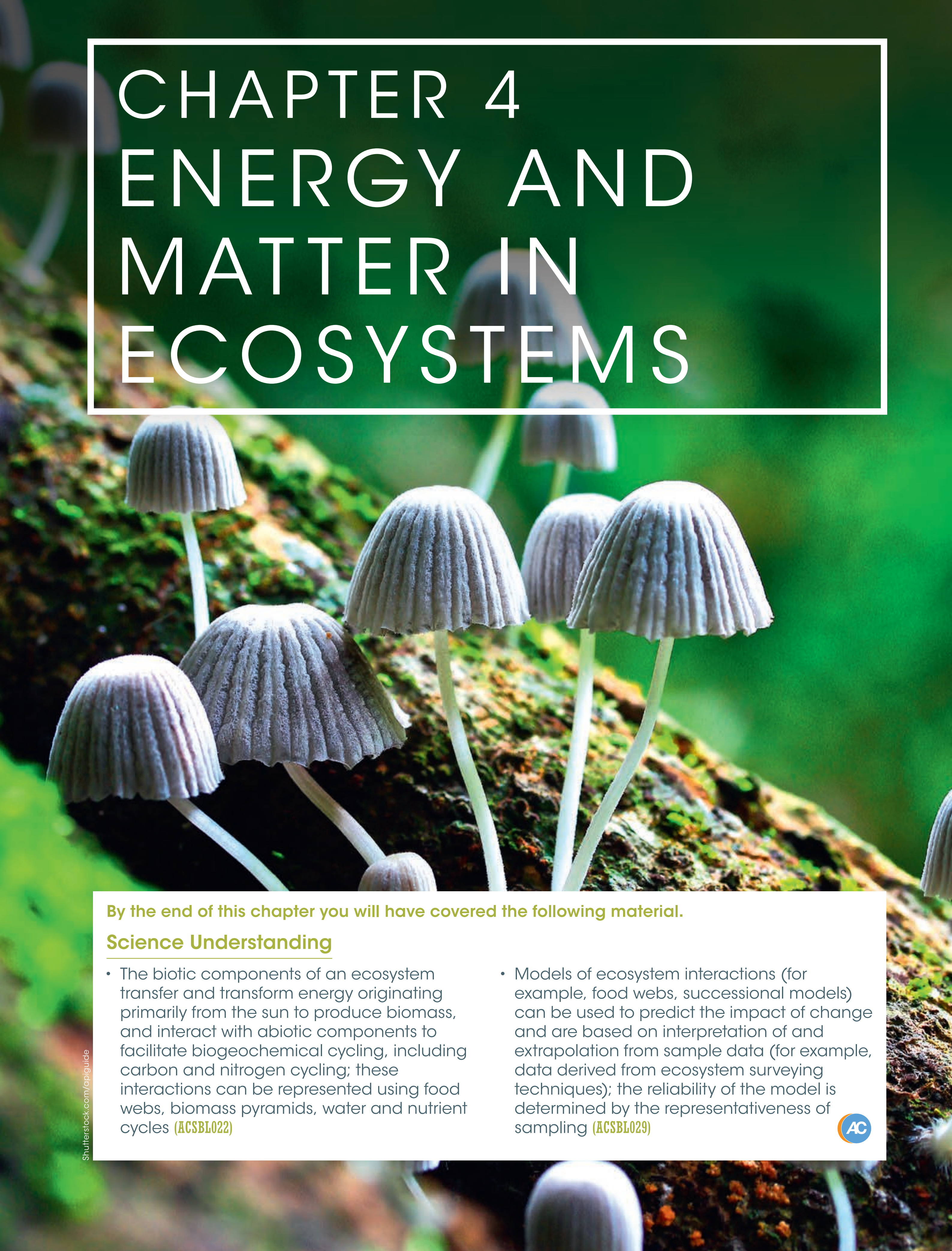
CHAPTER 4 ENERGY AND MATTER IN ECOSYSTEMS



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By the end of this chapter you will have covered the following material.

Science Understanding

- The biotic components of an ecosystem transfer and transform energy originating primarily from the sun to produce biomass, and interact with abiotic components to facilitate biogeochemical cycling, including carbon and nitrogen cycling; these interactions can be represented using food webs, biomass pyramids, water and nutrient cycles (ACSBL022)
- Models of ecosystem interactions (for example, food webs, successional models) can be used to predict the impact of change and are based on interpretation of and extrapolation from sample data (for example, data derived from ecosystem surveying techniques); the reliability of the model is determined by the representativeness of sampling (ACSBL029)

Figure 4.1 ▶
The Sun's energy is constantly supplied to warm Earth. This drives weather and ocean systems. A thunder storm is the result of stored solar energy.

Getty Images/Jeremy Woodhouse

Wherever life exists, in the deep sea trenches kilometres below the surface of the oceans, in the geothermal springs of New Zealand or in the Antarctic, life depends on a source of energy and a supply of matter. Ecosystems across the world are linked in networks of energy and nutrient exchange between living things (**biotic**) and their non-living surroundings (**abiotic**). The winds, the tides and the circulation of the oceans in one part of the world affect what happens in another part of the world.

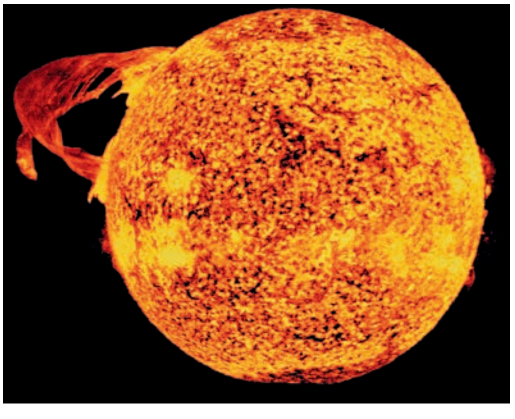
Matter consists of atoms and is required to build and maintain complex structures throughout the universe. These atomic building blocks interact with each other to create different substances through chemical reactions. Earth's matter has remained unchanged for 4.5 billion years and so must be recycled to build new substances.

