formed.

4 How are divergent and convergent boundaries related to the rock cycle?

KEY TERMS

Hydrothermal vent: an area where cold ocean water that has seeped into the Earth's crust is superheated by underlying magma and forced through vents in the ocean floor

6.4 Hydrothermal vents

Hydrothermal vent systems were discovered in 1977 along the Galapagos Rift in the Pacific Ocean by scientists from Woods Hole Oceanographic Institute (WHOI) using the deep sea submersible *Alvin*. Hydrothermal vents (Figure 6.6) occur in deep ocean water, usually 2000 m or more below sea-level, within mid-ocean ridge systems. At this depth, the pressure is over 200 atmospheres and there is no light. These are unique circumstances for the development of an ecosystem.

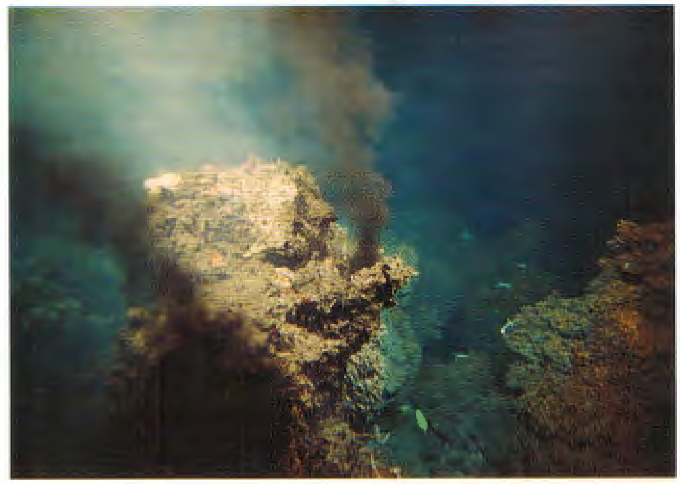


Figure 6.6. A hydrothermal vent along the Juan de Fuca Ridge in the northern Pacific Ocean.

Hydrothermal vents are formed when cold ocean water seeps through cracks in the thin crust surrounding divergent boundaries (Figure 6.7). As the water moves through the crust to an area directly over a magma chamber, it dissolves minerals (for example iron, copper and zinc sulfides) from the rocks, turning it black. Once heated by the magma, the water reaches temperatures well over 100 °C but never boils because of the extreme pressure in the region. This superheated water then escapes the crust through a fissure above.

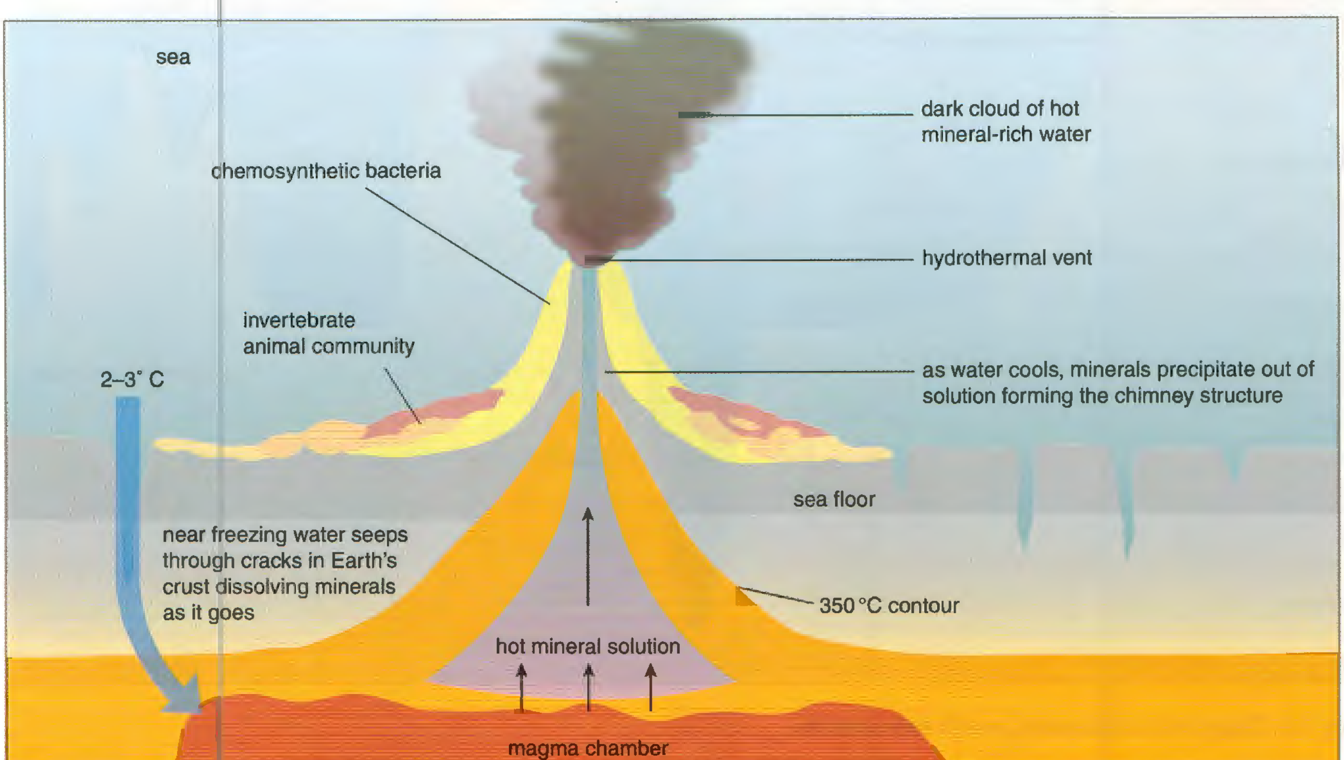


Figure 6.7. Formation of a hydrothermal vent.

As the superheated water meets the near freezing water on the ocean floor it begins to cool. As the water cools, the minerals precipitate out of solution. This means the minerals form solids, which settle near the fissure, piling on top of each other. This forms a chimney, or vent, for the superheated water that can be up to 60 m high. These hydrothermal vents release water at temperatures over 350 °C. They are often referred to as 'black smokers' because of the black smoke-like look the water has as it escapes from the chimney. The chemicals contained in the water are the basis for energy capture, chemosynthesis, in these dark waters (see Chapter 2).

SELF-ASSESSMENT QUESTIONS

5 Why do you think it took until 1977 for scientists to discover hydrothermal vents?

6 Would you describe this environment as extreme? Why or why not?

6.5 Seabed

The ocean floor is divided into specific regions based on physical structure and location. The **continental margin** comprises approximately 28% of the ocean floor. This region of the ocean floor divides the thin, but dense, oceanic crust from the thicker, less dense, continental crust located at the edge of continents. Within the continental margin are three distinct zones (Figure 6.8).

- The **continental shelf** is the flat, shallow area extending from the shore to the continental slope. This area tends to be featureless because of the deposition of sediments as a result of wave action. The average width of continental shelves is 70 km, but they range from 20 km to 1500 km. The widest continental shelves happen in areas where there is little tectonic action taking place.
- The **continental slope** begins where the continental shelf ends. This region is a fairly steep area of the

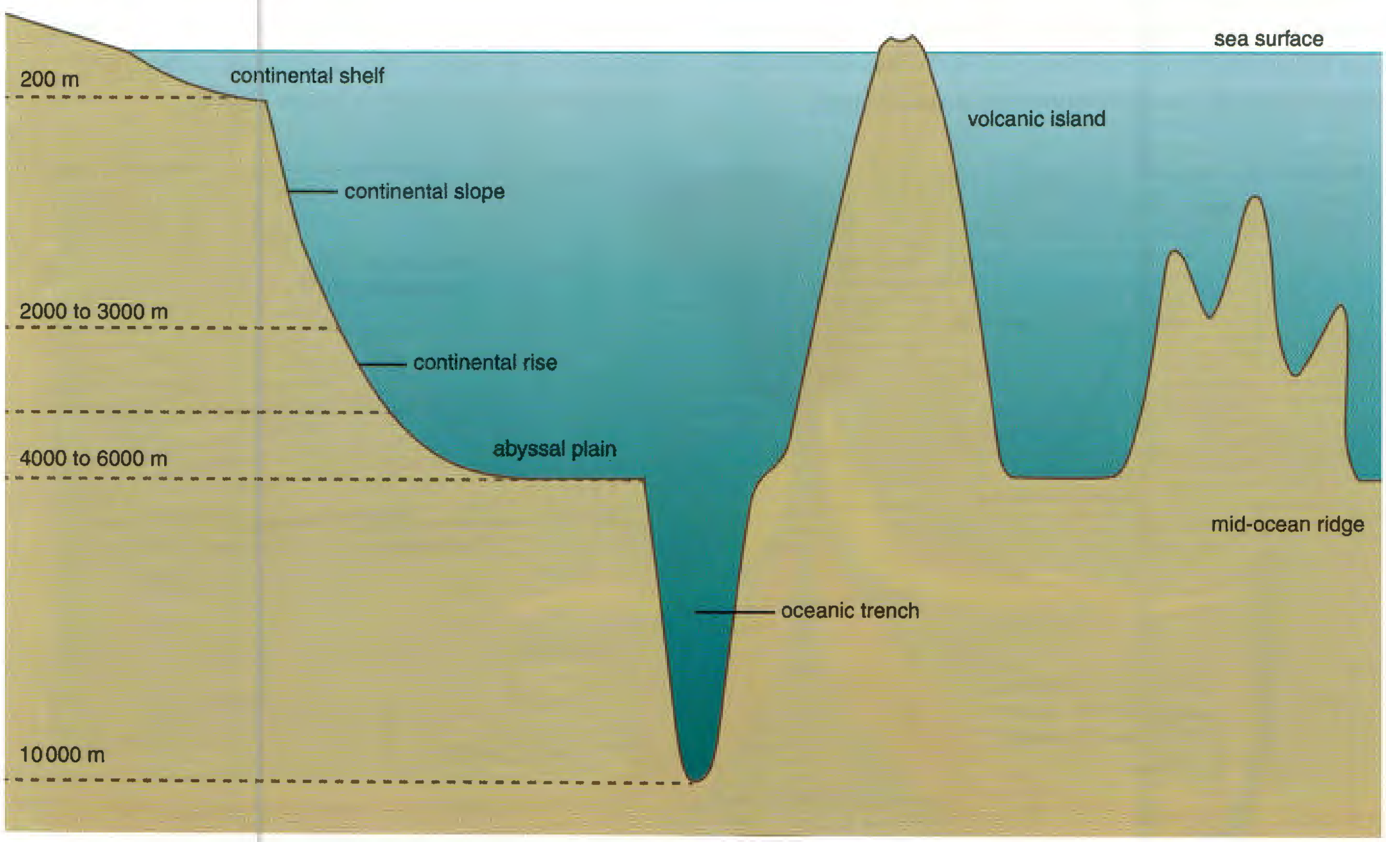


Figure 6.8. Diagram of the seabed, not drawn to scale.

seabed that descends into the ocean basins. This area is even steeper when located near a convergent boundary because of the presence of trenches.

- The **continental rise** is a narrow edge to the continental slope connecting the continental slope to the seabed.

KEY TERMS

Continental margin: the submerged area next to a continent, which includes the continental shelf, continental slope and continental rise

Continental shelf: a gently sloping surface that extends from the low tide line to the continental slope, typically where a great deal of sand deposits

Continental slope: a relatively steep sloping surface between the continental shelf and the continental rise

Continental rise: a gently sloping surface at the base of the continental slope where sand deposits

Leading from the continental rise are incredibly flat areas of the ocean floor called abyssal plains. These areas are located at depths between 3000 and 6000 m below sea-level and can typically be found between the continental rise and a mid-ocean ridge. Abyssal plains make up more than 50% of the Earth's total surface area. This flat plain is formed when the uneven, rocky surface of the seabed is slowly covered in sand and decomposing organic matter that sinks to the bottom of the ocean.

6.6 Isostasy

The term **isostasy** means 'weighing the same'. In geology, isostasy refers to the buoyancy of different rock layers as they float on other layers. The buoyancy of each rock type is determined by its density and thickness. This concept explains why the Earth's crust is able to float on the denser molten rock of the mantle the way an ice cube floats in a glass of water. Figure 6.9 shows this process in stages.

KEY TERM

Isostasy: a process similar to buoyancy but related to the Earth's crust floating on the flexible mantle

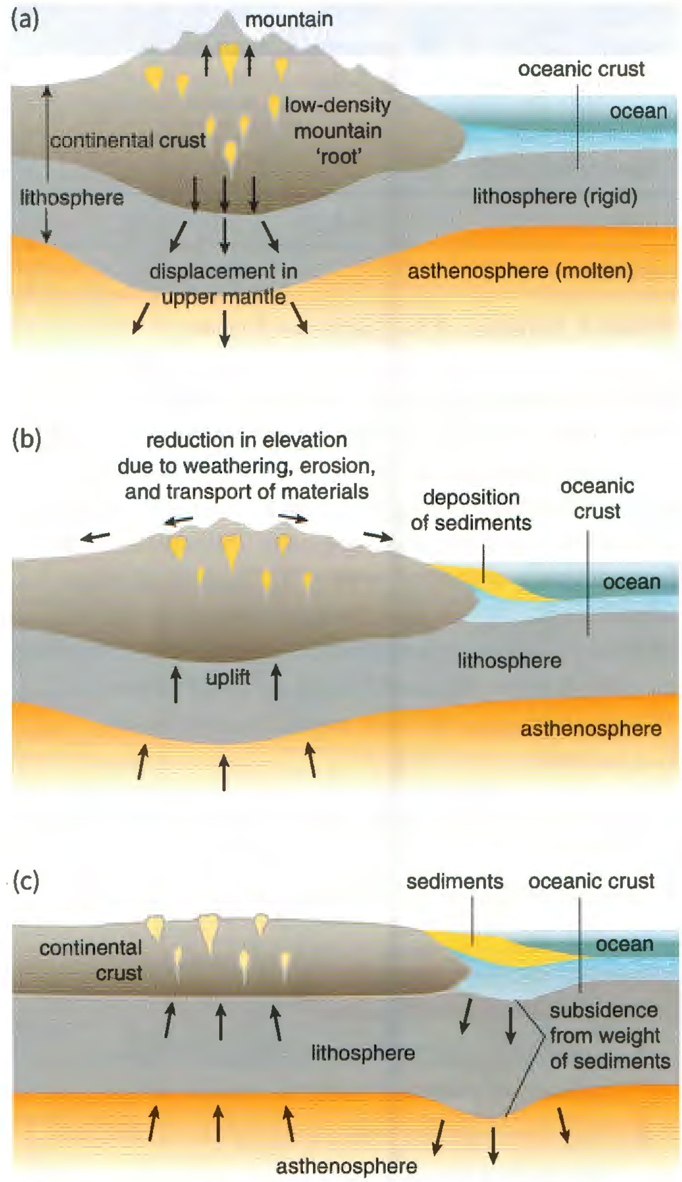


Figure 6.9. Process of isostasy and how shallow seas are formed.

Isostasy allows scientists to create a model of the Earth representing the way each rock layer floats on the underlying mantle. Table 6.1 shows the approximate densities of the Earth's rock layers for reference. Both continental crust and oceanic crust float on the mantle because they have a lower density than the rock in the mantle. However, the continental crust tends to float higher on the mantle than the oceanic crust. This is because, even though the continental crust is a thicker layer of rock, its density is lower than that of oceanic crust.

layer	density / g cm^{-3}
continental crust	2.7–3.0
sediments on continental shelf	2.4
oceanic crust	3.0–3.3
mantle	3.3–5.7

Table 6.1. Densities of the Earth's rock layers.

During the last ice age, much of the planet's ocean water was frozen as ice, lowering sea-levels worldwide. These lower sea-levels meant that most, if not all, of the continental shelf regions were above water at the time. Now that these areas are back under water, they form the base of shallow seas at the outermost edge of continents. Remember, the continental shelf is a relatively shallow area of the ocean covered in sediments as a result of the erosion of rocks on the continents. The depth of water in these areas is controlled by two factors:

- changes in sea-level as a result of the melting or freezing of sea ice
- changes in land height as a result of isostatic changes.

SELF-ASSESSMENT QUESTIONS

7 Would you expect the continental shelf near a convergent plate to be wide or narrow? Why?

8 How does isostasy create shallow seas during non-ice age time periods?

6.7 The littoral zone

The area of the ocean most commonly studied is that of the **littoral zone**. This is the area of the shore where land meets sea and is also known as the intertidal zone. The littoral zone is the area between the high water mark during spring tides and the lowest part of the shore that is permanently submerged. This area of the ocean is varied and is categorised according to:

- the shape of the shore
- wave action and erosion
- the substrate that makes up the shore
- the organisms that live there.

KEY TERMS

Littoral zone: the benthic, or bottom, zone between the highest and lowest spring tide shorelines, also referred to as the intertidal zone

Morphology: the study of the forms of things

Morphology of the littoral zone

The shape of the sea shore depends primarily on the geology of the land lying closest to the shore and the level of exposure to erosion on that shore. This means that sea shores may be nearly flat areas covered in fine particles of mud or nearly vertical areas with large rocks. Scientists studying the different shape and make-up of sea shores are studying the **morphology** of that shore. The two factors that scientists focus on when studying morphology are the slope of the shore and the size of the sediment found on the shore. Table 6.2 shows some different categories and diameters of sediments commonly found on sea shores.

particle type	diameter / mm
silt	0.002–0.02
fine sand	0.02–0.2
coarse sand	0.2–2.0
gravel (small stones)	>2.0

Table 6.2. Diameters of common sediment types.