Energy sources for life

All complex systems on Earth require a constant supply of energy to drive them. It is the supply of energy that allows matter to be combined into an almost infinite range of complex structures. For example, the developing offspring of mammals begins with the fusion of two cells, one from each parent, eventually forming a complete and independent organism. While it is not immediately obvious, the energy that drives this process is provided to the growing offspring by the Sun.

Energy is essential for a system to do work. Energy cannot be recycled, like matter, but must be supplied continuously.

Figure 4.2 ▼
The Sun provides energy to all planets of the solar system as heat and light. It is the major source of energy that drives the diverse ecosystems on Earth.



Alamy/david gregs

The Sun's energy

The Sun provides most of Earth's energy in the form of **radiant energy**. Energy in the form of heat energy warms our planet's surface, and this in turn warms the atmosphere that drives all of the geochemical processes, tides, weather systems and ocean currents. The amount of energy in sunlight depends on the wavelength of the incoming light. Because the Sun **emits** visible, infrared and ultraviolet light, the associated energy is very large (Figure 4.2). Even though the amount of solar energy is vast, it is of little use to a living organism unless it can capture this energy and transform it into another form that it can use.

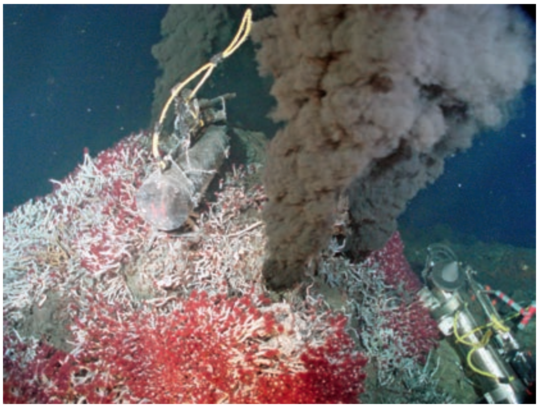
Other sources of energy include geothermal energy, which is heat generated from Earth's core. Some of this extreme heat escapes to generate geothermal activity on Earth's surface and in the ocean. Hydrothermal vents are regions in the deep ocean where volcanic magma heats seawater to more than 300°C. On Earth's surface, volcanic activity creates extreme environments. For example, the Wai-o-tapu geothermal reserve, near Rotorua in New Zealand, has numerous hot springs and geysers (Figure 4.3). These environments are home to diverse communities that can tolerate the lack of sunlight, high temperatures, extreme pressures and acidity. Large communities of chemotrophic bacteria (*Archaebacteria*) use simple inorganic chemical compounds including sulfur and iron as their source of energy and matter. In the hydrothermal vent regions (Figure 4.3), chemotrophs support ecosystems consisting of diverse communities including, giant tube worms.

HYDROTHERMAL VENTS

Learn what diverse communities flourish in these regions and how they depend on each other for survival.

Energy has many forms and drives all processes on Earth. Energy is essential for the maintenance of highly organised structures like living organisms.

▼ Figure 4.3
Hydrothermal vents and geothermal regions sustain ecosystems that consist of organisms that thrive in extreme environmental conditions.



Getty Images/NOAA

Getty Images/Christopher Chan

QUESTION SET 4.1

Remembering

1 Recall the original source of energy for all ecosystems of organisms on Earth.

2 Define 'geothermal'.

Understanding

3 Distinguish between solar energy, radiant energy, heat energy and ultraviolet light.

How do living organisms use energy?

Plants and algae have evolved a way to utilise the Sun's energy, establishing an energy structure upon which all organisms depend. **Autotrophs** are organisms adapted to transform the Sun's energy into high energy chemical bonds during the synthesis of organic materials from basic inorganic ingredients taken in from the environment. Energy is therefore stored in these chemical bonds and is released when the chemical bonds are broken. It is these autotrophs, also known as **producers**, that produce all of the organic matter, or food, which all other organisms in an ecosystem rely on for nourishment (Figure 4.4).

How do producers transform the Sun's energy?

See Chapters 7 and 9 for more details on the process of photosynthesis.

Producers transform sunlight into chemical energy in a biochemical process called photosynthesis. Plant cells have specialised organelles called chloroplasts that contain the pigment chlorophyll. This pigment is able to absorb most of the wavelengths in sunlight. Green plants use the red and blue wavelengths to the greatest extent, but this narrow range accounts for only about 2–10% of the total visible light that strikes the leaves. Of this, 10% is trapped in the high energy bonds during the production of **carbohydrates**.