Rocky shores

Rocky shores are areas of shore that are characterised by the presence of a rocky substrate (Figure 6.10). Rocky shores vary widely in slope from nearly vertical cliff faces to wide flat expanses of rocks. The size of the rocks making up the shore also varies from very large boulders to much smaller pieces of gravel and pebbles.

Figure 6.10. A rocky shore with tide pools in Cozumel, Mexico.

Geologically speaking, rocky shores tend to be made of primarily granite or igneous rocks, which are incredibly resistant to weathering and take a much longer time to break down than softer rocks such as sandstone. Rocks along these shores often exist in a gradient, with the largest rocks occurring farthest from the water at the high-water mark and the smallest rocks occurring nearer the low-water mark. Scientists believe this gradient is caused by the pounding of waves wearing away those rocks closest to the water line first and not being able to reach those farther up the shore. It is not surprising that these shores are the most resistant to erosion even though they also tend to be the most open and exposed.

Sandy shores

A normal sandy shore is made of loose deposits of sand (silica), small pieces of gravel and shells. Sandy shores are formed by the **erosion** of sandstone and **deposition** of sediments by the waves. Sandy shores are constantly in motion as the ocean moves the sand up and down the beach. These shores tend to have a gradual slope towards the ocean.

KEY TERMS

Erosion: a natural process where material is worn away from the Earth's surface and transported elsewhere

Deposition: a geological process where sediments, soil and rocks are added to a landform or land mass

Muddy shores

Muddy shores are found in protected regions and are shores least exposed to erosion. There tends to be no slope on muddy shores, giving rise to the name mud flat. A lack of erosion and little to no water movement allows the deposition of a layer of very fine silt particles and organic materials.

Estuaries

Estuaries form in sheltered or partially enclosed areas where fresh water and salt water meet; this mix of water is called brackish. Because these areas are sheltered from the erosive action of waves, the bottom is often made of fine sand and silt that falls out of suspension when the water is still. The water in estuaries is very murky, with high turbidity as a result of the fine sediments. Other names for estuaries include bays, lagoons, sounds and sloughs.

KEY TERMS

Estuary: a partially enclosed, tidal, coastal body of water where fresh water from a river meets the salt water of the ocean

Delta: a low-lying triangular area at the mouth of a river formed by the deposition of sediments

Deltas

Deltas form at the mouth of a river where it meets the sea. These shores are named after the Greek letter delta (Δ) because they usually have a triangular shape (Figure 6.11). As a river flows towards its mouth, it picks up sediment along the way. The river begins to widen as it approaches the sea, slowing down the speed of the water. When the water slows enough, the sediments begin to settle on the bottom of the river. Over time, these sediments deposit and accumulate into sandbars and other small landmasses, forming a wide fan-shaped structure resembling a branching tree. If the landmasses build up enough, it is possible for the delta to form new tributary channels of the river. The most well-known river deltas are the:

- Mississippi River Delta, leading to the Gulf of Mexico in the United States
- Nile River Delta, draining into the Mediterranean Sea in Egypt.

Figure 6.11. Nile River Delta.

Ecosystems of the littoral zone

Ocean ecosystems are a product of the environment in which they exist. Many abiotic factors, including temperature, exposure to air, stability of the substrate and salinity, have a role in the formation of an ecosystem. These and others are responsible for the development of the many ecosystem types located within the littoral zone.

This chapter focuses on the formation of the three ecosystems that can develop in the littoral zone of oceans: rocky shores, sandy shores and mangroves.

Rocky shores

Living on a rocky shore is not easy. Organisms have a lot to contend with, including fluctuating temperatures, wave action and exposure to air based on the tides. Other factors that they have to adapt to are the slope of the shore, what type of rocks make up the substrate, whether the habitat is in a temperate or tropical region, and how much sunlight is available at any time during the year. It may therefore come as a surprise to you that rocky shores are typically habitats with significant biodiversity (Figure 6.12).

In spite of the difficulties organisms may face living on a rocky shore, these areas provide habitat and stability to a multitude of species within the littoral zone. The rocky substrate provides many places for organisms to attach to, a necessity for survival in a place where waves can wash organisms and substrate away. Algae, barnacles, sea anemones and many species of mollusc make their home attached to the rocky surface. The need for safe anchorage makes space, not food or light, the main resource that organisms compete for in this ecosystem.

In order to reduce competition for space, species in rocky shore ecosystems space themselves vertically on the rocks in a pattern called **zonation**. To determine the upper limit of a species' zone, scientists look for physical factors affecting survival: temperature tolerance and length of time the species can spend out of water before **desiccation**. To find the lower level of a species' zone, scientists look at biological factors: competition between other species and predation. The intertidal zone on a rocky shore can be divided into three major areas (Figure 6.13).

Figure 6.12. Rocky shore flora and fauna at Cannon Beach, Oregon.

KEY TERMS

Zonation: a separation of organisms in a habitat into definite zones or bands according to biological and physical factors, common in rocky shore habitats

Desiccation: the process of drying out or losing moisture

- High-tide zone: this area only has water during high tides. Organisms here must be able to withstand long periods of time without water or food. These organisms risk desiccation or drying out. Typical organisms located in this zone include chitons, crabs, isopods and barnacles.
- Middle-tide zone: this area is exposed to air twice a day at low tide, so organisms must have a coping method to deal with desiccation. Typical organisms in this zone include limpets, periwinkles and mussels.
- Low-tide zone: this area is usually covered with water, except during the lowest spring tides (Chapter 7). Organisms found here have very few adaptations for living outside water and dry out or overheat easily. Typical organisms found here include seaweed, algae, sea stars, sea urchins, sea anemones and oysters.

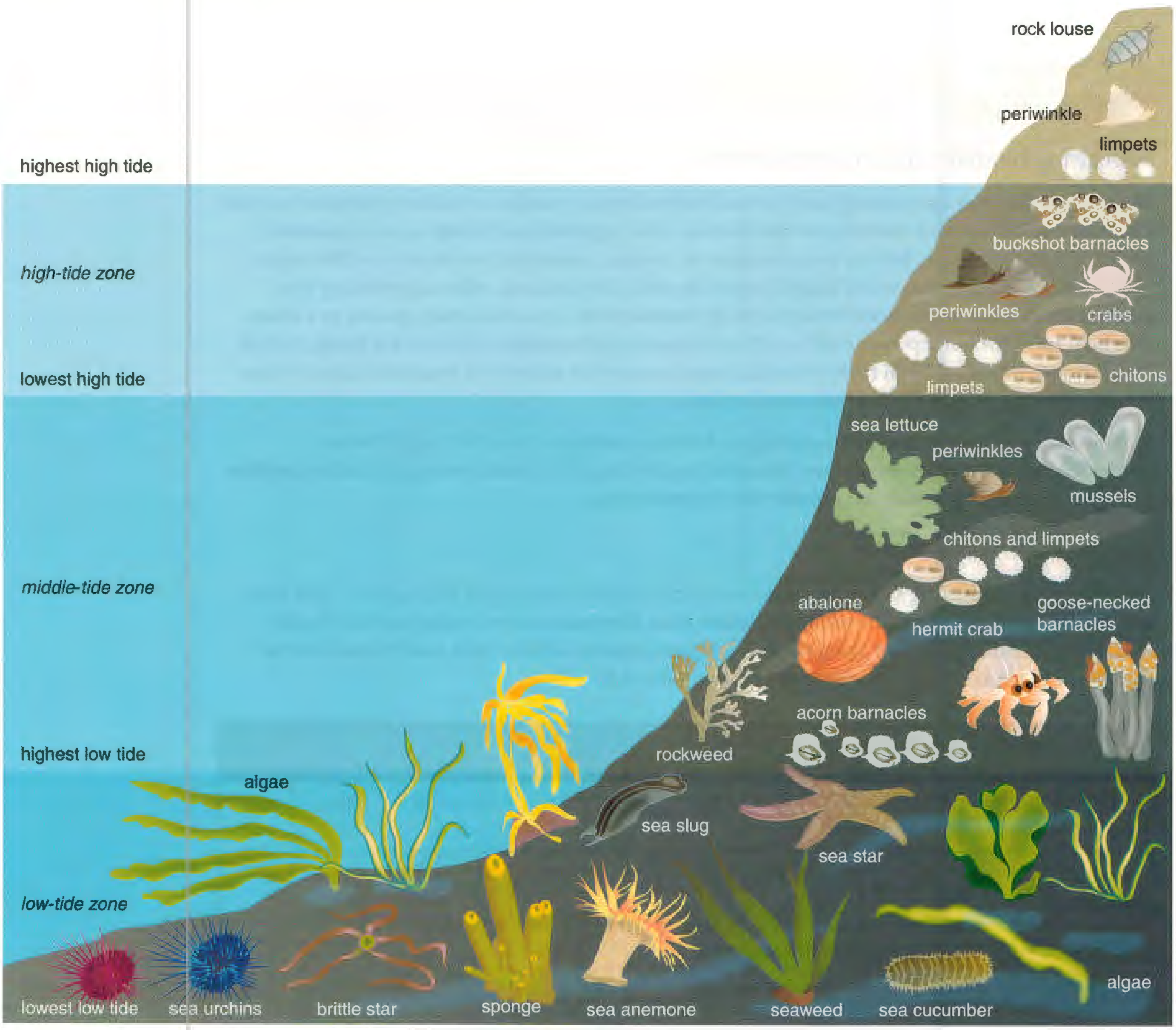


Figure 6.13. Diagram of zonation patterns on a rocky shore.

Within each of these zones, tide pools may exist. Tide pools form when seawater fills a particularly low spot in the rocks during low tides (Figure 6.10). Tide pools are important for organisms in the higher zones to survive because they create an area where they can cool down, carry out gaseous exchange and feed. As the tide comes back in, the water in the tide pool is replaced and refreshed so there are few problems with increased salinity or decreased oxygen.

Sandy shores

Sandy shores produce a unique set of circumstances for organisms to deal with. The most difficult factor organisms have to be adapted for is the ever-shifting substrate. Sandy shores are incredibly unstable, as a single wave or gust of wind can remove a lot of the fine sand the organisms live on. Most organisms therefore deal with this situation by living *in* the substrate rather than *on* the substrate. Organisms found on a sandy shore tend to be burrowers or **infauna**, such as ghost crabs, cockles and other bivalves, and annelid worms like ragworms and lugworms. These challenges explain why sandy shores tend to have low biodiversity compared to rocky shores.

KEY TERM

Infauna: animals living within the sediments of the ocean floor, river or lake beds

Maths skills

Measuring biodiversity on a rocky shore

The quadrat survey is a commonly used method for biodiversity studies as it allows scientists to create a standard unit of area for studying the distribution of an organism over a large area. A quadrat is normally square in shape, but can be rectangular or circular, depending on the needs of the study. The size of the quadrat also varies depending on the study. For instance, when determining tree biodiversity in a forest, the quadrat may be 10 m^2 because of the size of the study species; in a rocky intertidal zone, the quadrat may only be 0.25 m^2 because much smaller organisms are being studied. Quadrat surveys are useful in rocky intertidal areas because the majority of organisms located there are slow-moving, attached to the substrate or plants.

Scientists use a method of random sampling to determine where to place the quadrat when conducting a survey. This prevents any bias affecting the data. The counts from each quadrat are then averaged to reach an approximate number for the entire area.

Worked example

Scientists were conducting a quadrat survey on a rocky shore in Vancouver, BC, Canada. They were specifically investigating the abundance of leather stars (*Dermasterias imbricate*) and the Pacific blue mussel (*Mytilus trossulus*) along the shore. Square quadrats of 1 m^2 were used to measure the abundance in ten randomly selected locations (see Table 6.3).

sample area	1	2	3	4	5	6	7	8	9	10
number of leather stars in 1 m^2	3	15	0	8	4	17	12	1	2	9
number of mussels in 1 m^2	20	49	9	47	12	100	48	10	16	32

Table 6.3. Results of 1 m^2 sample area calculations.

Standard deviation

Often scientists include standard deviation in their results when they analyse their data. Standard deviations tell you how spread out the numbers in a data set are. The smaller the standard deviation, the closer the numbers are to the mean. This can tell you, for example, how variable a population is within a community. The equation for standard deviation is:

$$S = \sqrt{\frac{\Sigma(x-\bar{x})^2}{n-1}}$$

These symbols all relate to the different steps you need to complete to find the standard deviation. This equation can be broken down into stages. The standard deviation (S) for the leather star data given in Table 6.3 is calculated as shown below.

- Calculate the mean value ($\bar{x}$) for the leather star population:

$$\bar{x} = \frac{(3+15+0+8+4+17+12+1+2+9)}{10} = 7.1$$

- Then for each quadrat, subtract the mean ($\bar{x}$) from its number (x) and square the result, giving you: $(x - \bar{x})^2$. So for quadrat 1: $(3 - 7.1)^2 = 16.8$.

Table 6.4 shows the results of this step for all 10 quadrats.

sample area	1	2	3	4	5	6	7	8	9	10	mean
number of leather stars in 1 m^2	3	15	0	8	4	17	12	1	2	9	7.1
$(x - \bar{x})^2$	16.8	62.4	50.4	0.8	9.6	98.0	24.0	37.2	26.0	3.61	32.9

Table 6.4. Working out the mean values for the leather stars.

- The next step is to calculate $\Sigma(x - \bar{x})^2$ by adding all of the $(x - \bar{x})^2$ values. So, $\Sigma(x - \bar{x})^2 = 328.81$
- Then, divide your value for $\Sigma(x - \bar{x})^2$ by (n–1), where n is the number of values you have (10, in this case). This should provide you with a value of 36.53.
- Finally, take the square root of your calculated value.
- Using this equation, your standard deviation should be 6.04.

Questions

1 a Calculate the mean numbers per m^2 for the mussels, using the data in Table 6.3.
  b Calculate the standard deviation for the population of mussels.

2 Based on your knowledge of rocky intertidal zone communities, predict which quadrats were placed in the lower intertidal zone and which were placed in the upper intertidal zone.

Organisms on a sandy shore also show vertical zonation patterns similar to those on a rocky shore (Figure 6.14). Once again, the area inhabited by an organism is determined by both physical and biological factors, such as predation and the ability to resist drying out. The primary difference between zonation on rocky shores and sandy shores is that it is less noticeable on sandy shores because of the burrowing nature of the organisms that live here.

Because there is no place for attachment on a sandy shore, seaweeds cannot survive here. The only producers that may occur on a sandy shore are phytoplankton brought in by the tides. Therefore most of the organisms on sandy shores are detritivores that collect organic material from between sand grains as they burrow. This is particularly the case on coasts where sand is mixed with muddy deposits. However, a sand and mud shore is more stable than a shore of sand alone, so more biodiversity is present.

Mangroves

Mangroves are trees that prefer to live in coastal or estuarine environments between latitudes 25 °N and 25 °S. There are more than 110 species of mangrove, many of which are found in Indonesia where mangrove biodiversity is highest. These trees survive in saline habitats because of the lack of competition from other plants. Mangroves tend to form woodland habitats that provide the basis for incredibly biodiverse habitats. Areas where mangroves grow are referred to as mangrove swamps, mangrove forests or just mangroves.

Within a coastal or estuarine habitat, there are two primary physical factors that mangroves have to contend with that can impact their survival:

- high salt content in the water
- low oxygen content in the substrate.

High salt content

Mangroves have several adaptations for dealing with the high salt content of coastal and estuarine waters. Red mangroves (*Rhizophora mangle*) have two methods for living in salt water. The first method begins at the roots, which have become nearly impermeable to salt because

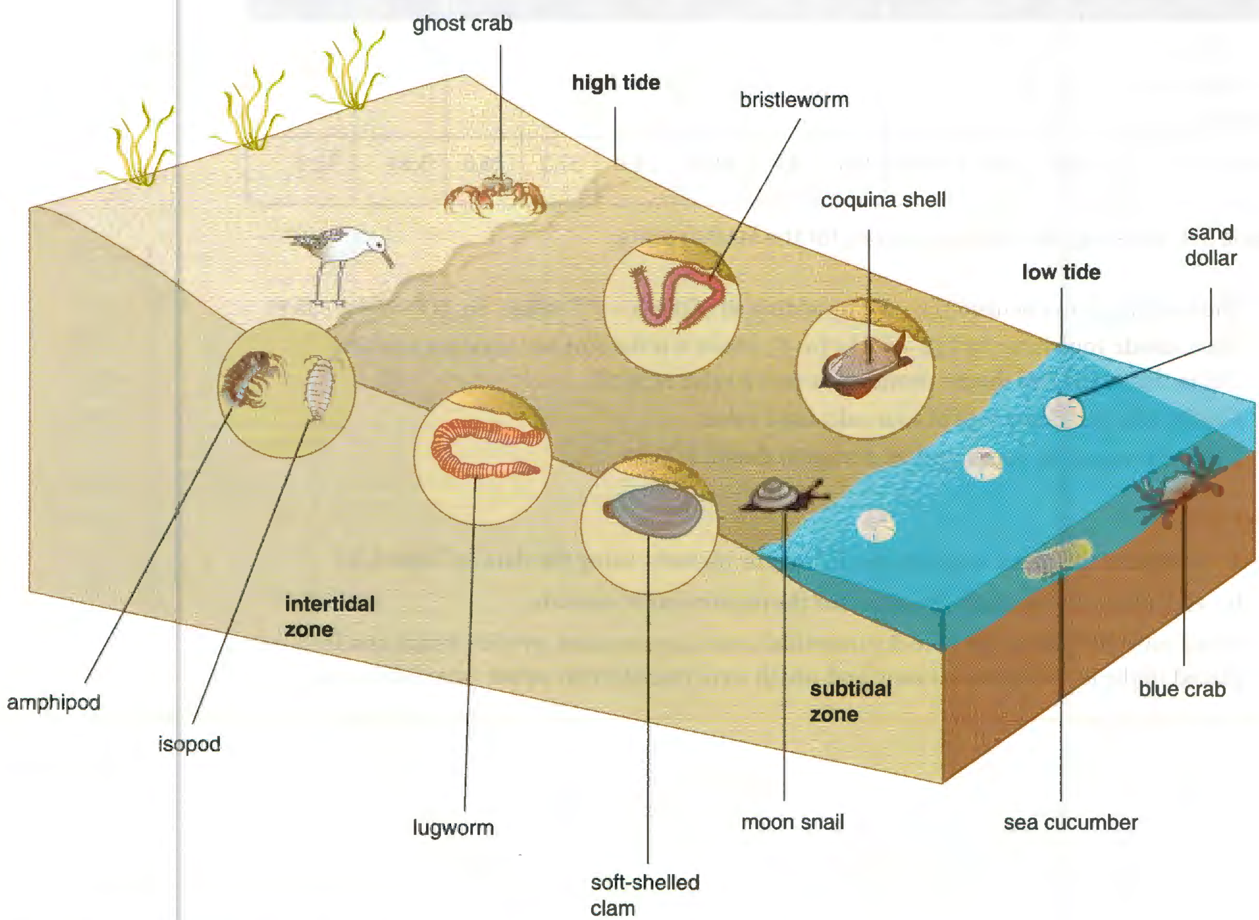


Figure 6.14. Common zonation patterns on a sandy shore.

of a very efficient filtration method. Some scientists have hypothesised the use of a 'sacrificial leaf', where red mangroves deposit excess salts that make it past the filtration system. However, other studies dispute this hypothesis. Black mangroves (*Avicennia germinans*) expel salt through pores on the underside of their leaves.