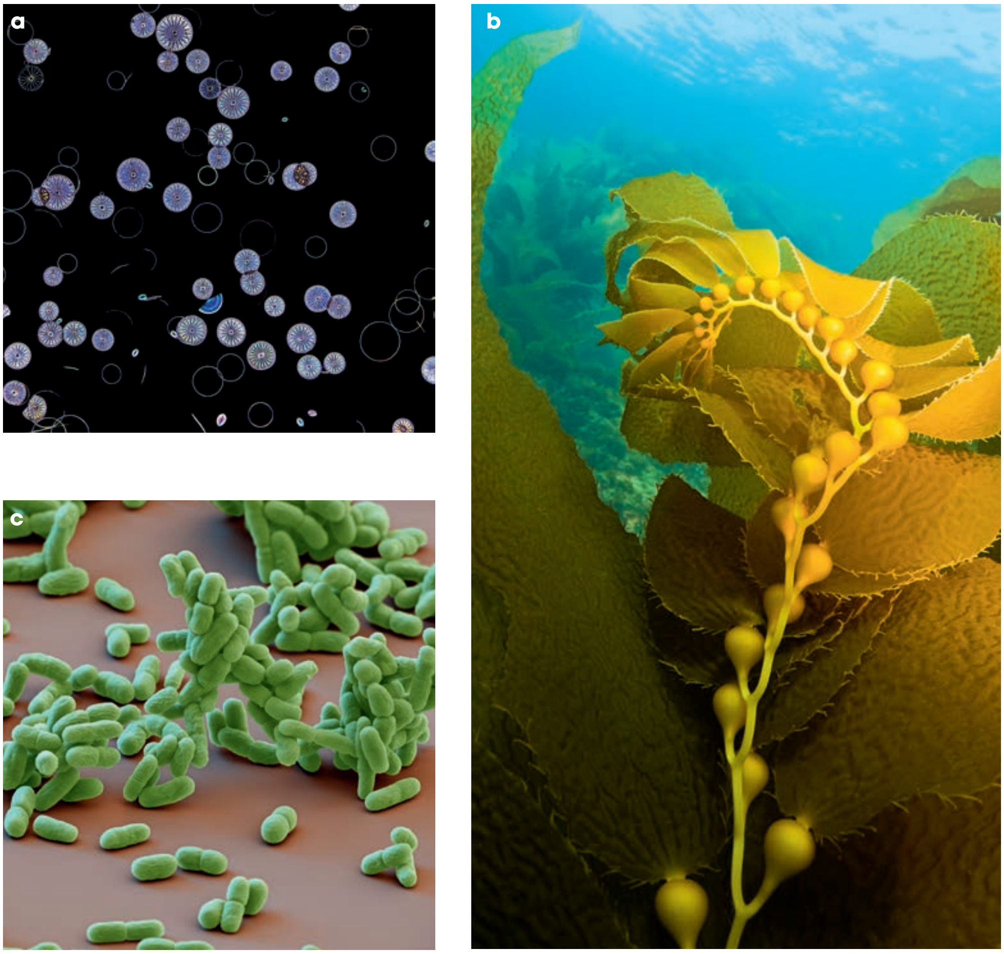


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Figure 4.4 ▶ Photosynthetic autotrophs including a) algae, b) plants and c) cyanobacteria transform energy from sunlight and store it as chemical energy in the bonds of glucose.

Chapter 12 discusses the structures of plants and their functions, including the role of xylem.

The essential raw ingredients in plentiful supply for carbohydrate synthesis are water and carbon dioxide. Plant leaves absorb atmospheric CO_2 gas while water is delivered from the soil to the leaves via a series of tubes called xylem. Even though the air we breathe has 21% O_2, 78% nitrogen and a modest 0.035% CO_2, this comparatively small percentage of CO_2 in the air mixture is amplified when it is dissolved in the water that bathes the plant cells. This amplification effect is due to the high solubility of CO_2 in water. In contrast, O_2 does not dissolve well in water.

Organisms such as humans are **heterotrophs** – members of the community that cannot synthesise their own organic compounds from inorganic materials. So how do we manage? Heterotrophs depend on autotrophs directly or indirectly for their energy needs and their supply of matter. They do this by consuming other organisms, and therefore are also known as **consumers**. Consumers include animals (Figure 4.5), fungi and many kinds of bacteria.

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◀ Figure 4.5
A lion is a heterotroph that consumes large prey.

Photosynthesis, producers and productivity

Glucose molecules produced from photosynthesis are linked together into long chains forming complex carbohydrates. Cellulose is one such molecule that is used to build the cell wall and is the bulk of the plant material. Another glucose polymer called starch is used as an energy store for plants during periods of reduced sunlight.

Not all producers make the same amount of plant mass. How well a producer converts light energy into carbohydrates during photosynthesis is referred to as its **photosynthetic efficiency**. This depends on the availability of raw materials and sunlight. Temperature influences the rate at which chemical reactions occur, so prevailing environmental temperatures can affect this efficiency. Therefore, the production of organic materials from the glucose made in photosynthesis is greater in some seasons compared with others, and also varies according to latitude and altitude. For example, tropical forests cover only about 4% of Earth's surface but contribute about 25% of the world's yearly **gross primary productivity (GPP)** of organic matter. Some trees grow to extraordinary heights in their competition for light.

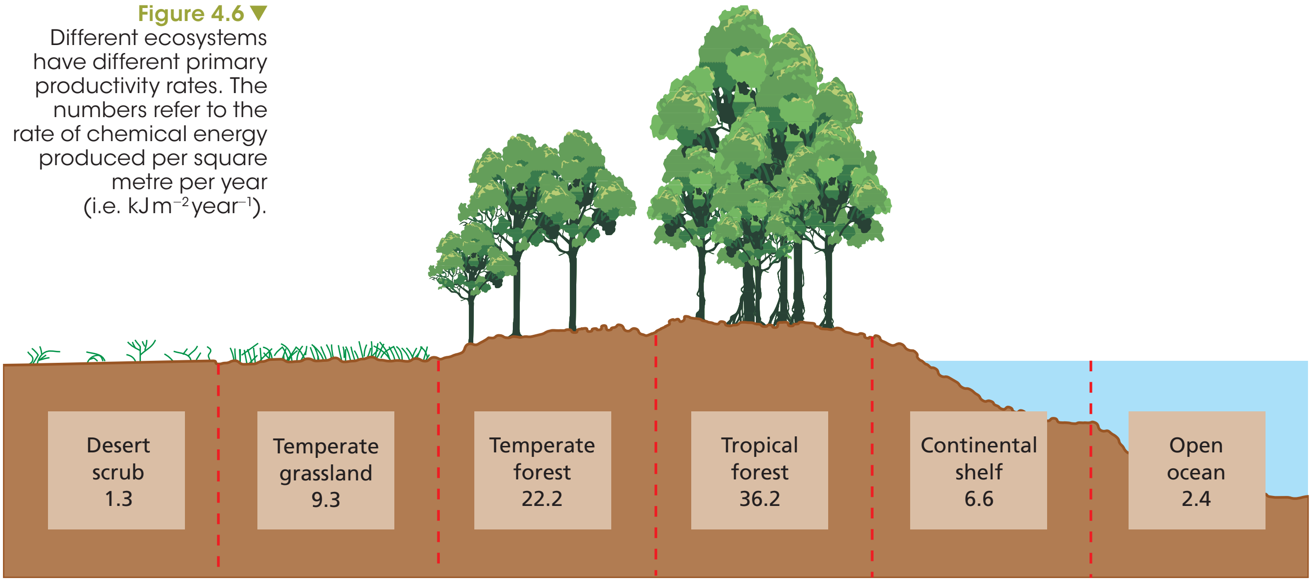
The oceans cover a large area of Earth's surface. Ocean ecosystems depend on producers such as phytoplankton to trap huge amounts of light energy. This in turn results in vast amounts of organic material. However, their primary production is not as efficient as that of terrestrial ecosystems because light does not penetrate deep water and nutrients are not freely available. Although GPP refers to the total amount of organic matter made in an ecosystem by producers, not all of this material is available to the consumers for food, and therefore, their energy requirements. Some of this material is used by the producers themselves for their own energy needs. So the amount of energy, or carbon, fixed by producers (GPP), minus that required for cellular respiration by the producers, is the amount of energy available to consumers. This remaining amount of **biomass** (dry weight of organic matter), and therefore of energy, that is available to consumers is called the **net primary productivity (NPP)**.