Anoxic soil

Red mangroves use prop roots to hold themselves above the water level at high tide and absorb the oxygen they need through their bark. Black mangroves do not possess prop roots. Instead their roots are specially designed with pneumatophores that act as snorkels and stick up out of the water. These pneumatophores allow the roots of the tree to breathe even during high tides (Figure 6.15).

Figure 6.15. Black mangrove (*Avicennia germinans*) tree with pneumatophores protruding from the water at high tide.

The root systems of red mangroves are called prop roots because they primarily exist above the substrate and prop up the tree. The unusual design of prop roots allows them to have a specific function in this ecosystem as well as serve the traditional purpose of tree roots (Figure 6.16). Prop roots help prevent erosion by storms such as hurricanes and reduce wave energy, similar to a coral reef. This feature of mangroves is why they are protected in Florida in the United States and why they are being replanted in many places in Indonesia. Because these roots provide a cage-like structure under the water at high tide and collect sediment, many organisms find a home among the roots. Algae, oysters, sponges, crabs, barnacles, fish and other crustaceans all live among mangrove roots, making mangrove a keystone species in this environment.

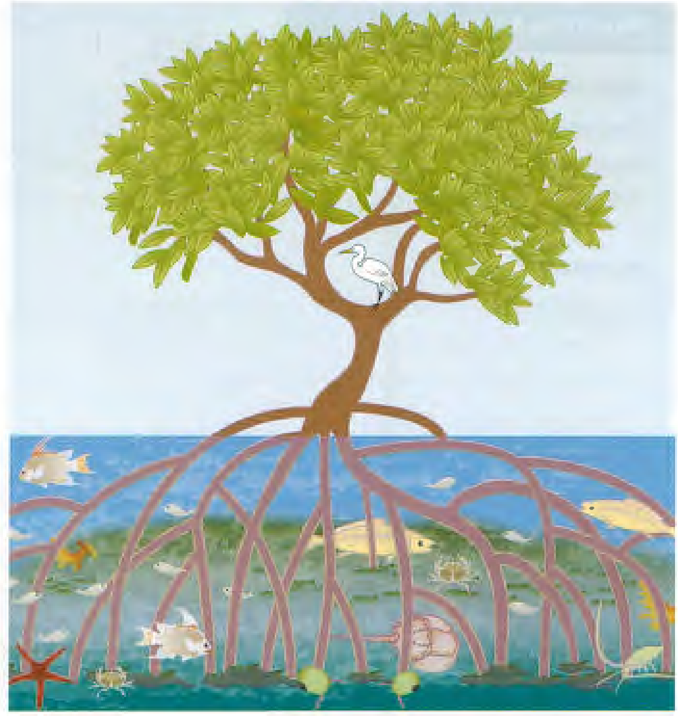


Figure 6.16. Illustration of red mangrove (*Rhizophora mangle*) showing how the prop roots retain sediments and act as a habitat for local species.

The extensive root system also makes mangroves unique in their ability to grow their own habitat. When a mangrove tree produces seeds, or propagules, they float around in the ocean for a period of time (each species requires a specific length of time). Eventually, the propagule will come to rest on a piece of land and begin to root. In some cases the 'land' is just a sand bar or area of high **sedimentation**. Once the propagule takes root, a new mangrove tree begins to form. The roots of the newly formed tree begin to act as a trap for sediment and slowly build an island as more mangrove colonise the trapped sediment.

KEY TERM

Sedimentation: the act or process of depositing sediment from a solution (e.g. seawater)

SELF-ASSESSMENT QUESTIONS

9 What is the primary difference between an estuary and a delta?

10 Why are rocky shores able to house more biodiversity than sandy shores?

11 How do the roots of the red mangrove work to create an ecosystem?

PRACTICAL ACTIVITY 6.1

Sediment-settling tube

Purpose

Sediment-settling tubes are used to determine how quickly different diameter sediments settle when water stops moving.

Materials

- One clear plastic tennis ball can with lid, or a 45 cm clear plastic watertight tube with PVC caps on both ends
- Four containers, one each containing:
  - diatomaceous earth
  - sand
  - soil
  - pebbles
- Enough water to fill the tube
- Electrical or duct tape
- Timer or stopwatch

Method

- Make sure the tube is capped at one end.
- Pour material from the four containers into the tube.
- Add water to fill the tube up to near the top.
- Place the remaining cap on the open end and secure with tape.
- Shake the tube so that all the material is mixed in the water.
- Set the tube down on a flat surface and allow the material to settle.
- Start timing as soon as the tube is set down.
- Time how long it takes for all of the material to settle to the bottom.

Conclusions

1 How does this tube represent the sedimentation seen on different types of shore?

2 Based on this tube and your knowledge of substrate types, rank the shores (sandy, rocky, muddy) from greatest to least amount of wave action, and explain your ranking.

3 Using what you know about mangroves and this demonstration, explain why mangroves play a vital role on sandy shores.

CASE STUDY

Mangrove benefits, loss and restoration

Mangroves are found in tropical and subtropical areas around the world. Several species of mangrove trees will live in a typical mangrove swamp, depending on the tolerance of each species to salinity and anoxic soil. Those species that are able to spend the longest time submerged, and with the greatest tolerance for salinity, will grow best nearest the sea. The other species will grow in zones up the shore based on their tolerance of these factors.

Benefits of mangroves

There are many ecological and financial benefits to mangroves growing along a coastline. Mangroves act as a buffer for coastal regions against tropical cyclones and other heavy storms by creating a wave break. The roots of the mangroves closest to the shore, particularly red mangroves, help prevent erosion by holding sediment in place. These root systems prevent the need for **beach renourishment** along exposed coasts, saving millions of dollars.

Ecologically speaking, mangrove forests are a natural way of fighting global climate change. Mangroves absorb carbon dioxide, the primary greenhouse gas released through the burning of fossil fuels, and store it in their extensive root systems. In tropical ecosystems, mangrove forests are the most carbon-dense forests. Mangrove forests in Indonesia contain over 3 billion metric tonnes of carbon within the soil, living trees, roots and dead branches.

KEY TERM

beach renourishment: the process of dumping sand from another location onto an eroding shoreline to create a new beach or to widen the existing beach.

Deforestation

The world's largest area of mangrove forest, nearly 3 million hectares, is located in Indonesia, a mangrove biodiversity hot spot. Since 1980, Indonesia has lost approximately 40% of its mangrove forest, compared with a global destruction rate of 20%. This gives Indonesia the reluctant honour of the fastest rate of mangrove destruction worldwide. Worse, the deforestation of these areas is responsible for 42% of the global greenhouse emissions released as a result of the destruction of coastal ecosystems (for example marshes, mangroves and seagrasses).

There are several causes of mangrove loss globally: logging, conversion of land to agriculture, and devastation of land as a result of pollution, such as oil spills. The primary cause of mangrove loss in Asia, however, is aquaculture, particularly shrimp farming. Between 1988 and 2008 the world production of shrimp from these farms rose drastically from 500 000 metric tonnes to 2.8 million metric tonnes. Indonesia, China and Vietnam have destroyed huge swathes of mangroves in order to support this industry, despite the fact that doing so has harmed other local industries and fishermen in the region.

Reforestation

Many governments have come to realise that the financial benefits of having intact mangrove forests outweigh the needs of one particular industry (Figure 6.17). Coastline protection, the addition of new land through the natural sedimentation process created by the mangrove root system, and nursery services for young fish, all have financial value to the countries involved. Studies showing how vital intact mangrove systems are to ecosystems and services have convinced governments that reforestation is necessary to protect their populations from rising sea-levels and tropical cyclones. The government of Belize, realising the financial importance of their mangrove forests (over US\$150 million year^{-1}), has implemented strict regulations to protect mangroves from deforestation. At a loss of only 2% over the last 30 years, their regulations are considered to be successful.

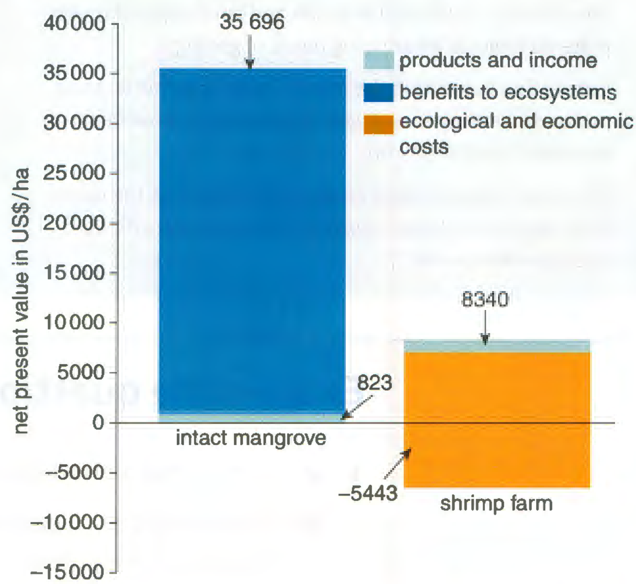


Figure 6.17. Comparing the economic and social value of mangroves and shrimp farms.

The governments of Vietnam and Indonesia have begun to take steps to restore their mangrove forests. In both cases, an emphasis has been placed on repairing local economies using mangrove forest restoration. People are encouraged to replant mangroves in order to improve local fishing and provide construction materials, pulp for paper and ecotourism.

Questions

1 Explain how mangrove forests slow down climate change.

2 Calculate the difference between the total net value (both social and economic) of intact mangroves and shrimp farms.

3 Imagine you are a conservationist working to convince a local government to rebuild the mangrove forest. Write a speech to the government explaining why intact mangrove forests are better for the economy than shrimp farming.

Summary

- Scientists once thought the ocean floor was completely flat and void of topography, but we now know otherwise.
- The creation of different habitats and landscapes through plate tectonics is an amazing result of geology.
- Convection currents in the mantle move gigantic tectonic plates, generating three types of boundary (convergent, divergent and transform).
- These boundaries create an array of features on the ocean floor, such as mid-ocean ridges, volcanoes, trenches and hydrothermal vents
- While the deepest seabeds may be one of the last ocean provinces scientists will ever get to visit, their importance to what lies above them cannot be denied.
- Marine ecosystems, like all other ecosystems, rely on what lies beneath them for their survival.
- The differences in the ocean floor, particularly along coastlines, create the many types of ecosystems present in the oceans and on the shores.

Exam-style questions

1 **a** Define what is meant by the term intertidal zone. **[1]**

b Compare the physical factors affecting organisms living on a rocky shore to those living on a sandy shore. **[4]**

c **i** Define the term vertical zonation. **[1]**

ii Explain how the physical and biological factors of a rocky shore ecosystem contribute to vertical zonation of the organisms that live there. **[2]**

[Total mark: 8]

2 **a** List three major lines of evidence supporting the theory of plate tectonics. **[3]**

b Describe the movement at each of the following plate boundaries and state one feature located there:

i transform boundary **[2]**

ii convergent boundary **[2]**

iii divergent boundary **[2]**

[Total mark: 9]

3 **a** State where you would expect to locate hydrothermal vents. **[1]**

b Outline how hydrothermal vents form. **[4]**

c Hydrothermal vents are considered to be extreme environments. Suggest an explanation for why that may be. **[3]**

[Total mark: 8]

4 **a** Describe the habitat where you would expect to find mangrove trees. **[3]**

b List and explain two adaptations mangroves have in order to survive within their habitat. **[2]**

c Explain how red mangroves benefit coastal ecosystems. **[4]**

[Total mark: 9]

5 *Tevnia* are a species of tube worms typically found at hydrothermal vent ecosystems. These marine invertebrates have free-swimming planktonic larvae and eventually grow into adults that form a symbiotic relationship with chemosynthetic bacteria. Researchers wanted to determine if high pressure attracted the tube worm larvae to settle in that ecosystem. Three containers of seawater were set up. Each container was kept at a different pressure: 0 atm (to represent sea-level), 100 atm (to represent a mid-level depth in the ocean) and 250 atm (to represent the pressure at a hydrothermal vent). Approximately 250 larvae were released into each container. Temperature, pH and salinity were carefully controlled. After 3 days, the numbers of larvae that had settled within each container were counted. The results are shown in Table 6.5.

container	number of tube worm larvae settled
0 atm	15
100 atm	87
250 atm	95

Table 6.5. Number of tube worm larvae settled in each container.

a Using the data in Table 6.5, describe the effect of pressure on the attachment of *Tevnia* larvae. **[2]**

b The attachment of *Tevnia* is also affected by other factors, including pH.

Outline a laboratory-based experiment to determine whether pH plays a role in settlement of *Tevnia*. **[5]**

[Total mark: 7]

EXTENDED CASE STUDY

Each letter needs sentence
5 facts each letter

Estuary loss in South Florida

Estuaries in Florida

Estuaries are an important ecosystem in the marine environment of Florida, USA. These areas, where fresh water from rivers joins salt water from the sea, provide habitat for more than 70% of the fish, crustaceans and shellfish that are important commercially and recreationally to Florida. These organisms primarily spend time in the estuaries when they are newly hatched or juveniles, as the adults return to estuaries in order to breed.

Because of the inflow of nutrient-rich fresh water from the rivers, estuaries are highly productive ecosystems. Phytoplankton, algae and seagrasses can all be found in estuaries, where the access to nutrients and sunlight in the shallow water increases the rate of photosynthesis. These producers then provide energy in the form of food to other organisms higher up the food chain. When the producers die, detritivores break down the remains, adding even more nutrients to the environment. All of this energy and nutrition combine to create an excellent nursery area for small fish and invertebrates.

Lake Okeechobee and its drainage problem

Lake Okeechobee, located in South Florida, is the seventh largest fresh-water lake in the United States. Its area is more than 1900 km^2, but it is a very shallow lake with an average depth of only 2.7 m. It is an integral part of the Everglades ecosystem that provides Florida with its fresh water. However, as water flows from the Kissimmee River into Lake Okeechobee it carries tonnes of fertiliser and pesticide waste from farms upstream.

Historically, when too much water entered Lake Okeechobee, the lake would overflow and send water down into the Everglades with vital nutrients. However, that flow was changed after two devastating hurricanes moved over a newly settled South Florida. In 1926, the Great Miami Hurricane killed 300 people after moving inland. Just 2 years later, in 1928, the Okeechobee hurricane hit Florida. After moving over land, the hurricane passed over Lake Okeechobee, causing a storm surge that drove water over the minimal mud dike. This flooded the neighbouring towns, killing thousands (the exact number is not known because of poor residential records).

After these hurricanes cost so many lives, the US Army Corps of Engineers built a flood control system, including the Herbert Hoover dike, to prevent damage from future storm surges. The dike was expanded a few years later to accommodate larger storms. Since then the dike has prevented most of the outflow from Lake Okeechobee into the Everglades system, holding on to vital nutrients and water.

C: Lake Okeechobee and Florida's estuaries: what's the connection?

Too little water

Because water that flows into Lake Okeechobee is kept there instead of being allowed to flow out as it naturally should, an incredible amount of pesticides, fertilisers and sediment has built up on the bed of Lake Okeechobee. In 2007, a severe drought affected South Florida and the water levels in Lake Okeechobee dropped to historic lows. Many parts of the lake bed were exposed and accessible to people and wildlife. Water management officials thought removing the mud would help restore the lake's substrate to a sandy bottom and increase water clarity, making the water healthier. Officials tested the mud to see if it could be used in agriculture as a compost, but discovered that it contained high levels of toxins such as arsenic. The mud was therefore considered to be too toxic for agricultural or commercial use, making its disposal a challenge. It was not until Tropical Storm Fay in 2008, when 1.2 m of rain raised the water levels in Lake Okeechobee, that some improvement was seen in the lake quality.

D. Too much water

Since 2008, the water levels in Lake Okeechobee have continued to rise as a result of storms and the seasonal rain of South Florida. Unfortunately, the lake can only contain so much water before the 70-year-old dike holding back its waters is in danger of being damaged. The US Army Corps of Engineers tries to keep the lake level between 3.8 m and 4.7 m to reduce the strain on the dike; but in years like 2016, when rain levels are abnormally high, maintaining these levels becomes impossible without draining the lake. Additionally, flood water from the sugar plantation fields that surround Lake Okeechobee is directed into the lake, adding more polluted water and sediment to the already toxic mix. Since 2013, the US Army Corps of Engineers has had to pump billions of gallons of polluted water from Lake Okeechobee to prevent damage to the Herbert Hoover dike. If the dike is destroyed and the waters from Lake Okeechobee overflow into the five neighbouring counties, the potential damage and loss of life could rival that seen when the levees in New Orleans broke during Hurricane Katrina in 2005.

When draining Lake Okeechobee, water managers send water from the lake into two major canal systems, one to the east and one to the west. To the east the water drains into the St Lucie River estuary, and to the west the water drains into the Caloosahatchee River estuary. In both cases the normal inflow of fresh water into the estuary is elevated and causes incredible damage to the estuary ecosystems, and the ecosystems they are connected to, such as the Indian River Lagoon.

E Damage to the estuaries

As billions of gallons of water are pumped out of Lake Okeechobee and into estuaries on both the east and west coasts of Florida, residents, environmentalists, scientists and policy-makers are all wondering if this is the right thing to do. The evidence of pollution is clear: aerial photos show a mass of brown water entering the clear blue waters of the estuary. However, pollution is not the only risk to the estuaries caused by these releases: the lack of salt in the water can cause just as many issues for the aquatic life of the region.

Estuaries rely on the inflow of fresh water from rivers to combine with the salty seawater from the ocean to reduce salinity. The organisms living in estuaries are adapted to living in this medium salinity, brackish water. Too much fresh water coming into the estuaries reduces the salinity to dangerous levels for many of the plants and animals found in these waters. These reduced salinity levels are the most likely cause of multiple fish-kill events and a massive die-off of seagrasses and oyster beds lining the estuary bottom. Additionally, a number of (potentially toxic) algae blooms cloud the water whenever large releases of water from Lake Okeechobee enter the estuaries (Figure 6.18).

Figure 6.18. Algal bloom where water from Lake Okeechobee meets the water of the Caloosahatchee River Estuary.

F. While too little salinity is a problem for those estuaries on the east and west coasts of central Florida, too much salinity has become a problem for Florida Bay in the south. By not allowing fresh water to drain naturally through the Everglades, Florida Bay is unable to maintain its historical salinity levels. In February 2016, Florida's Governor, Rick Scott, asked the US Army Corps of Engineers to raise the water levels in canals flowing southwards to divert water from Lake Okeechobee away from the central estuaries and allow it to flow south. While this will do nothing to fix the pollution problem, it will reduce fresh-water outflow to the east and west by sending it south towards the Everglades and Florida Bay.

G. Possible solutions

Unfortunately, there are no ready solutions in the near future to handle the billions of gallons of water necessary to reduce water levels, and protect the estuaries and the people who are connected to Lake Okeechobee. Some relief should come in 2019 when the US Army Corps of Engineers plans to have completed a reservoir designed to hold some of the necessary water. In the meantime, politicians are asking for relief from the federal government; but that is unlikely to be successful because any positive outcome will not be seen immediately, and decision-makers like to see quick results.

Questions

1 How could this outflow of fresh water affect not only the estuary the river leads to, but also the environment outside the estuary?

2 How do you think these water releases affect Florida's economy? Make sure to discuss both the economy related to the coast and estuaries, and the economy related to agriculture.

3 The release of water from Lake Okeechobee has already been held responsible for the die-off of seagrasses within the affected estuaries. How does this die-off impact upon the available energy within these ecosystems?

4 Beyond repairs to the Herbert Hoover dike, what other repairs or changes need to be made to improve the water quality and quantity flowing from Lake Okeechobee?

Chapter 7
Physical and chemical oceanography

Learning outcomes

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

- explain how volcanic activity, run-off and dissolved gases affect the chemical composition of seawater
- describe how evaporation and precipitation affect the salinity of seawater
- explain how temperature and salinity create gradients and layers within the ocean, and how those layers can be mixed
- explain why different concentrations of dissolved oxygen exist within bodies of water
- discuss how tides are formed and influenced by many factors
- explain how ocean currents and upwelling are caused
- explain the causes and effects of El Niño events in the Pacific Ocean
- describe how monsoon winds are formed in the Indian Ocean
- explain the cause and impact of tropical cyclones
- apply what you have learnt to new, unfamiliar contexts.

7.1 Understanding the ocean

When scientists study chemical and physical oceanography, they are really studying the forces that make the entire ocean able to function. On the surface, chemical and physical oceanography appears to be merely the study of the ocean's chemistry and physical properties. While that is an accurate definition, it does not touch on the real purpose for studying these fields: most people study the chemistry of water and forces within the ocean to understand how they make life possible. How can organisms exist in waters with nearly zero dissolved oxygen? How can the flooding rains that are blown in with the monsoons be a benefit to the communities affected? How does the ocean moderate the world's climate? What causes the tides that control the mating behaviour of so many animals? All of these questions and thousands more have been answered by studying how the ocean functions.

This chapter covers a broad range of topics under the very large umbrella of chemical and physical oceanography. From minerals dissolved in the ocean's waters to the destructive winds of tropical cyclones and everything in between, chemical and physical oceanography explain many of the mysteries of marine science. However, the most important aspect of all these individual pieces is how they fit together. When scientists study coral reefs, they cannot just study the individual polyps that make up the reef. They must also look at the nutrients available in the water: are there too many or too little? They must look at the run-off entering the ocean from the coast: is it toxic? If so, how toxic? They need to study sea surface temperatures in order to predict both coral bleaching and tropical cyclones. In all aspects of ocean life, the environment around an organism is of paramount importance to its survival.

7.2 Chemical oceanography and the chemical composition of seawater

Chemical oceanography is the study of ocean chemistry and the behaviour of those chemicals found within the ocean. Surprisingly, 'only' studying the chemicals found within the ocean is not particularly limiting. Nearly every element in the Periodic Table has been located, in some form, within the ocean's vast waters. Understanding the movement of these chemicals requires a fundamental knowledge of ocean circulation, climate and the interactions between the atmosphere, geosphere and hydrosphere on this planet.

KEY TERMS

Salinity: a measure of the quantity of dissolved solids in ocean water, represented by parts per thousand, ppt or ‰

Evaporation: a change in state from liquid to gas below the boiling point of a substance

Salinity

When studying chemical oceanography, traditionally you start by looking at the **salinity** of seawater. Salinity is a measure of the concentration of salts within a body of water. There are two methods commonly used to determine the salinity of a water sample.

- Total dissolved solids (TDS)
  Using this traditional method, a scientist **evaporates** a known volume of water and then weighs the solids left behind. This method is not particularly good for use in the field because of the equipment and time needed.
- Electrical conductivity
  This more modern method is faster and easier to use when out in the field. An electric current is passed between two metal plates, and how well the current moves between the plates is measured. The more dissolved salts (solutes) in the water, the greater the conductivity (ease of flow) between the plates. The information gained from electrical conductivity can be used to estimate the total dissolved solids.

The unit used for salinity is parts per thousand (ppt or ‰). This unit was originally derived using TDS. Scientists would take 1000 g of seawater and evaporate it. The solutes left behind, usually ions called salts, were then weighed, making them the 'parts' that make up 1000 g of water. After hundreds of years of water samples, scientists now know that the average salinity of the open ocean is 35‰.

Composition of seawater

The first true scientific study of the open ocean happened between the years of 1872 and 1876 on HMS *Challenger*. This 70 000 km scientific voyage was the first of its kind.

Led by Charles Wyville Thomson, the Royal Society of London purchased an old warship and retrofitted it with scientific laboratories. These laboratories enabled scientists aboard to collect data in the fields of natural history and chemistry. More than 4000 new species of marine life were discovered on this journey, along with vital chemical oceanography.

When the *Challenger* returned home in 1876, the water samples taken during the voyage were sent to William Dittmar. After analysing the samples, Dittmar discovered the same six ions made up the majority of the solutes in seawater (Table 7.1). Additionally, he found that, regardless of the concentration of salts in the water, the ions were always present in the same percentages. He termed this phenomenon the 'theory of constant proportions'.

From Table 7.1, you can see that the majority of the salts in the ocean are sodium and chloride. This should not be a surprise as seawater tastes like table salt, which is a common name for sodium chloride (NaCl). Other ions, such as sulfate, magnesium, calcium and potassium, play vital roles in the biology of the ocean. Many other ions are also present but in such small concentrations that they are called micronutrients (for example nitrogen, phosphorus and hydrogencarbonate). Dittmar's theory of constant proportions holds true for the open ocean and, generally, for coastal regions.

However, further research has found that ion concentrations can be changed by local events, such as atmospheric **dissolution**, volcanic eruptions and run-off (Figure 7.1). These are the three major sources of ions in the world's ocean, and each is discussed in this chapter.

KEY TERM

Dissolution: the dissolving of a solute into a solvent

Effect of atmospheric dissolution on the chemical composition of seawater

Gases in the atmosphere (nitrogen, carbon dioxide and oxygen) are in a state of equilibrium with the gases dissolved in ocean water. As the concentration of a particular gas in the atmosphere increases (carbon dioxide, for instance), the concentration of that gas in seawater also rises. Mixing, as a result of turbulence and wave action, works to maintain this equilibrium. The more turbulence there is, the easier it is for gases in the atmosphere to dissolve into the ocean. This can lead to higher concentrations of carbon dioxide and oxygen within the first 200 m depth of the ocean than are found in the atmosphere. Factors contributing to the concentration of gases in seawater include the following.

- The solubility of the gas
  Solubility refers to the ability for a particular solute, like carbon dioxide, to dissolve in a solvent, like seawater. Carbon dioxide is very soluble in seawater because of its ability to form carbonic acid, a weak acid, when introduced to water. Oxygen, while more soluble than nitrogen, is less soluble than carbon dioxide. Oxygen and nitrogen are less soluble because they do not chemically combine with the water molecules. This means that the level of carbon dioxide held by seawater is higher than that of oxygen and nitrogen.
- The temperature of the seawater
  Cold water is able to hold more gas than water at warmer temperatures. This means that water found near the poles will hold more oxygen than water found in the tropics (Table 7.2).

KEY TERM

Solubility: the ability of a solute to dissolve into a solvent

ion	mean concentration in seawater / parts per thousand (‰)	Ratio of ion : total salts / percentage (%)
chloride (Cl^-)	19.35	55.04
sodium (Na^+)	10.75	30.61
sulfate (SO_4^{2-})	2.70	7.68
magnesium (Mg^{2+})	1.30	3.69
calcium (Ca^{2+})	0.42	1.16
potassium (K^+)	0.38	1.10

Table 7.1. Concentrations of the six most common ions in seawater.

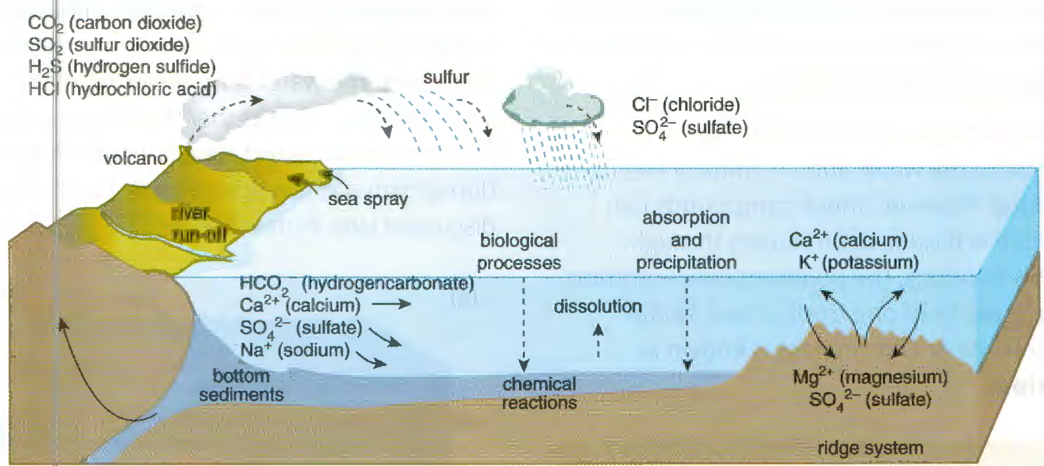


Figure 7.1. How chemicals get into our oceans: atmospheric dissolution, volcanic activity and run-off.

temperature of water / °C	concentration of dissolved oxygen / mg dm^{-3}
0	14.6
5	12.8
10	11.3
15	10.2
20	9.2
25	8.4

Table 7.2. Relationship between temperature and the maximum concentration of dissolved oxygen in fresh water.

- The salinity of the seawater
  Gases are able to dissolve better into water with lower levels of salinity. Therefore you would expect to find higher levels of oxygen in an estuary than in the open ocean or the Dead Sea.
- The presence of organisms in the seawater
  Organisms play a large role in determining how much of each gas is found in the different layers of the ocean. Nitrogen gas that is dissolved can be transformed into ammonia by nitrogen-fixing bacteria. This makes the nitrogen easier to use for other organisms. At the surface, producers take in dissolved carbon dioxide for use in photosynthesis. Consumers and producers both use dissolved oxygen for respiration.

Effect of volcanoes on the chemical composition of seawater

When volcanoes above sea-level erupt, they pour tonnes of hot ash into the atmosphere. Within that ash are many minerals and gases that impact our oceans. In particular, carbon dioxide (CO_2), sulfur dioxide (SO_2), hydrogen sulfide (H_2S) and hydrogen chloride (HCl) leave the volcano mixed with the particulates of ash. When these gases enter the atmosphere they mix with atmospheric water, especially water already condensed into a cloud. When the cloud becomes **precipitation**, the dissolved gases rain down into the ocean as part of the hydrological cycle. The addition of these ions into the water changes the ion concentration for a brief time.

Volcanoes that are still submerged can also impact upon the ion concentrations of the seawater around them. These volcanoes, located at either convergent or divergent plate boundaries, erupt releasing the same gases into the water. Submerged volcanoes have been releasing hydrogen chloride and chlorine gas into the ocean since the ocean was first formed. In fact, they have released so much chlorine gas they are considered to be the primary source of chloride ions found in today's seawater.

KEY TERMS

Precipitation: water that falls from the atmosphere to the Earth's surface as rain, sleet, snow or hail

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

Effect of run-off on chemical composition of seawater

Run-off is water that flows over the Earth's surface due to precipitation or melting snow or ice. As this water flows over city streets or through farmers' fields, it dissolves many substances and carries them along. These substances could include vital nutrients, pesticides, fertilisers, oils and other pollutants. Eventually, most of this water, as part of the hydrological cycle, finds its way to the oceans, either directly or by first flowing into a river. So, while run-off is not considered a pollutant, it is capable of carrying many types of pollution into the ocean.

Many of the pollutants carried by run-off have a very low concentration in the water and are initially seen as non-threatening. However, these compounds can be absorbed into the tissues of producers through uptake. Once this happens, the pollutant concentration increases as it passes from one trophic level to the next within a food chain. This process is known as **biomagnification**.

KEY TERM

Biomagnification: the increasing concentration of a substance, such as a toxic chemical, in the tissues of organisms at successively higher levels in a food chain

Since the Industrial Revolution, many examples of biomagnification have come to light. In the United States, the use of a pesticide known as DDT was responsible for the near extinction of several predatory bird species, including the bald eagle. Another example comes from Minamata city in Japan.

Fertilisers carried to the ocean can also pose a unique risk to marine ecosystems. Most chemical fertilisers contain a mixture of nitrogen and phosphorus. Both of these nutrients are necessary for the growth and health of plants, including algae and phytoplankton, and are normal in the ocean in low concentrations. Nitrogen and phosphorus are considered to be limiting factors in marine ecosystems because their low concentrations helps control the population of producers. However, chemical fertilisers contain very high concentrations of these elements and, when dissolved in run-off, their presence can disrupt local coastal ecosystems. Excessive fertiliser in run-off is a primary cause for harmful algal blooms (HABs) that can be toxic to both the environment and humans.

Effects of evaporation and precipitation on salinity

While 35‰ is the average salinity of ocean water, the actual salinity at any given location does vary. In areas with fresh-water run-off or melting glaciers, for example, the salinity may be much lower. This lower salinity is caused by the addition of water, rather than the removal of salts. Precipitation (for example rain or snow) also lowers the salinity of a body of water by diluting the salt in the seawater with incoming fresh water. Estuaries are a great example of salinity varying throughout a body of water. Near the mouth of the river within an estuary, the water is considerably less saline than the water nearest the ocean. The water lying at the top of the water column in an estuary is also fresher than water on the bottom. This means that salinity levels within an estuary change during high and low tides (Figure 7.2). This phenomenon is discussed later in this chapter.