NPP for an ecosystem can be calculated if we know the amount of biomass in grams over an area in meters squared, in a given time frame, usually a year. It is important to understand that this is a rate of change of biomass over one year and is expressed in the appropriate units as:

- mass: $g\,m^{-2}\,year^{-1}$
- energy: $kJ\,m^{-2}\,year^{-1}$.

What happens to the remaining mass or energy? To answer this question we need to know the energy needs of the organisms together with how matter and energy are passed along from one organism to another in the community occupying the ecosystem.

Figure 4.6 ▼ Different ecosystems have different primary productivity rates. The numbers refer to the rate of chemical energy produced per square metre per year (i.e. $kJ\,m^{-2}\,year^{-1}$).



ACTIVITY 4.1

PHOTOSYNTHESIS

An experiment was conducted to determine the effect of light intensity on the rate of photosynthesis in a sample of the aquatic plant *Elodea*. The plants were exposed to a range of light intensities at a constant temperature of 25°C. The rate of photosynthesis was measured by the volume of oxygen, in millilitres (mL), collected in 10 minutes. The results are shown in the table below.

Table 4.1 Rate of photosynthesis of *Elodea*

Relative light intensity (arbitrary units)	Volume of oxygen collected in 10 minutes (mL × 10^{-3})
50	3
100	7
200	17
250	20

What did you discover?

1. Graph the data from the table. Use the values 0 to 250 arbitrary units for relative light intensity.
2. The 'compensation point' is defined as the light intensity that produces a rate of photosynthesis equal to the rate of respiration in a plant sample. At this point the volume of oxygen collected is zero. Using your graph or the data in the table, estimate the value of the compensation point in this experiment.
3. State the dependent variable in this experiment.
4. The experiment was conducted at 25°C. State two factors other than temperature that would need to be kept constant in this experiment.

Consumers obtain matter and energy from producers

Consumers cannot carry out photosynthesis and therefore cannot derive their energy directly from the Sun. Animals of all sizes, from insects to elephants, must obtain their energy from the food they eat. Herbivores, including grazing animals, consume large amounts of plant material.

They extract energy stored in chemical bonds by a process called **cellular respiration**. Food is broken down into small particles by mechanical and enzyme action in the mouth and stomach. Hydrochloric acid present in the stomach assists the breakdown of proteins. As food is passed from the stomach to the small intestine, enzymes continue the breakdown of food substances into small molecules.

Enzymes are catalysts that allow chemical reactions to occur much faster than they would normally. Catalysts increase the rate of reactions by lowering the activation energy required to start a reaction. They bring reactants close to each other and in the right orientation to react effectively.

Herbivores have enzymes that can digest cellulose, the major component of the plant cell wall. This enzyme breaks the chemical bond between individual glucose molecules making up the cellulose, which is the crucial first step in a herbivore's ability to extract the Sun's energy from plants. Cellular respiration involves a series of chemical reactions that extracts the energy in glucose bonds to form adenosine triphosphate (ATP). This molecule provides cells with the energy they need to perform their many functions.

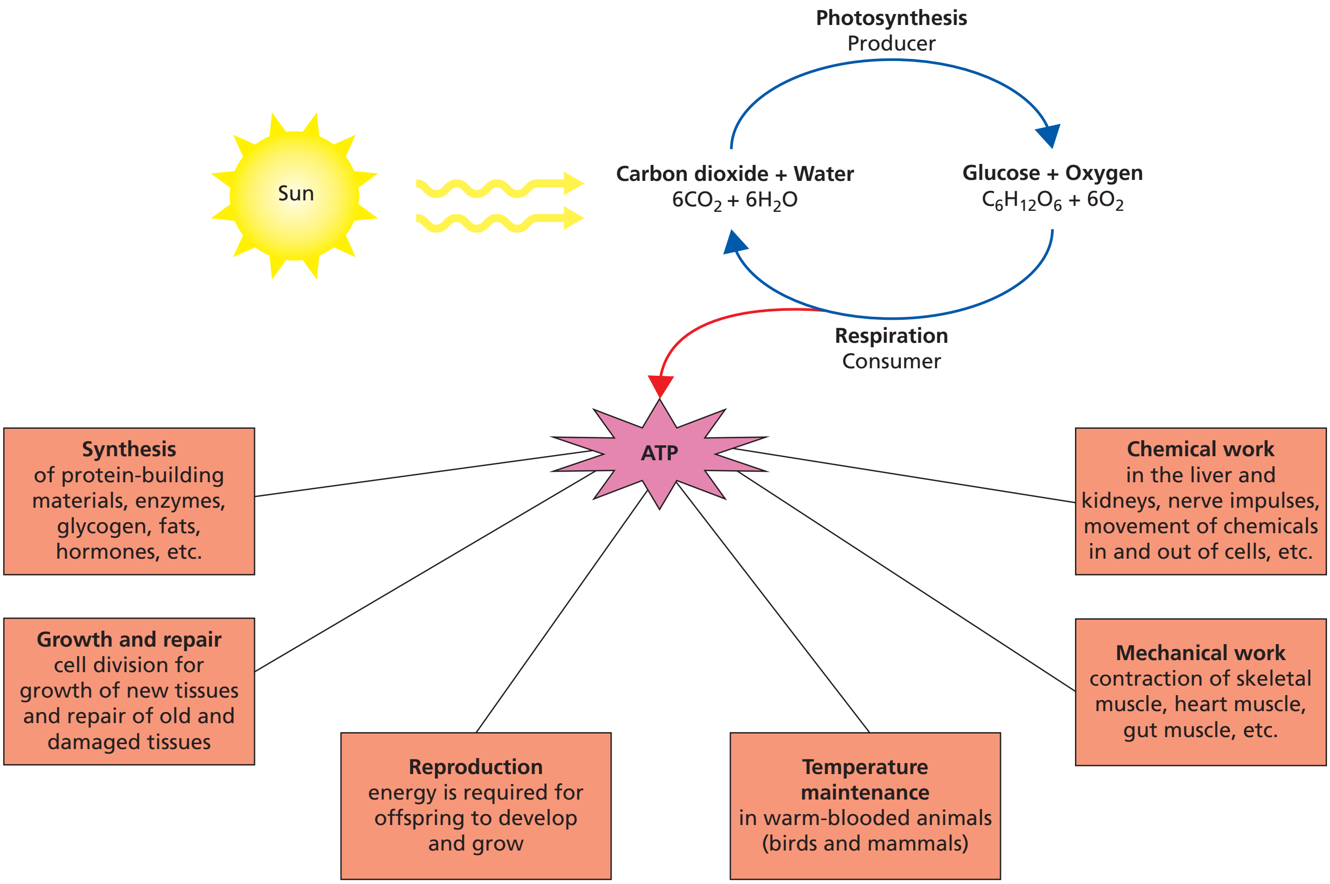
See Chapter 7 for more on cellular respiration, Chapter 11 for digestion and Chapter 9 for the process of energy transfer using ATP.