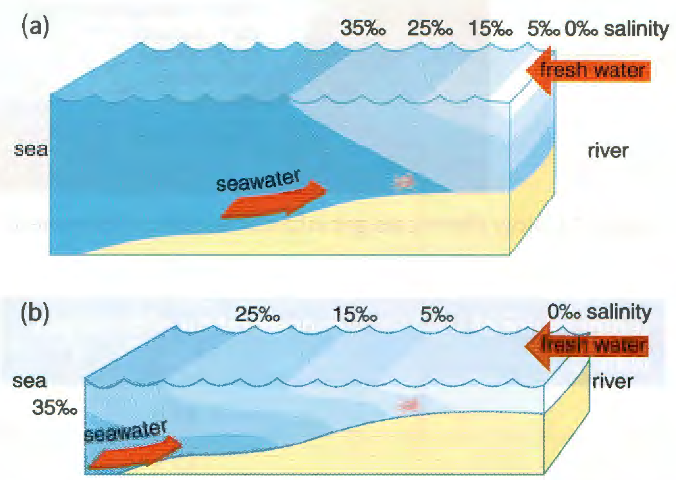


Figure 7.2. Salinity levels in an estuary at (a) high tide and (b) low tide.

Salinity higher than 35‰ is often found in regions with above-average evaporation rates and a limited fresh-water inflow. When the salts are even more concentrated, the water is described as **hypersaline**. One example of a hypersaline environment is the Dead Sea, an inland sea found between Jordan and Israel. The salinity levels are ten times that of the open ocean. Salinity is so high that salt coats the beach as a result of evaporation (Figure 7.3).

KEY TERMS

Hypersaline: when a body of water has a salinity level greater than 35‰

Dissolved oxygen (DO): oxygen that has dissolved into water

Dissolved oxygen and the oxygen minimum layer

The concentration of **dissolved oxygen (DO)** varies throughout the ocean. As mentioned above, both temperature and salinity affect the concentration of dissolved oxygen in the ocean. The higher the water temperature, the lower the oxygen concentration. Also, the higher the salinity, the lower the dissolved oxygen concentration, although this difference is slight.

Figure 7.3. Dead Sea salt crystallises along the shore and looks like snow.

CASE STUDY

Dead Sea

The Dead Sea is a hypersaline lake located in the Middle East in the Jordan Rift Valley. On its eastern shore lies the country of Jordan, while its western shore borders Israel and the West Bank. At 377 m deep, the Dead Sea is considered to be the deepest hypersaline lake in the world. This depth also helps make the Dead Sea the lowest elevation on land, at 423 m below sea-level.

This 50 km long and 15 km wide body of water is considered to be one of the saltiest places on Earth. The salinity of the water in the Dead Sea ranges from 280 to 350‰. The salinity varies depending on the time of year and where in the water column the measurement was taken. Measurements taken nearest the surface tend to be higher because of the high evaporation rates in the desert-like conditions of the Jordan Rift Valley. As typical ocean water contains salinity levels of only 35‰, the waters of the Dead Sea are, on average, 8.5 times as salty.

For thousands of years, the Dead Sea has been a vacation destination. The salty waters are rumoured to have healing powers because of its mineral content. Swimming here is really just floating on the incredibly dense waters. According to historical rumour, the first health spa was located at the Dead Sea for Herod I (37–34 BCE).

It is ironic that the Dead Sea is considered to be a place of health and healing considering that salinity levels make it impossible for most animals to live there. Only a few species of archaea, bacteria and fungi are capable of making their homes in the Dead Sea on a continuous basis. However, during 1980, a particularly rainy winter reduced the salinity so much that a new type of algae became established and turned the waters red.

Today, the Dead Sea is used to produce a major component of fertilisers: potash. Potash is the common name for potassium chloride and it has been mined from the Dead Sea since 1929. In order to remove potash from the waters of the Dead Sea, shallow evaporation pools have been created in the southernmost portion of the lake (Figure 7.4). This allows sunlight to evaporate water from the brine and leave the salts behind. The waters of the Dead Sea are replenished by the Jordan River. However, in order to make these pools successful, the southern end of the Dead Sea has had several barricades, or dikes, built to prevent water from the Jordan River from flowing in naturally. This allows the corporations mining the potash, such as Dead Sea Works, to control rainwater flow.

Unfortunately, this evaporation process, which has been happening for nearly 100 years, has caused a severe drop in water levels. Between 1970 and 2006, the water levels in the Dead Sea dropped an average 1 m $year^{-1}$. This reduction has been followed by a drop in groundwater, leading to sinkholes, when the underground salt structures collapse.

Questions

1. Potassium is a minor component in seawater. When seawater is evaporated, which minerals would you expect to find the most of?
2. Evaporation is a major factor in the salinity of the Dead Sea. What role does it play in the ocean?
3. How does the increased salinity of the Dead Sea due to the fertiliser industry impact upon the microscopic organisms that live there?

Figure 7.4. Aerial views of the Dead Sea taken in 1972, 1989 and 2011.

The area of the ocean with the greatest concentration of dissolved oxygen is the top 100 m of the ocean, known as the surface layer. Within this layer, the dissolved oxygen concentration can reach 'supersaturation'. This means there is more oxygen dissolved in the seawater than it would normally be able to carry. Two major factors work together to increase the amount of dissolved oxygen to supersaturation level: the motion of the water and photosynthesis by producers. The more turbulent the water, the more oxygen is mixed into it by the movement of the waves. Meanwhile, producers, like phytoplankton and algae, use photosynthesis to create glucose and generate oxygen as a byproduct. This oxygen adds to the amount of dissolved oxygen in the surface layer. Dissolved oxygen is removed from this layer by the respiration of organisms.

Below the surface layer of the ocean, the concentration of dissolved oxygen changes dramatically. As the depth of the ocean increases, the level of dissolved oxygen decreases until it reaches the **oxygen minimum layer**. The oxygen minimum layer typically occurs at a depth of around 500 m, but has been found anywhere between 100 and 1000 m deep depending on location. Some organisms are capable of living within the oxygen minimum zone, despite the lack of dissolved oxygen, but they do need special adaptations for survival. Most of the organisms found here are fairly inactive, which reduces their need for oxygen. The gills of the fish in this area are incredibly efficient at extracting oxygen from water, even at the low levels present in this layer. Additionally, many of the organisms here have a very oxygen-efficient form of hemoglobin, a blood protein responsible for carrying oxygen throughout the body.

After reaching the oxygen minimum layer, the oxygen concentration begins to increase deeper into the ocean. Three reasons exist for this subtle increase in oxygen (Figure 7.5).

- First, the organisms found below the oxygen minimum layer are in an area with very few food resources. This lack of food reduces the need for the organisms to respire, so they survive with less oxygen.
- Second, the solubility of oxygen increases as the temperature decreases. As you go deeper into the ocean, the temperature decreases to near-freezing. The lower temperature means oxygen is more likely to stay dissolved in the water.
- Third, as pressure increases, the solubility of oxygen increases. For every 10 m you sink into the ocean, the pressure increases by one atmosphere. This pressure keeps the water and oxygen molecules packed closely together, allowing for greater solubility of the oxygen.

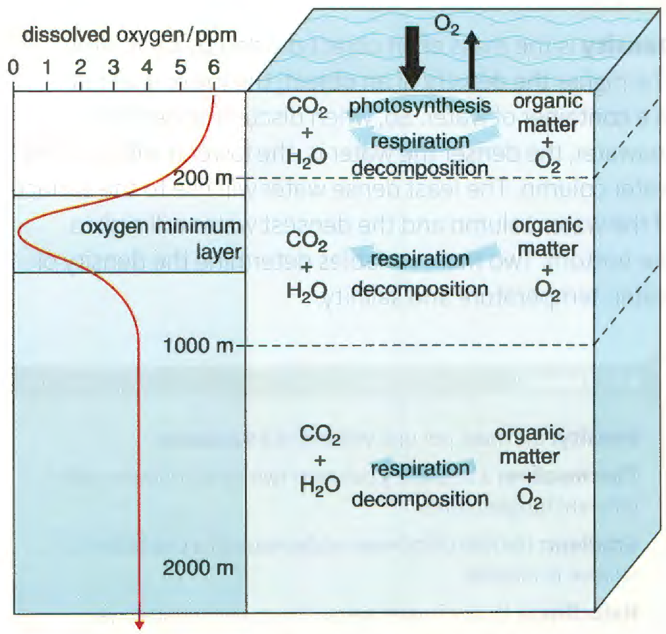


Figure 7.5. Oxygen minimum layer in the eastern tropical Pacific Ocean and the biological processes responsible.

KEY TERM

Oxygen minimum layer: the layer within the ocean where the concentration of dissolved oxygen is at its lowest, typically found between 100 and 1000 m deep

SELF-ASSESSMENT QUESTIONS

1 What are the three most important gases in seawater, biologically speaking? How do they impact upon life in the ocean?

2 How do volcanoes and run-off change the composition of the world's ocean?

Layers in the ocean

From the surface, the ocean appears to be a uniform mass of water. Through the many scientific studies that have taken place since the *Challenger* expedition, scientists now know that the water in the ocean is anything but uniform. Temperature, salinity and density change with depth, creating layers within the sea.

Density

Density is the mass of an object divided by its volume. The higher the density of an object, the lower it will sit in a container of water. So, when discussing density in seawater, the denser the water is, the lower it will sit in the water column. The least dense water will rise to the surface of the water column and the densest water will sink to the bottom. Two main variables determine the density of water: temperature and salinity.

KEY TERMS

Density: the mass per unit volume of a substance

Thermocline: a boundary between two layers of water with different temperatures

Gradient: the rate of increase or decrease of a characteristic relative to another

Halocline: a layer of water below the mixed surface layer where a rapid change in salinity can be measured as depth increases

Temperature

Temperature is the factor most responsible for changes in density. As temperature increases, density decreases. This is why, when looking at a profile of the water column in the ocean, the warmest water sits on top of the water column. This warm layer is fairly shallow and it sits on top of colder, denser water. Between the two layers is an area where the temperature abruptly changes, known as the **thermocline** (Figure 7.6). Water at the surface may reach 25 °C or higher in tropical seas, but is more likely to be 1 °C at depths of 2000 m or more. In polar seas, the temperature **gradient** is less drastic. In these areas, the surface water is likely to be about 10 °C and cools with depth to about 1 °C, with only a very faint thermocline, if one is present at all.

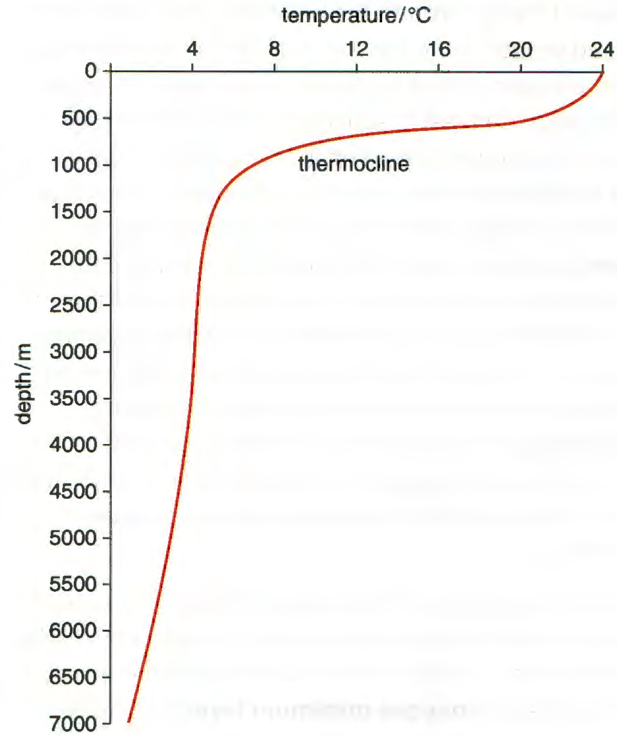


Figure 7.6. Thermocline in a typical tropical sea.

Salinity

Salinity has less of an impact on density than temperature, but the interaction between salinity and temperature makes it worth mentioning. As salinity in the ocean increases, so does the density of the water. Therefore, water with the lowest density floats on top of water with higher densities. This is why in an estuary, fresh water sits above the salt water. Between the less saline, and therefore less dense, surface waters and the more saline, more dense, bottom waters, there is an area where salinity changes significantly with depth. This area is called the **halocline**.

This would indicate that the saltiest water in the ocean is at the seabed. For the most part this is true, but there is one exception: tropical seas. In tropical seas between 30° N and 30° S, the temperatures create high evaporation rates at the surface. This results in a very warm, but also very salty, layer across the surface of the ocean. This layer floats on the surface, in spite of its increased salinity, because the temperature is so high. Just below that layer, the salinity profile shows a steep decrease in salinity, the halocline, until 750 m, followed by a slow increase, as expected (Figure 7.7).

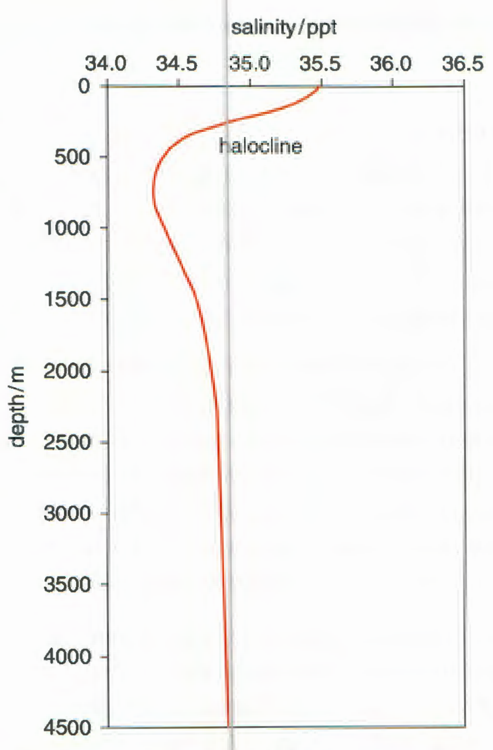


Figure 7.7. Typical halocline in a tropical sea.

Mixing of the layers

The surface layer of the ocean, from zero to 200 m deep, is the best-mixed area of the ocean. As the wind blows across the surface of the ocean, currents and turbulence are created. This water movement mixes the first 200 m of the ocean, making it fairly uniform in both temperature and salinity.

Mixing of the layers within the ocean can also be density driven. For example, if the surface of the ocean cools, the density of the water will increase. As the density increases, the water sinks, carrying with it all the nutrients and dissolved gases that it contained at the surface, mixing with the higher density water that is rising.

SELF-ASSESSMENT QUESTIONS

3 What impact do temperature and salinity have on density?

4 Sketch what you would expect the thermocline to look like in an Arctic environment.

PRACTICAL ACTIVITY 7.1

Creating a halocline

This practical demonstrates how a halocline forms in marine ecosystems. It can be modified to create a thermocline using hot and cold water.

Materials

- Small aquarium or clear, rectangular container capable of holding 2 litres of liquid
- Scale
- Two 1 dm^3 beakers
- 35 g salt, any type
- Blue food colouring
- Red food colouring

Method

- Prepare salt water (35 ppt).
  - Weigh 35 g of salt using the scale.
  - Place the salt into one of the 1 dm^3 beakers.
  - Place this beaker onto the scale.
  - Add water until the scale reads 1000 g (approximately 4 cups of water).
  - Add a few drops of blue food colouring and mix until consistent.
- Prepare fresh water.
  - Place 1 dm^3 of water into the second beaker.
  - Add a few drops of red food colouring and mix until consistent.
- Place fresh water into the aquarium and let it settle till calm.
- Slowly add salt water along the side of the aquarium.

Conclusions

1 As you are adding the salt water to the aquarium, what do you notice?

2 Why do you think this is happening?

3 Predict what would happen if a volume of hot, salty water was added to the tank.

4 Is there a halocline in your aquarium? Sketch a diagram of your aquarium to indicate where it is.

7.3 Physical oceanography

When studying physical oceanography, a scientist must take into account many physical factors that are in fact completely outside the ocean. Physical oceanography involves the gravitational pull of the Moon and Sun, the atmosphere, and the uneven heating of Earth's largely water-based surface. All these pieces of the global environment play a part in the formation of and changes within the marine environment.

Tides

A **tide** is the regular rise and fall of bodies of water as dictated by the gravitational interactions of the Moon, Earth and Sun. Tides can be found in all coastal areas as well as large lakes. Most coastal areas have tides with an interval of 12.5 h, creating two high tides and two low tides each day. Tidal patterns like this are called **semi-diurnal** and the tides are easy to predict. Areas with only one high tide and one low tide each day have a **diurnal** tidal pattern.

KEY TERMS

Tide: the periodic rise and fall of the surface of the ocean resulting from the gravitational pull of the Moon and Sun

Semi-diurnal: occurring twice daily

Diurnal: occurring daily

Tidal range

Tidal range, or tidal amplitude, is the difference in height between the low-water mark and the high-water mark on a coastline (Figure 7.8). Tidal range varies all over the world and from day to day. This variance is due to the gravitational effects of the Moon, Earth and Sun as well as physical features of the coastline where the tide is occurring.

Spring and neap tides

Spring tides create the greatest tidal range for coasts. These tides are not reliant on seasons, but rather on phases of the Moon. Spring tides occur during the phases of new moon (when the Moon is dark) and full moon. So a spring tide can be predicted to happen twice a month.

During spring tides, the Earth, Moon and Sun are in a straight line, with either the Earth between the Sun and Moon or the Sun and Moon on one side of Earth (Figure 7.9). This alignment amplifies the gravitational effects the Moon and Sun have on Earth, creating what is often called a larger than usual ocean bulge. This results in the highest of the high tides and the lowest of the low tides.

Neap tides have the smallest tidal range, with the highest low-tide marks and the lowest high-tide marks. During these tides, the Sun and Moon are at a right angle to each other, with the Earth as the pivot point (Figure 7.9). Neap tides occur during the first- and third-quarter moon phases. During this time the Sun and Moon are pulling the ocean in opposite directions, creating a smaller than average ocean bulge.

KEY TERMS

Tidal range: the difference in height between the high-tide mark and the low-tide mark over the course of a day, also called the tidal amplitude

Spring tide: a tide that occurs when the Sun and Moon are aligned, causing the largest tidal range

Neap tide: a tide that occurs when the Moon and Sun are at right angles from each other, causing the smallest tidal range

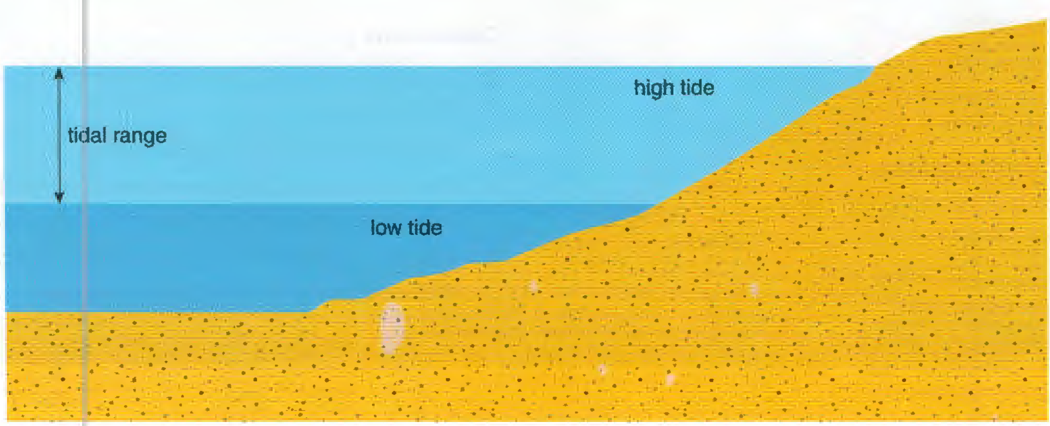


Figure 7.8. How to determine tidal range.

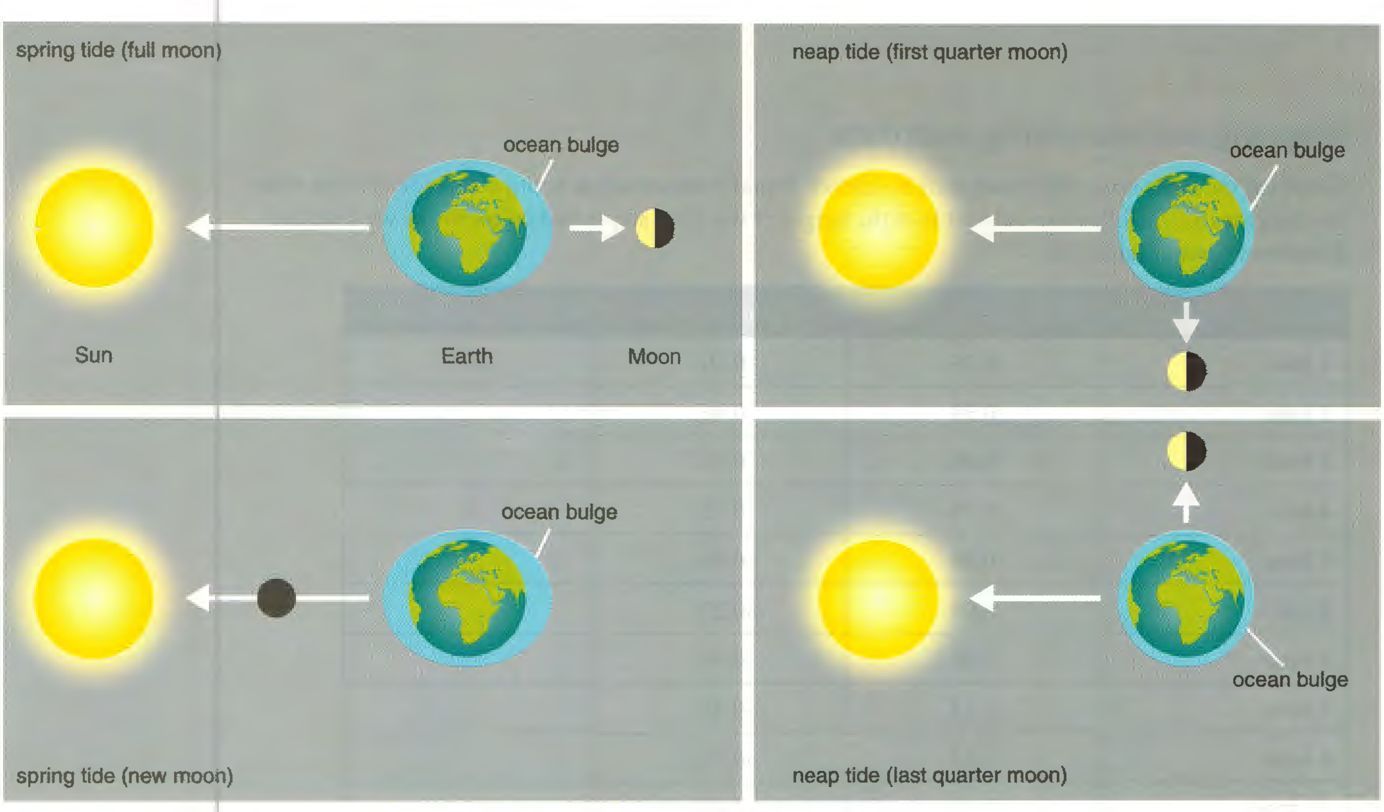


Figure 7.9. Positions of the Sun, Moon and Earth and how that determines the tide.

Physical factors affecting tidal range

Depending on the type of tide, as well as certain physical factors, the tidal range in different parts of the world can vary from 12 m to nearly nothing. The factor with the greatest influence on the tidal range is the coastline itself. The slope of the coast and the size of the body of water it contains, combined with local weather conditions, all influence the tidal range.

The shape of the coastline plays a large role in the size of the tidal range. If the tide is entering a particularly narrow channel (for example a river mouth or entrance to an estuary), the tidal height is increased because the water is being forced into a smaller area. If, however, the tide is happening along an open beach, the tidal height is much smaller because the same volume of water is more spread out.

An extreme example of the coastline changing the tidal amplitude is the Bay of Fundy in Canada, home to the highest tidal range in the world. The average spring tide range here is 14.5 m. The highest water level recorded in the Bay of Fundy, 21.6 m, occurred during the tropical cyclone Saxby Gale in 1869, providing evidence of another physical factor affecting tides: the weather.

Weather is a major factor in tide heights. In particular, changes in wind and air pressure can have incredible effects on tidal range. During a tropical cyclone, air pressure is much lower than usual, allowing water to swell. There are also high winds capable of pushing water onto the shore. Combined, these two factors are capable of creating a **tidal surge**, which is a dangerous rising of water higher than the predicted levels of the tide.

> **KEY TERM**
>
> **Tidal surge:** the coastal flood or tsunami-like phenomenon of rising water, associated with low pressure weather systems, also called a storm surge

Open ocean, seas and lakes

In the open ocean, tidal ranges are small, approximately 0.6 m. For the most part, the difference between high and low tide is unnoticeable, unless you enter the continental margin, where the water begins to get shallow. Small bodies of water, like the Mediterranean or Red Sea, also have tidal ranges, but they are minimal. Small tidal ranges even occur in large lakes, such as Lake Superior in the northern United States, but the effect is usually masked by the winds blowing across the lake.

Maths skills

Graphing and interpreting tidal data

Graphing data sets is an important skill in science. Equally important is being able to determine what the data mean. The following data set is of the height of the tides above and below mean sea-level for Barcelona, Spain (Table 7.3).

date	high-tide level / m	low-tide level / m	tidal range / m
1 June	0.55	0.50	0.05
2 June	0.59	0.46	
3 June	0.66	0.31	
4 June	0.76	0.13	
5 June	0.90	−0.06	
6 Jun	0.98	−0.23	
7 June	1.05	−0.37	
8 June	1.13	−0.46	
9 June	1.18	−0.50	
10 June	1.19	−0.48	
11 June	1.15	−0.42	
12 June	1.05	−0.31	
13 June	0.90	−0.17	
14 June	0.72	−0.02	
15 June	0.53	0.12	
16 June	0.34	0.25	

Table 7.3. Height of tides above and below mean sea-level in Barcelona, Spain.

Worked example

Tidal range is determined by subtracting the low-tide value from the high-tide value.

$$\text{high tide} - \text{low tide} = \text{tidal range}$$

As an example, 1 June has been completed for you: 0.55 – 0.50 = 0.05

Questions

1 Before setting up a graph, calculate the tidal range for each date and complete Table 7.3.

2 a Using standard graphing paper, create a graph representing the change in tidal range over time. Make sure your independent variable (date) is on the *x*-axis and your dependent variable (tidal range) is on the *y*-axis.

b Using your knowledge of tides, circle the date(s) of the spring tide(s) on your graph and explain why you chose that date(s).

c Using your knowledge of tides, draw a square around the date(s) of the neap tide(s) on your graph and explain why you chose that date(s).

KEY TERMS

Current: a continuous physical movement of water caused by wind or density

Coriolis Effect: a force that results from the Earth's rotation that causes objects or particles in motion to deflect to the right in the Northern Hemisphere and to the left in the Southern Hemisphere

Currents

Within any large body of water, you will find **currents**. In the ocean, currents are the continuous movement of seawater in a particular direction. Currents carry with them nutrients, dissolved gases and heat. Organisms can use currents to travel from place to place. Currents are created by different physical forces acting on the water, such as wind, the **Coriolis Effect**, temperature, salinity and tides. There are two major types of currents in our oceans: surface currents and deep-water currents.

Surface currents

Surface currents are typically driven by the wind. These currents are steady and dependable as a result of global wind patterns caused by an uneven heating of the Earth's surface by the Sun. Areas with large amounts of solar radiation (for example the equator) have excess heat in the air, causing it to rise in the atmosphere. As that air rises, it begins to lose some of its heat energy until it begins to sink in areas with less radiation and cooler temperatures. This movement of air in convection currents forms predictable winds, leading to constant surface sea currents at different latitudes (Figure 7.10).

In the Northern Hemisphere, these currents tend to have a clockwise spiral, while in the Southern Hemisphere they have a counter-clockwise spiral. These spiral patterns are caused by the Coriolis Effect. The Coriolis Effect is a result of the Earth's rotation. As an object moves across the rotating Earth, the object swerves slightly to the left or right rather than travelling in a straight line. So, as wind blows the seawater across the ocean surface the rotation of the Earth actually deflects the water at a 45° angle. That is why wind and currents have spiral patterns away from the equator in both hemispheres (Figure 7.11).

Deep currents

Deep-water currents (thermohaline circulation) are driven by differences in density caused by salinity and temperature. These currents happen along the ocean floor and cannot be detected by satellite imagery the way surface currents can. The movement of these currents over the planet is called the 'global conveyor belt' (Figure 7.12). These slow-moving currents carry a huge volume of water: more than 100 times the flow of the

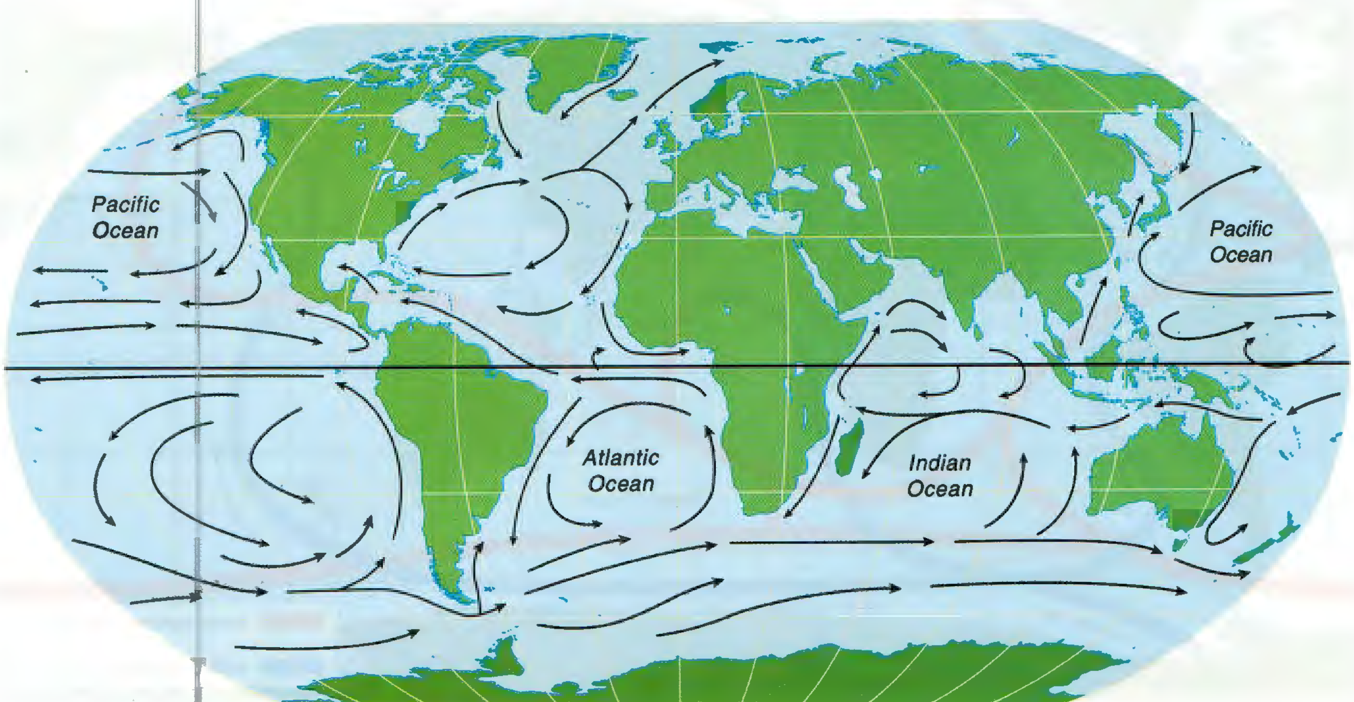


Figure 7.10. Surface currents in the ocean.

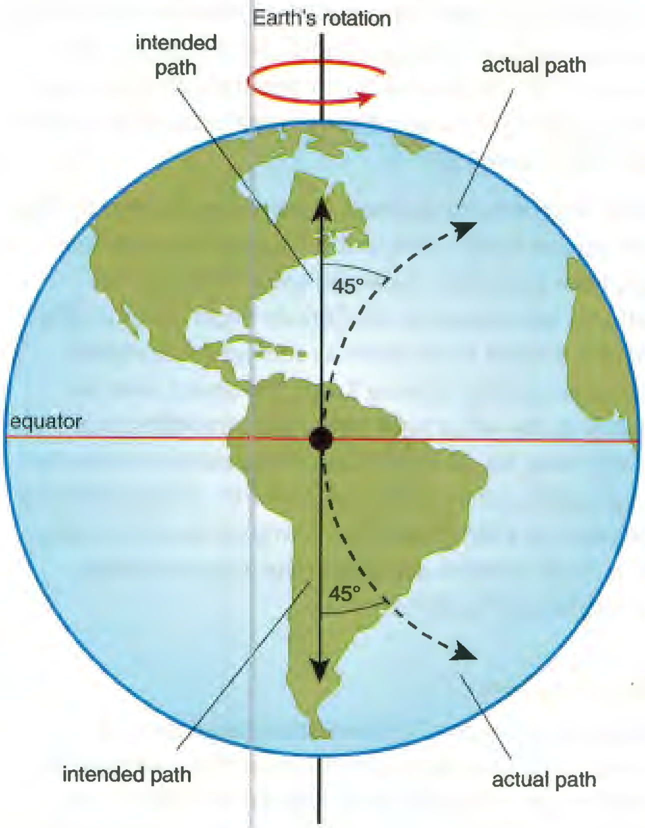


Figure 7.11. Diagram of the Coriolis Effect on objects moving over the Earth's surface.

Amazon River. The global conveyor belt starts at the North Pole when the cold water freezes into sea ice, leaving behind the salts, which do not freeze. This now denser water downwells, causing a mixing of the water column, until it reaches the bottom of the ocean. The water then begins moving south through the Atlantic Ocean towards Antarctica. In Antarctica, it picks up more cold water and then splits. One part of the belt goes towards the Indian Ocean and the other towards the Pacific Ocean. In the Indian Ocean, this cold water moves northwards towards the equator, bringing nutrients to the eastern African coasts. The water warms as it moves towards the equator, so it begins to rise to the surface. When the water cannot rise any longer, it loops back through the south Indian Ocean as a warm surface current.

The cold water in the Pacific Ocean moves through the equator toward the northern Pacific. As this water warms it also rises, becoming a warm surface current along the western coast of North America. This warm current then wraps around the northern coast of Australia and reconnects with the Indian Ocean portion of the global conveyor belt. Together, these warm currents flow through the Atlantic Ocean back towards the North Pole, where the entire process will begin again.