HOW MUCH ENERGY DOES SUGAR HAVE?

Video showing the combustion of a gummy bear that contains sugar (sucrose), the sweetener in most confectionery.

Why is energy so important?

Energy is required for animals to carry out work. This may include foraging for food, avoiding predators or for long treks during the annual migration and, in the case of homoeothermic organisms, for keeping them warm. Some energy is used to keep bodily functions working, building or repairing new tissues, and for the production of gametes in reproduction (Figure 4.7).



▲ **Figure 4.7**
The energy originating from the Sun is used by organisms to perform work. This must include growth and repair of damaged tissues, interacting with the environment including fighting infection, foraging for food, playing, learning new skills, reproducing offspring and escaping from predators.

WOW

Super kelp!

Giant kelp off the east coast of Tasmania is one of the fastest growing plants on Earth and in favourable conditions can grow more than 30 cm per day.

How much energy is allocated to each of these general functions depends on a number of factors. A juvenile (young) individual, for example a tadpole, will allocate quite a high proportion of the energy available to it for growth but nothing for reproduction. A mature individual, in this case the frog, will devote more energy for reproduction and practically nothing for growth.

ACTIVITY 4.2

ANALYSING PRODUCTIVITY

Lake Eyre (Kati Thanda) is located in South Australia, 700 km north of Adelaide. Every three years floods fill the lake basin that, in the dry season, has very little water. Table 4.2 shows the average productivity of various plant ecosystems.

Table 4.2 Plant productivity and biomass

Ecosystem	Average productivity ($g\,m^{-2}year^{-1}$)
Algal beds and coral reefs	2500
Tropical rainforests	2200
Swamps and marshes	2000
Estuaries	1500
Temperate deciduous forests	1200
Boreal forests	800
Temperate grasslands	600
Lakes and streams	250
Tundras	140
Open oceans	125
Deserts	90
Extreme deserts	3

What did you discover?

1. Using the information provided in the table, what plant productivity would most resemble Kati Thanda during flood? Explain why you think this might be the case.
2. Identify which ecosystems have the highest and lowest productivity. Account for the difference between these two ecosystems.
3. Explain how biomass can be used to calculate productivity.
4. Critically evaluate where the annual production of organic matter (i.e. GPP) would be greater: a coral reef or an alpine meadow of the same area. Explain your answer.
5. Urban expansion has involved the draining of swamps and marshes in many parts of the world, in order to build housing and cities. Assess the effect of this practice on the amount of energy available.
6. Between 2000 and 2005, the Amazon rainforest was being cleared at a rate of 22 392 km^2 per year. Calculate:
   a. the total area cleared in those 5 years
   b. the total productivity lost over that time as $g\,m^{-2}year^{-1}$.

QUESTION SET 4.2

Remembering

1 Identify what living things are able to photosynthesise and explain how the structures they possess enable them to do this.

2 List the factors or conditions necessary for photosynthesis to take place.

Understanding

3 Producers are sometimes referred to as 'energy converters'.

  a Explain what this means in your own words.

  b Explain the significance of producers to the ecosystem.

4 Distinguish between GPP and NPP.

Modelling the ecosystem: transfer of energy and matter

Scientists study the interactions of complex systems to find out how they are sustained and to predict how they are changed if disruptions occur. A system is a set of interacting components that together form a complex network. We can describe systems using the IPO model. This can be summarised simply as:

Inputs → Processing → Outputs (+ Storage)

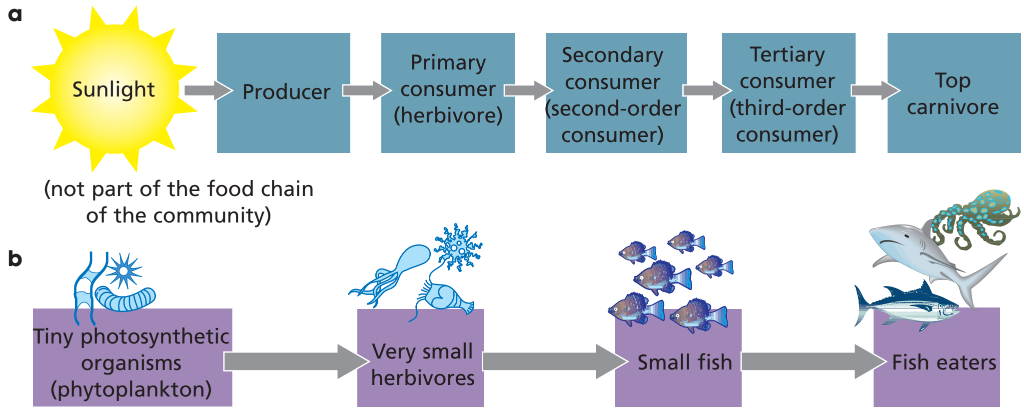
In photosynthesis, for example, the inputs are water and carbon dioxide and the outputs are oxygen, carbohydrates, water and energy. The energy that drives the process of photosynthesis is sunlight.

Ecological systems are very complex and include a large number of biotic and abiotic factors. Ecologists want to know what types of relationships occur within communities and the ecosystem because this gives valuable information about how an ecosystem is maintained. A **model** is an artificial and simplified representation of the real situation. Simplifying the model system limits the number of dependent and independent variables to those considered relevant or of critical importance to the system. There are many different types of experimental models; however, the aim is to attempt to mimic the real-world situation as closely as possible. This allows scientist to make reliable predictions about the real system if adverse changes were to occur. This predictive power means that ecologists can intervene in a timely manner to prevent an ecological problem leading to catastrophe such as an animal becoming extinct through loss of habitat or food. Models must include the major stages where changes in a variable occur.

Food chains

Food chains and **food webs** are examples of qualitative and predictive models that allow ecologists to monitor the sustainability of an ecosystem by investigating feeding relationships. Each link in the chain is referred to as a **trophic level** ('trophic' = feeding). Each organism in the chain feeds on, and therefore obtains its energy and matter from, the preceding one. One consumer is consumed by the next organism in the chain so energy and matter are transferred progressively from one trophic level to the next.

Figure 4.8 ▶ a) A generalised food chain; b) A food chain in the ocean



Animals that feed directly on producers are **herbivores** or **first-order consumers**. **Carnivores** that depend directly on herbivores are **second-order** (or secondary) **consumers**, and so on. The **top consumers** are not preyed upon but, like most of us, die of old age, disease or injury. Animals that feed on the dead remains of other animals are **scavengers**. Some organisms are both herbivores and carnivores, and are called **omnivores**. Figure 4.9 shows how a generalised food chain and an ocean food chain can be constructed. Note that larger animals such as sharks must eat large quantities of food to meet their energy requirements.

Table 4.3 A who's who of consumers in ecosystems

Type of consumer	Description of role	Examples	
Primary consumers (herbivores)	Feed directly on producers	Wombats, kangaroos, sheep, many insects	 Shutterstock.com/Mike Charles
Secondary consumers (carnivores)	Feed on primary consumers	Dingoes, kookaburras, fur seals, platypuses	 Shutterstock.com/Johan Larson
Top consumers	Feed on secondary consumers	Australian wedge-tailed eagles, sharks	 Shutterstock.com/Stubblefield Photography
Omnivores	Feed on both plants and animals	Foxes, humans, bandicoots, bilbies	 Shutterstock.com/Tom Wang

Type of consumer	Description of role	Examples	
Scavengers	Feed on dead organisms	Foxes, Tasmanian devils, ravens, dingoes, goannas, quolls	 Shutterstock.com/Czesznak Zsolt
Detritivores	Feed on dead or decaying organic remains and wastes	Dung beetles, earthworms, yabbies	 Shutterstock.com/john michael evan potter
Decomposers	Decompose (break down) complex molecules of the organic material in or on which they live	Fungi, some bacteria	 Shutterstock.com/Steve Bower

The food chain can also be thought of as an energy chain, but at each trophic level or link in the chain a proportion of the available energy is lost due to inefficiencies during transfer and the remaining energy is transferred to the next level. Some energy is lost from the chain as heat energy released in cellular respiration, and some lost as chemical energy in organic wastes of dead plant and animal tissues, collectively called **detritus**.

This loss of energy means that from one link to the next along the chain, progressively less energy is available for successive levels. These food chains and the ecosystem will remain as long as the Sun continues to provide a continuous supply of energy.

Energy loss in food chains

Food chain models often have discrepancies between what is predicted from the model and what is actually observed in the field. In the real situation, no energy transfer process is completely efficient. In other words, there will always be losses along the way. Accounting for such discrepancies increases the accuracy of how the model food chain describes the real situation in nature. The percentage of the energy at one trophic level that ends up in the next trophic level is referred to as **trophic efficiency**.

The oceans are home to our great producers. Some of the highest trophic efficiencies are found there. For example, the trophic efficiencies of **zooplankton** feeding on **phytoplankton** can be more than 40%. So it is important to monitor what is happening to populations of these and other organisms that form the links in the food chains.

A useful rule in ecology is that about 10% of the energy at one trophic level is passed on to the next level. The remaining 90% is lost to the surroundings as heat energy and chemical energy in wastes. The trophic efficiency of herbivores, for example, equals the percentage of the NPP of the producers that is transferred to the herbivores. Similarly, the trophic efficiency of the second-order consumers (carnivores) is the percentage of the energy it receives from the herbivores.

> The 10% rule in ecology states that only about 10% of the energy at one trophic level is passed on to the next level. The remaining 90% is lost to the surroundings as heat energy and chemical energy in wastes.

If populations of lower-order consumers become reduced, the small population of top consumers is at risk of being adversely affected or even wiped out. For example, the population of eagles in an ecosystem is much smaller than the populations of rabbits and small native animals on which they feed. Reduction in numbers of these populations would have a significant impact on the eagle's ability to obtain its energy requirements.

Brisbane's Moreton Bay is an example of an ecosystem that supports a very large and diverse range of communities. For the past 30 years, measurements in the bay have tracked changes to nutrients and sediments in the ecosystem. Industrial and sewage effluent, storm water and catchment run-off were thought to have contributed to the increased levels of these materials. Scientists did not know whether these changes would harm the ecosystem and its biodiversity. Before a solution to the problem could be found, information about the ecosystem's structure and function had to be gathered.

In 1994, scientists developed a conceptual model and a number of instruments to help understand the processes that were taking place in the bay. For example, marine plants such as sea grasses, phytoplankton, seaweeds and mangroves were identified as key indicators of the health of the bay and estuary. Changes to populations of these organisms would therefore provide clues about the health of the bay. Monthly measurements of nutrients, salinity, temperature and turbidity (which influence how much light penetrates the water column) were also taken in different parts of the bay.

Results of the Ecosystem Health Monitoring Program gave researchers an insight into the way the system operates. Every year, reports are prepared on the health of the ecosystem and strategies are developed to maintain it. These activities have provided information that has helped to develop improved practices to manage the ecosystem more effectively.

The insights from these studies have shown that ecosystems are delicate and can easily be irreversibly destroyed. Ecosystems provide essential services such as purification of air and water, renewal of soil fertility, decomposition of wastes, control of pests, regulation of climate and pollination of vegetation. These services support all life on the planet.

WOW

Pigs are efficient

Pigs have the highest growth efficiency of any domestic mammal, transforming up to 15% of the energy they ingest into muscle.