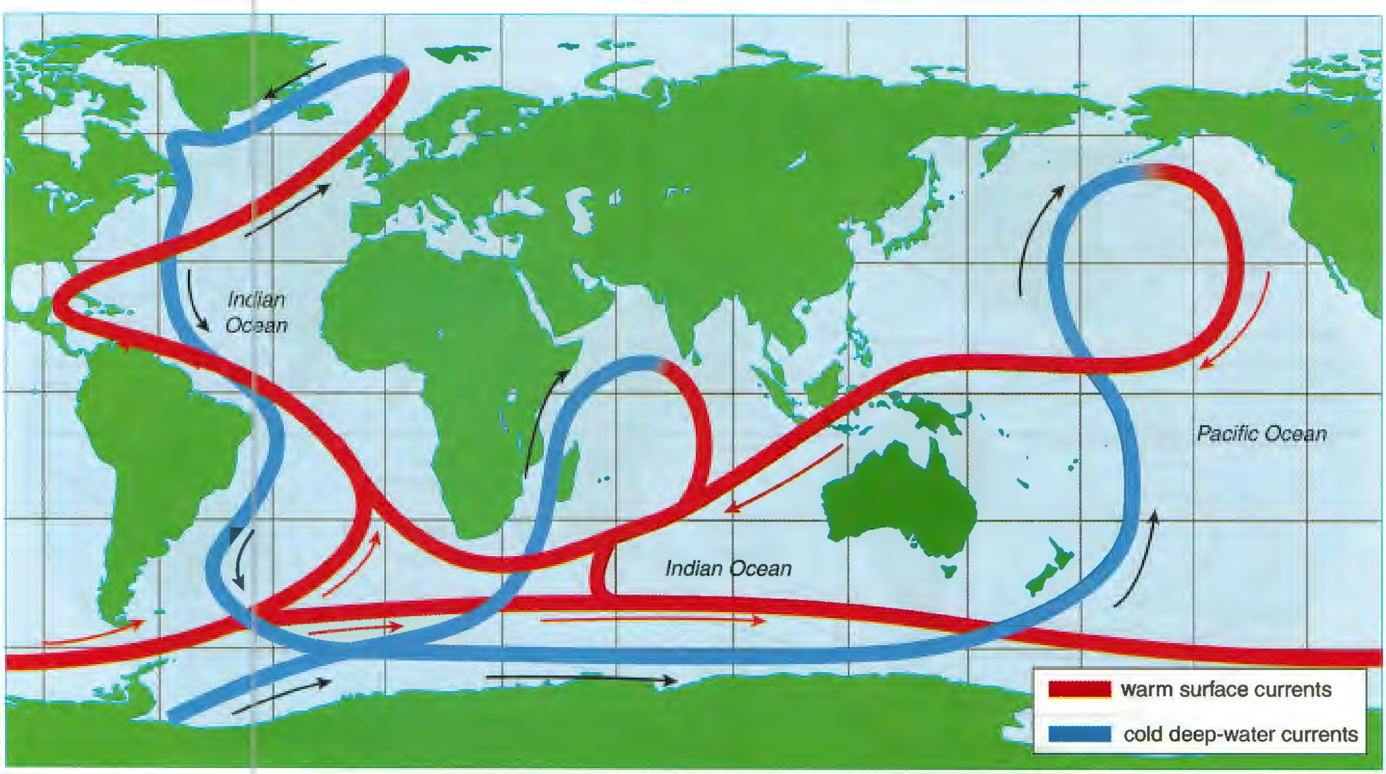


Figure 7.12. Thermohaline circulation (the global conveyor belt) showing the distribution of heat worldwide.

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

Upwelling

Upwelling is the movement of cold, nutrient-rich water from the seabed vertically to the ocean's surface. Upwelling can be caused by winds forcing the warmer surface water away from the coastline and creating a low pressure zone that brings colder water to the surface (Figure 7.13). Upwelling can also be caused by the topography of the seabed. A mid-ocean ridge, or sea mount, can deflect a cold water current upwards causing upwelling. This movement of nutrient-rich water upwards acts as fertiliser for surface waters, increasing the productivity of producers in the area.

An excess of producers and biomass then increases the biomass of consumers, making areas with upwelling very healthy ecosystems with a lot of biological productivity.

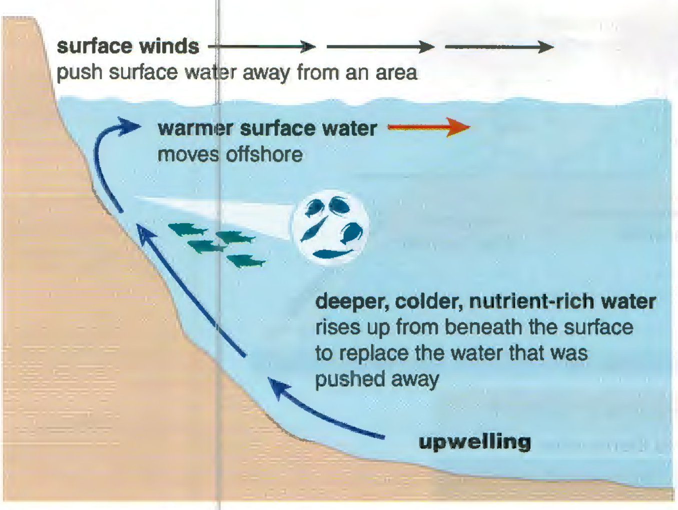


Figure 7.13. The process of upwelling as a result of surface winds.

> **SELF-ASSESSMENT QUESTIONS**
>
> **5** If you owned a seaside home and a bad storm brought heavy winds and high surf to your coastline, would you prefer it to be during a new moon or a quarter moon? Why?
>
> **6** Compare and contrast a current and a tide.

El Niño Southern Oscillation

Normal conditions

Under normal conditions (Figure 7.14), currents flowing north along the west coast of South America bring cold, nutrient-rich water towards the equator. This flow of water is part of the global conveyor belt. As strong south-westerly winds blow water away from the coast of South America, the cold, nutrient-rich water moves toward the surface, causing upwelling and high levels of productivity off equatorial South America. This leads to large numbers of small fish (for example anchovies and sardines), which support a substantial fishery industry, along with many species of sea birds and large marine consumers.

However, on the other side of the Pacific, these westerly winds push large amounts of warm water towards Australia and Asia. The water levels in the western Pacific Ocean are about 0.5 m higher than those found in the eastern Pacific Ocean. The warm water that has been pushed west evaporates, creating massive storm clouds and bringing large amounts of much-needed rain to Australia and Asia, while keeping the eastern Pacific fairly dry.

> **KEY TERM**
>
> **El Niño:** a warm current that develops off the coast of Ecuador around December, which can cause widespread death within local food chains

El Niño conditions

Every 3–5 years (sometimes as long as 7 years), the weather pattern in the Pacific Ocean changes. The change is referred to as **El Niño** or the El Niño Southern Oscillation (ENSO). The prevailing trade winds that normally blow from east to west along the equator stop blowing in their normal pattern. Instead these winds reduce, preventing warm water and moist air from moving to the west (Figure 7.15). The warm water builds up along the coast of South America, stopping the upwelling that usually occurs when the Humboldt Current brings cold water to the surface. Indonesia and Australia experience drought conditions, because of a reduction in rainfall, while Peru and the eastern Pacific experience increased rainfall.

Without the upwelling off the South American coast, there is no fresh supply of nutrients or colder water to reduce surface temperatures. As a result, many cold-water species die and primary productivity goes into a steep decline due to lack of nutrients. The lack of producers impacts upon every other level of the local food webs.

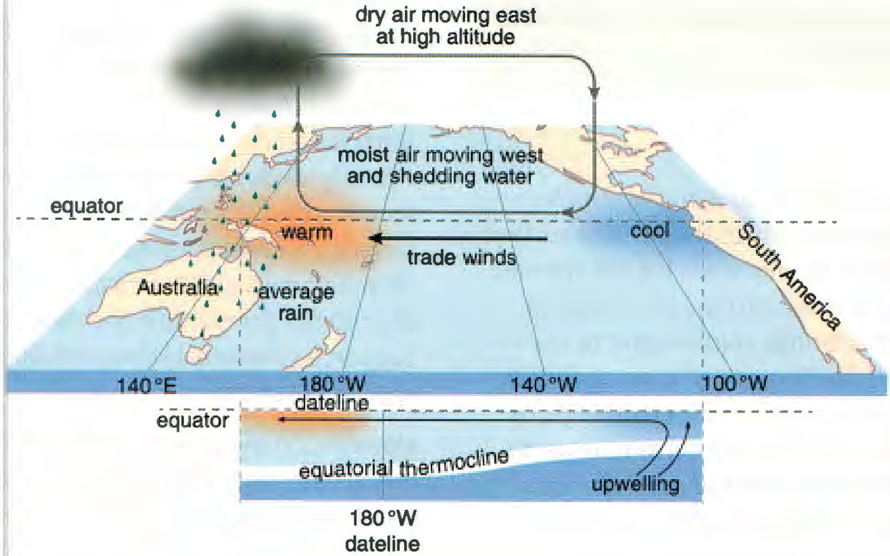


Figure 7.14. Normal weather conditions in the equatorial Pacific Ocean.

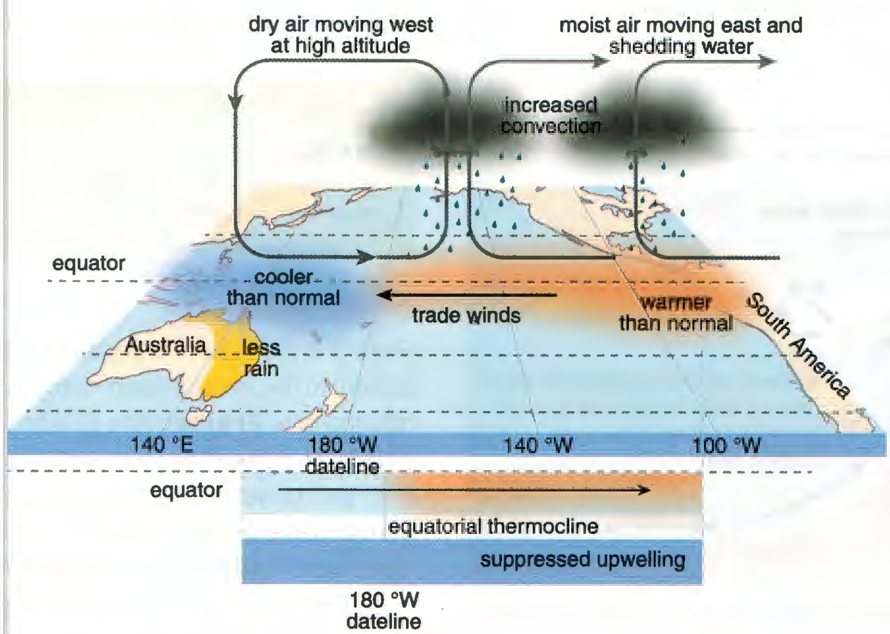


Figure 7.15. El Niño conditions in the equatorial Pacific Ocean.

This causes both the ecosystems and the fishing industries to fail during these times.

El Niño is a naturally occurring phenomenon, but its exact cause is not known. A problem with determining the cause is that not all El Niño years begin or progress in the same way. There has been some speculation that climate change is an exacerbating factor in the increasing occurrence of El Niño conditions, but it is unlikely that this is the only factor involved.

Major El Niño events

Scientists use the Oceanic Niño Index (ONI) to identify El Niño events. The ONI tracks average sea-surface temperature in the equatorial Pacific region in 3-month increments. If there are five consecutive overlapping 3-month periods with sea-surface temperatures at or more than +0.5 °C above average temperatures, they consider it to be an El Niño event. There have been a few 'very strong' El Niño events in the past few decades according to the ONI.

- 1982–83: sea-surface temperatures rose to 2.1 °C above average and caused massive flooding along the eastern Pacific basin.
- 1997–98: the strongest El Niño event recorded so far, sea-surface temperatures rose 2.3 °C above the average temperature.
- 2015–16: scientists believe this event may equal or surpass the 1997–98 event, sea-surface temperatures had risen 2.3 °C above the average sea-surface temperature by May 2016.

Monsoons

Asia is widely considered to be the largest continent. Because of its size, Asia is home to a multitude of biomes and climate conditions. From the warm, wet rainforest in south-east Asia to the cold, dry deserts in northern Asia, nearly every climate can be found in this large region. One feature of the climate in southern Asia is the **monsoon**. Monsoons are seasonal winds that come from the Indian Ocean.

KEY TERM

Monsoon: seasonal winds in India that blow from the south-west during the summer and the north-east during the winter

Monsoons are created by the uneven heat capacity of land and sea. During the summer months (May–August), the land absorbs solar radiation much faster than the Indian Ocean, creating a large temperature difference (Figure 7.16). The air over the landmass is then heated as the warmth from the land is re-radiated to the atmosphere. This air rises as its density decreases and draws in the denser, warm, humid air that was lying over the Indian Ocean. The wind created by this vacuum blows from the south-west and brings thunderstorms and torrential rain. Summer monsoons account for 80% of the yearly rainfall in India, causing flooding while also supporting their primary agricultural crops like rice and cotton.

In September, the temperature difference between the land and ocean begins to even out, reducing the winds. By October, and through the winter months, the oceans hold more heat than the landmass. This means the saturated air over the ocean begins to rise and become less dense. In order to fill the vacuum left by this rising air, cool, dry air from the landmass begins to blow toward the ocean from the north-east. The wind blowing from the north-east is called the 'post-monsoon'. All the moisture evaporated from the ocean remains over the ocean, where rainstorms

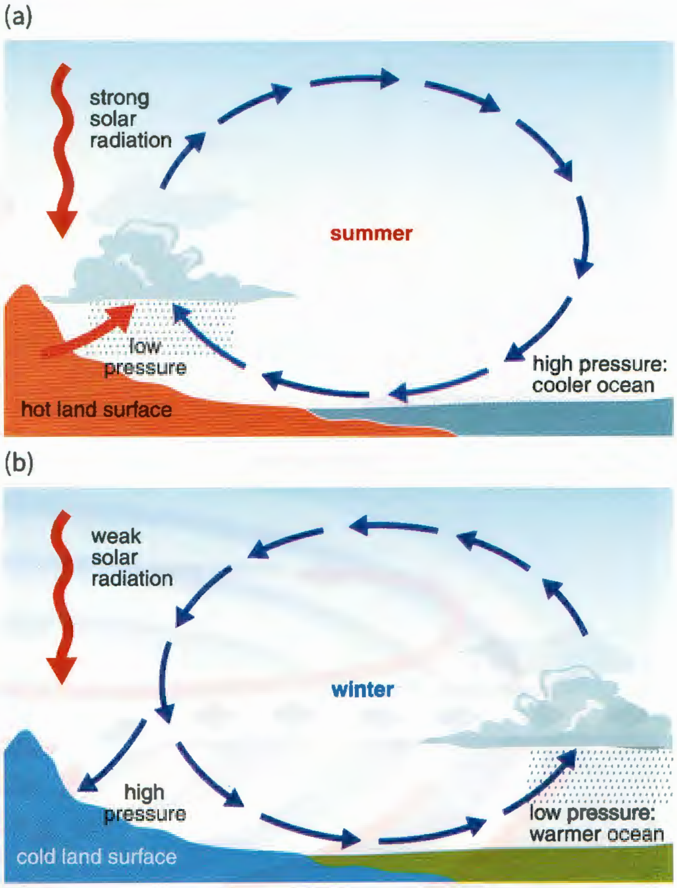


Figure 7.16. Monsoon winds during summer and winter.

release the water back into the ocean. Meanwhile the Asian landmass is left with drought conditions until the summer monsoons return.

Tropical cyclones

In the Indian and south Pacific oceans, large storm systems with wide, low-pressure centres, strong winds (over 120 km h^{-1}) and heavy rains are called **tropical cyclones**. Elsewhere, storms with the same physical structure and method of formation have different names. In the North Atlantic and north-east Pacific, these storms are called **hurricanes**. In the north-west Pacific, they are called **typhoons**. In this book, these storms are all called tropical cyclones.