Food chain modelling to measure trophic efficiency

Animals differ considerably in how efficiently they use the energy from the food that they eat. The efficiency of energy transfer from one organism to the next can vary from less than 0.1% to more than 10%. For example, insects do not need to use energy to keep their bodies warm. Therefore, more of the total energy derived from feeding is available to be passed on. Kangaroos on the other hand must keep warm and use a considerable amount of energy to do this. A higher percentage of energy is passed on from plants to insects to birds than from plants to a kangaroo. As a result, the loss of energy at each link limits the number of trophic levels a food chain can have (Figures 4.9 and 4.10).

Figure 4.9 ▼ Energy losses are inevitable as energy moves through any food system. The size of these losses depends on how efficiently energy is passed on to the next trophic level.

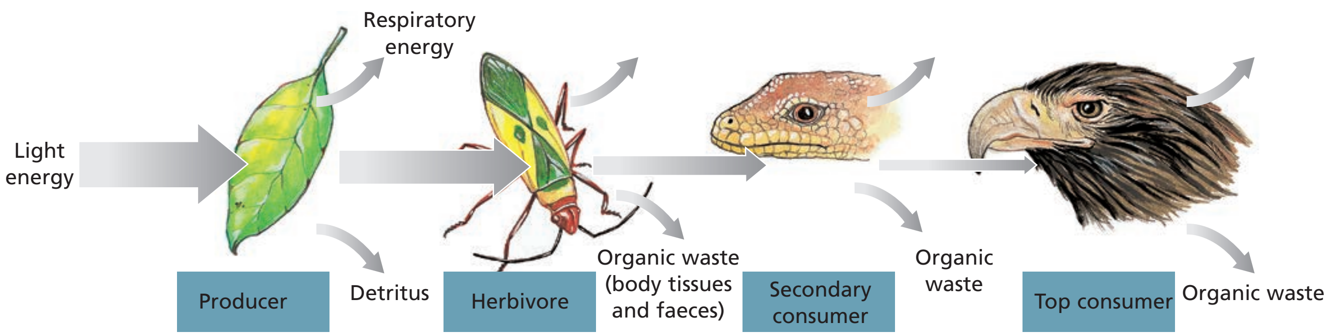
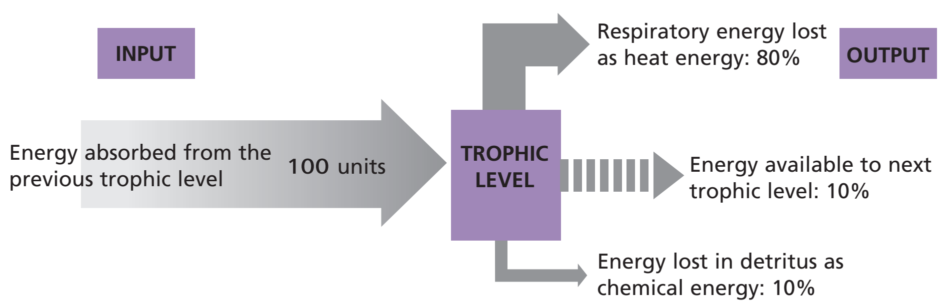
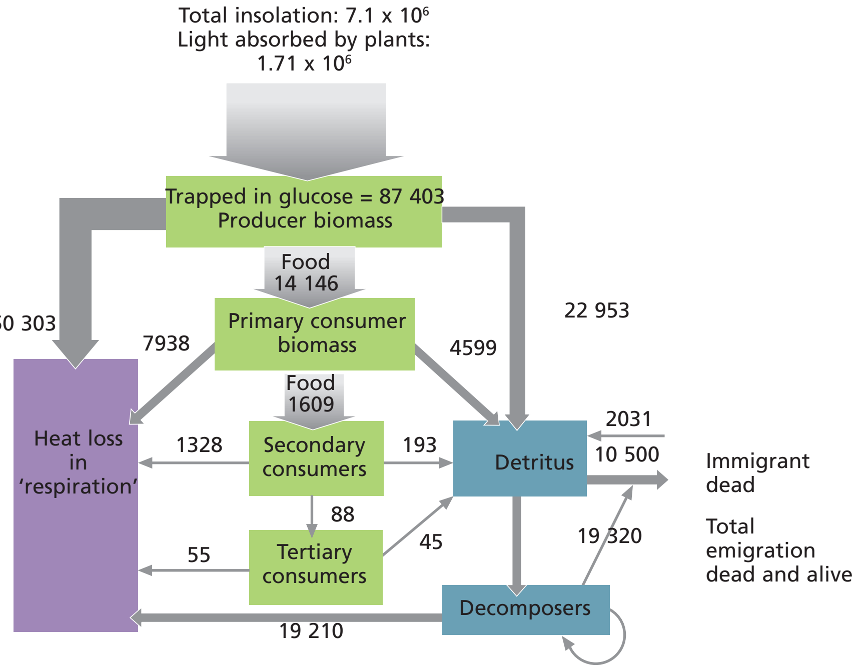


Figure 4.10 ▶ Trophic efficiency describes how much energy is available at each level and how much of this is available to the next level within a food chain. An estimate of the amount available to successive levels is 10%, which means that organisms higher up the food chain must consume more food to meet their energy needs.



Quantifying trophic efficiency

The first study to quantify trophic efficiency was undertaken by H. T. Odum in Florida over a period of four years. The results of his work are summarised in Figure 4.11. This model is still used by ecologists to calculate trophic efficiencies of a variety of ecosystems. The units used are kilojoules of energy per square metre per year ($kJ\,m^{-2}\,y^{-1}$). As shown in the figure, energy trapped from the Sun and stored by plants as carbohydrates is used up by the fourth trophic level (tertiary consumers) and so this limits the number of links in the chain. In other words, there is not enough energy to support higher trophic levels than the fourth level because energy input equals the total energy output.



Odum, H. T. (1957) Tropic Structure and Productivity in the Silver Springs Community, Florida. *Ecological Monographs, 27*(1), pp. 55-112.