KEY TERMS

Tropical cyclone: a localised, intense low-pressure wind system that forms over tropical oceans with strong winds

Hurricane: a tropical cyclone with wind speeds of more than 120 km h^{-1}, generally applied to those occurring in the Atlantic Ocean and northern Pacific Ocean

Typhoon: a tropical cyclone in the Indian Ocean or western Pacific Ocean

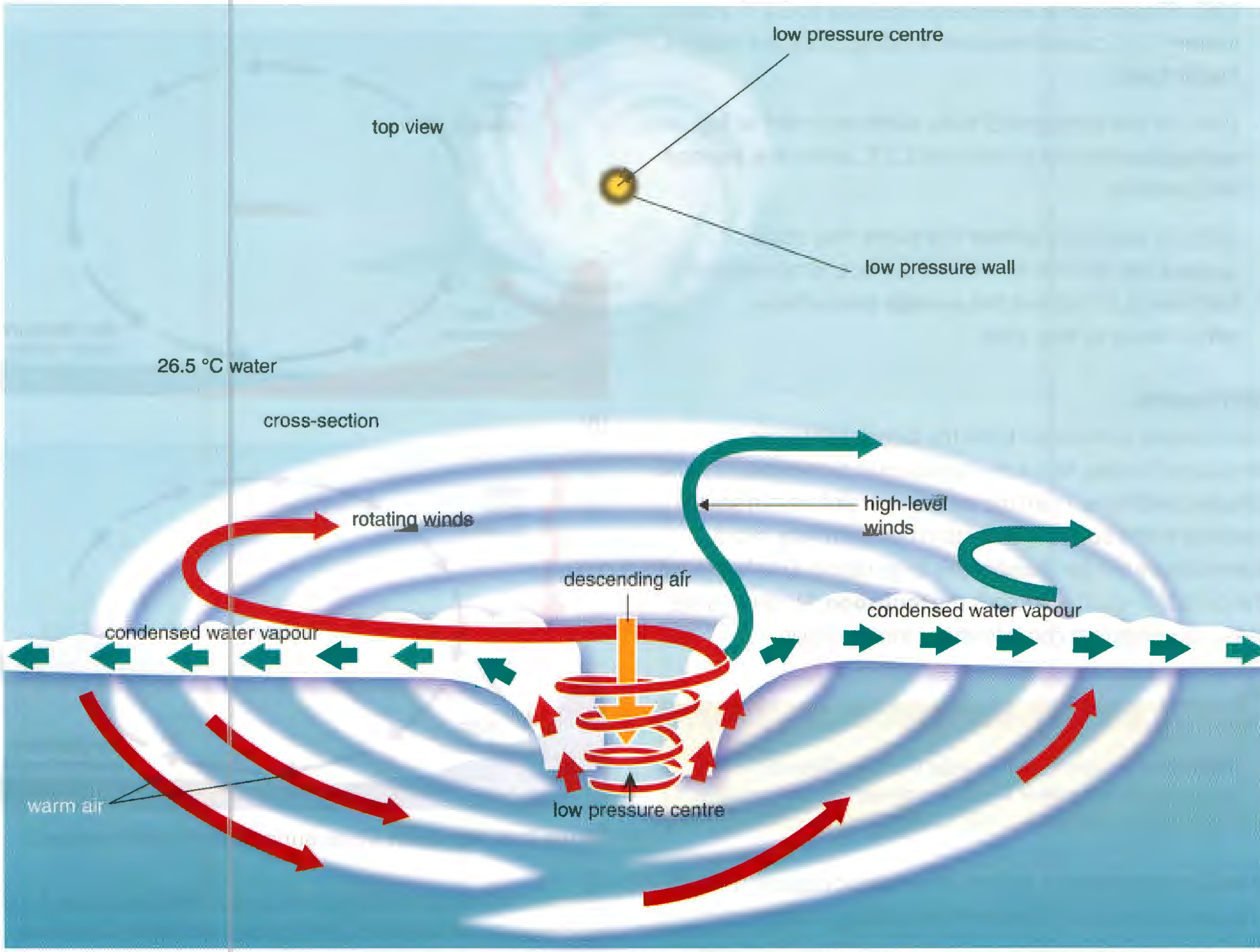


Figure 7.17. Formation of a tropical cyclone.

Formation

Everywhere in the world, these storms always form under the same conditions. For a tropical cyclone to form, there must be a large body of warm water (temperatures higher than 26.5 °C). As the air over this warm water heats up, it begins to rise because of its decreasing density, even as it is filled with water vapour through evaporation. This rising air creates a low-pressure area, often called 'the eye', over the water, drawing in cooler air. The cooler air begins to create winds as it too warms and rises, drawing evaporated water vapour with it. Once risen, the water vapour in the warm air **condenses** and releases large amounts of stored energy in the form of heat (**latent heat**). This heat energy works to warm even greater amounts of air, causing even more evaporation and drawing in larger winds and fuelling the development of a tropical cyclone (Figure 7.17).

KEY TERMS

Condensation (condense): when water changes from vapour to liquid, the energy needed to maintain the vapour state is released into the atmosphere

Latent heat: the quantity of heat gained or lost per unit of mass as a substance undergoes a change of state (for example vapour to liquid)

This system of warming and rising begins to spin because of the rotation of the Earth and the Coriolis Effect. As the air rises, it does so at a 45° angle from the winds coming into the low-pressure zone. In the Northern Hemisphere, cyclones rotate counter-clockwise; in the Southern Hemisphere, they rotate in a clockwise direction.

This spinning system of high winds and latent heat is not stationary. As the prevailing winds blow the warm water currents that feed these storms, they also push the storms in the same direction. In the northern Atlantic, for example, hurricanes are pushed by the north-east trade winds from the western coast of Africa across the Atlantic towards the Gulf of Mexico. Scientists use computer-based models to predict the path or 'track' of the storm.

Impacts on coastal communities

The high winds and torrential rains of tropical cyclones can be incredibly dangerous and destructive to the communities – both human and ecological – within their path. The wind during a tropical cyclone often blows steadily over 90 km h^{-1} and can gust up to 280 km h^{-1}. Such high winds destroy coastal properties and cause incredible damage to the built environment. Huge waves erode shorelines and damage moored boats.

Storm surges (drastic, unpredictable increases in sea-level) and heavy rainfall often accompany tropical cyclones. Between the storm surges and increased precipitation, flooding is inevitable in low-lying coastal areas. These floods are capable of causing many drownings within the storm area.

Ecologically speaking, these storms have both positive and negative impacts. The storms and accompanying storm surges lead to erosion, loss of shoreline and loss of coral reefs (see Chapter 5). However, the heavy rainfall may happen in places with a dry, arid climate. The influx of rain helps the people and organisms in the area survive. Additionally, storm surges carry many nutrients to coastal communities. This means that the reservoir of nutrients stored in the coastal waters is refilled. Producers in the affected area are no longer limited by a scarcity of nutrients and overall productivity is increased.

SELF-ASSESSMENT QUESTIONS

7 Describe how wind patterns are related to the El Niño Southern Oscillation.

8 How could El Niño lead to increased numbers of tropical cyclones?

Summary

- Chemical and physical oceanography share a connection that allows life to survive on this planet.
- Upwelling is caused by physical factors (for example temperature differences) that can change the chemical make-up of coastal ecosystems by bringing in fresh nutrients.
- These nutrients increase productivity in the area and support incredibly biodiverse food webs and major fishing industries.
- The average salinity of the ocean is 35‰.
- The salinity and gaseous dissolution of seawater vary depending on environmental and physical conditions such as temperature, density and pressure.
- Chemicals and gases enter the ocean through dissolution, run-off and volcanic eruptions.
- Layers form in the ocean based on temperature and salinity differences, creating varying degrees of density. The denser a layer is, the lower in the water column it will be.
- As temperature increases, dissolved oxygen decreases, except where there are a large number of producers photosynthesising.
- Spring tides have the greatest tidal range and happen when the Moon, Sun and Earth are in a straight line.
- Neap tides have the smallest tidal range and happen when the Moon and Sun are at right angles to each other.
- The uneven heating of the Earth creates winds that blow the water of the ocean, creating currents.
- The Earth rotates, forcing the winds and currents to move at a 45° angle (the Coriolis Effect), creating a circular pattern.
- El Niño happens when there is less cool water and therefore warmer conditions in the eastern Pacific, so upwelling off the western South American coast is suppressed. Cooler than normal conditions prevail in the western Pacific.
- Monsoons are seasonal winds that bring flooding in the summer and drought in the winter.
- Tropical cyclones form over warm water in areas with a low-pressure centre and bring strong winds and heavy rains.
- Tropical cyclones are also known as hurricanes and typhoons.

Exam-style questions

1 **a** Outline the principles behind the Coriolis Effect. **[4]**

b Explain the impact of the Coriolis Effect on tropical cyclones. **[3]**

c Table 7.4 shows the air pressure at different distances from the centre of a tropical cyclone.

distance from centre of cyclone / km	air pressure / millibars
100	980
80	976
60	970
40	964
20	956
0	916
20	956
40	964
60	970
80	976
100	980

Table 7.4. Air pressure at different distances from the centre of a tropical cyclone.

i Plot these data on a graph. **[4]**

ii Explain why the lowest pressure is at the centre of the cyclone. **[2]**

[Total mark: 13]

2 **a** Figure 7.18 compares normal and El Niño conditions in the Pacific.

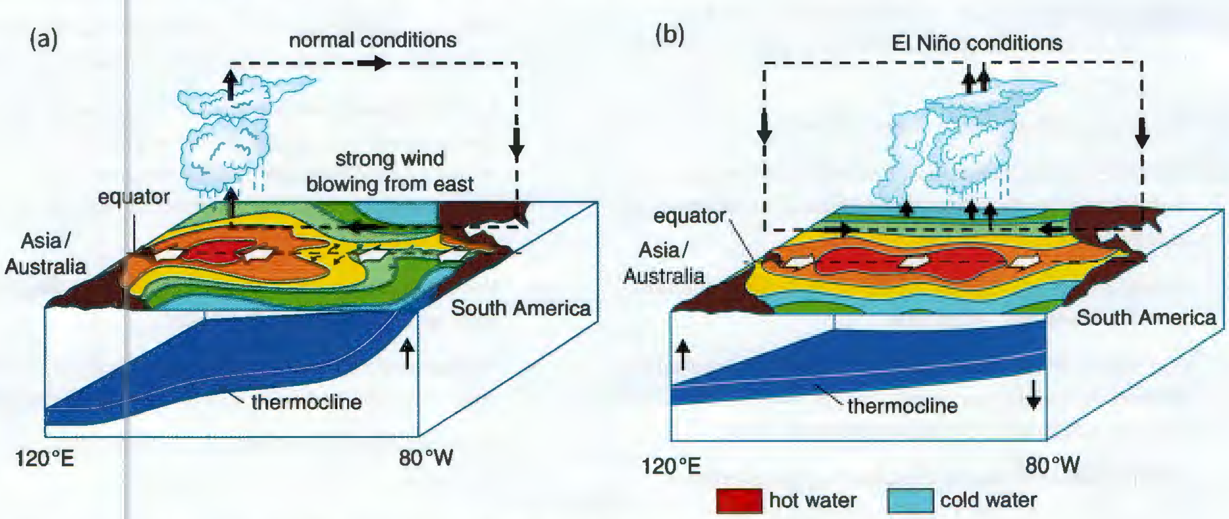


Figure 7.18. (a) Normal conditions and (b) El Niño conditions in the Pacific Ocean.

i With reference Figure 7.18, compare El Niño conditions with normal conditions in the equatorial Pacific. **[2]**

ii Using Figure 7.18, explain why there is a smaller fish harvest in El Niño years. **[6]**

b Outline how the weather conditions in an El Niño year can influence the formation of tropical cyclones in the Pacific Ocean. **[3]**

[Total mark: 11]

3 **a** Compare summer monsoons in India with those in winter. **[8]**

b Discuss the impacts of monsoons on the people of India. **[2]**

[Total mark: 10]

4 **a** Figure 7.19 displays the depth distribution of dissolved oxygen and carbon dioxide in the ocean.

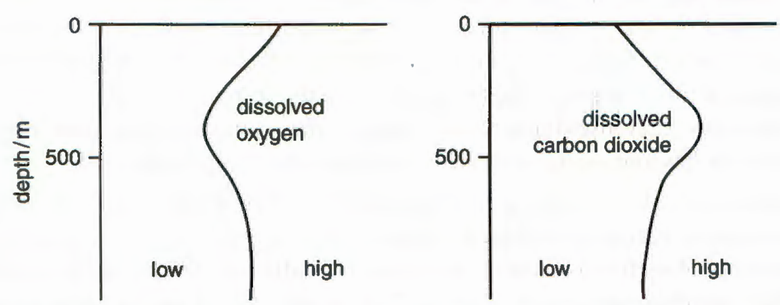


Figure 7.19. Depth distribution of dissolved oxygen and dissolved carbon dioxide in the ocean.

i With reference to Figure 7.19, describe how the oxygen minimum layer forms. **[5]**

ii Describe what is happening in the carbon dioxide graph of Figure 7.19. **[2]**

iii Suggest a reason for these data. **[2]**

[Total mark: 9]

EXTENDED CASE STUDY

Biomagnification in Minamata Bay

Minamata, Japan, is a small town on the western coast of Kyushu, the southernmost island in Japan's archipelago. Historically, this town was a fishing and farming village where the people were typically rural and poor. The majority of the people living there consumed the fish and shellfish caught in Minamata Bay, the estuary the town was built on.

Environmental damage

In 1932, the Chisso Corporation, a local employer of more than 20 years, moved a new industry into Minamata. Because of increasing demand, a factory for acetaldehyde was built on the shores of Minamata Bay by the Chisso Corporation. Acetaldehyde is an essential ingredient in plastic production, a relatively new technology at the time. A necessary component in the process used to make acetaldehyde is the heavy metal mercury. Unfortunately, the mercury used in this process also became part of the untreated waste water that was released into Minamata Bay.

While we now know that releasing untreated waste water into a water source is not a good idea, this was a common practice at the time. People did not have the scientific knowledge we now do to understand the environmental impacts these chemicals could have. For instance, people did not know that, when mercury was released into Minamata Bay, it was forming the compound methylmercury chloride, or simply methylmercury. They also did not know that this new compound was slowly being absorbed by the phytoplankton in the bay and working its way into the food web (see Chapter 2).

Mercury is a dangerous substance to have in a food web. Methylmercury chloride is even more dangerous because it is a compound capable of biomagnification. This means that, when eaten, methylmercury is not excreted or digested as most chemicals and foods typically are. Instead, the compound is stored in the different tissues of the organism that ingested it. These tissues, full of toxins, are then passed on to the next organism in the food chain as biomass. So, the further you go up the food chain, the more concentrated methylmercury becomes in the tissues of the organisms of Minamata Bay (Figure 7.20). These organisms include the humans reliant on the bay for sustenance.

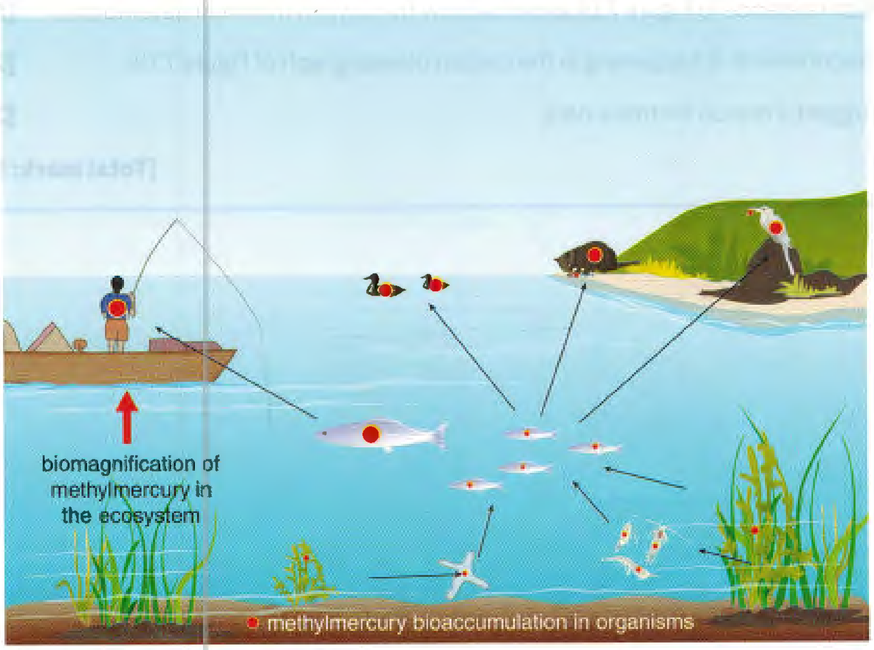


Figure 7.20. Biomagnification of methylmercury in Minamata Bay. The red dots represent the proportional concentration of methylmercury in the tissues of organisms.

Despite the elevated toxin levels in the bay's organisms, the results of the mercury toxicity were not immediately noticed. In fact, it was decades before people really began noticing the evidence that there was a problem. Of course, by then, many people in the town were already affected.

Evidence of toxicity

By the 1950s, fish began floating in Minamata Bay. Chisso paid the fisherman for any possible damage to the water of the bay, so this was overlooked. However, about this time local cats began acting very strangely. They began walking and swaying on two legs, giving an appearance of dancing, hence the name 'dancing cat disease' became popular. This dancing movement often left the cats disoriented, causing them to fall into the waters of Minamata Bay. When people saw this, they said the cats were committing suicide.

In the early 1950s, symptoms of the dancing cat disease began to appear in humans within the village. People began to have trouble walking and performing simple, everyday tasks, such as buttoning up a shirt. The symptoms progressed to paralysis, hearing loss, aphasia, convulsions and, in severe cases, death.

In 1956, there was an epidemic of the disease in the village. Scientists were called in to discover the cause of this debilitating disease. By the end of the year, evidence of mercury toxicity in the shellfish of Minamata Bay led researchers to discover that heavy metal poisoning was the cause of this disease. By measuring mercury levels in the tissues of organisms (Table 7.5) from the bay, cats and infected humans, scientists were able to create a clear chain of evidence for mercury poisoning. However, it was not until the 1960s that scientists were able to identify conclusively the Chisso Corporation's factory as the source of the mercury poisoning.

organism	mercury concentrations in tissue samples / ppm
oyster	5.6
grey mullet (fish)	10.6
china fish	24.1
crab	35.7
cat (liver)	up to 145.5
human (liver)	up to 70.5

Table 7.5. Mercury concentrations in tissue samples of organisms living in or near Minamata Bay.

Questions

1 Using Table 7.5, create a food chain of at least four animals illustrating how the toxins moved from one organism to the next.

2 Estuaries, like Minamata Bay, are usually sheltered areas with a narrow opening to the ocean. How do you think this amplified the biomagnification issue here?

3 Define biomagnification in your own words.

4 How does Table 7.5 support the conclusions of scientists that mercury toxicity was the cause of dancing cat disease?

Chapter 8
Physiology of marine primary producers

Learning outcomes

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

- explain the important role of primary producers in marine environments
- explain why different habitats are characterised by different primary producers
- describe the process of photosynthesis and how it is affected by limiting factors
- explain how accessory pigments are used by marine primary producers to use different wavelengths of light at different depths of the ocean
- apply what you have learnt to new, unfamiliar contexts.