◀ **Figure 4.11** The total energy in the Silver Springs Community, Florida

WOW

Koalas are efficient

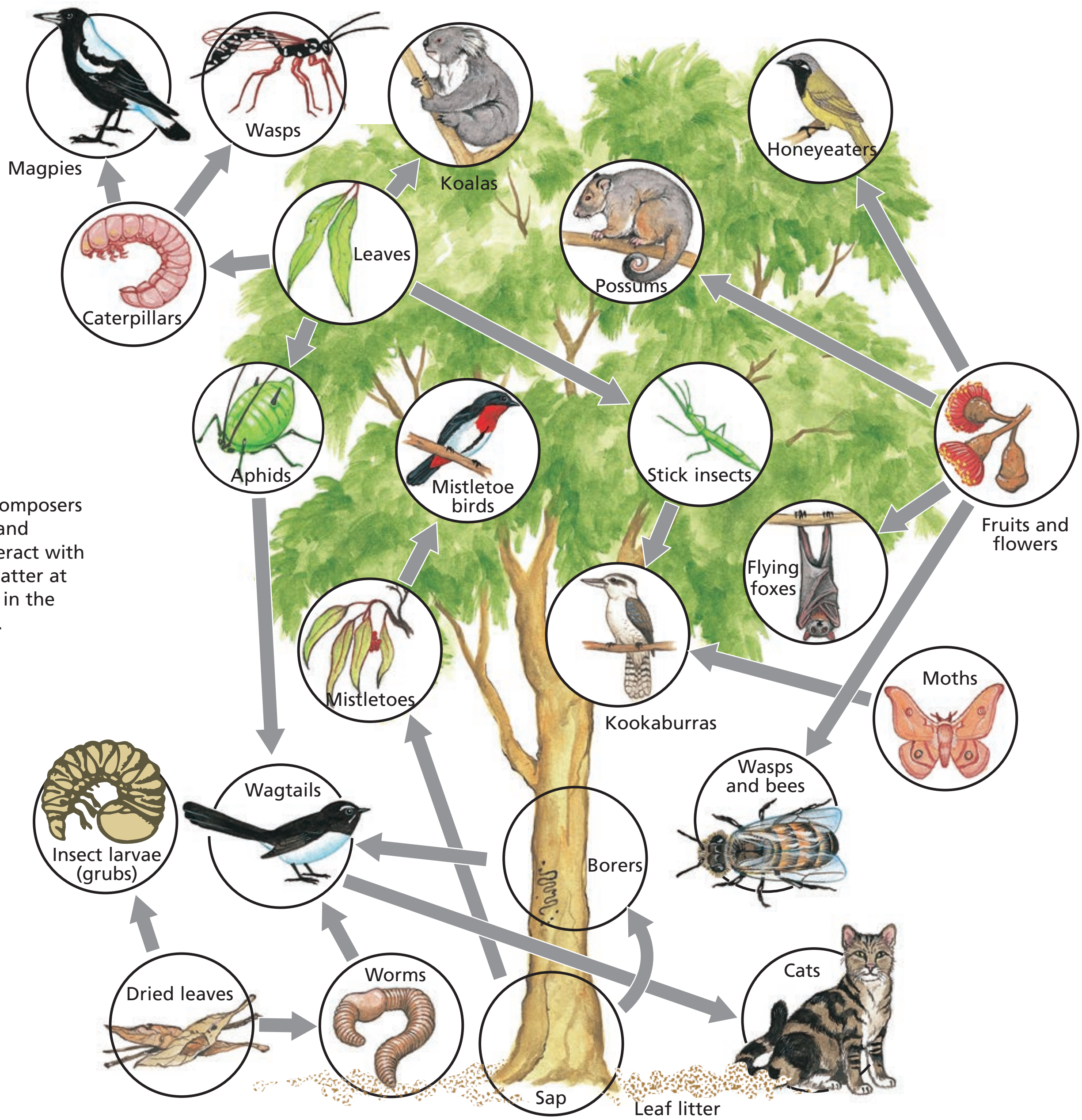
Eucalypt leaves are very low in energy. So, koalas adapted to thrive on a low energy food. Koalas are efficient energy conservers, using about 50% less energy to stay alive than most placental mammals of similar size.

Eat or be eaten: food webs are integrated food chains

We have seen that energy and matter is transferred along a food chain and that energy is lost along the way. What happens when the food runs out? Simple food chains are rare. Most species depend on more than one kind of organism for its food. Ecologists recognised that a herbivore as a primary consumer will feed on a number of species of plants and, in turn, will be eaten by several different kinds of carnivores. These secondary consumers are eaten, in turn, by other carnivores. Such networks of energy and matter form a food web. The feature that distinguishes a food chain from a food web is that an organism in one food chain can occupy a different trophic level from one that it occupies in another food chain. It can be a second-order consumer or a third-order consumer (Figure 4.12). In other words, food webs are dynamic interactions between organisms in an ecosystem.

Omnivore consumers, including humans, can occupy more than one trophic level in the food chain. As primary consumers, humans can obtain more of the available energy from plants directly without losses that occur by eating foods higher up the food chain. Consumption of livestock means that humans can only benefit from 1% of the total available energy from producers. If it is more energy efficient for omnivores to eat plants, why is it necessary for them to consume meats and animal products?

Members of populations of different species move in and out of different ecosystems, so an organism may be part of one food chain or web at one time but not at another time. For example, insects, birds and seeds commonly move between ecosystems wherever their needs are met. On a larger scale, migration of whole populations of animals such as albatross, mutton-birds, salmon or moths results in great changes to the pathways of energy and matter. Phytoplankton is a producer and a fundamental food source for marine animals. Phytoplankton can be carried great distances in ocean currents. As producers, organisms in the next trophic level, such as whales, migrate along with this food source.



Note: Decomposers (bacteria and fungi) interact with organic matter at every link in the food web.

Figure 4.12 ▲
A food web in a forest ecosystem

QUESTION SET 4.3

Remembering

1 Describe how producers are vital to a community.
2 Describe the relationship between a food chain and trophic levels.
3 Match the terms on the left with the definitions on the right.

a producers	i herbivores, carnivores, omnivores
b consumers	ii break down organic remains and products
c decomposers	iii photosynthetic autotrophs

4 List four examples to support the concept that food webs are dynamic.
5 What trophic level supports the entire food web?
6 Is it possible for a carnivore to occupy more than one trophic level in a food web? Give an example to support your answer.

Understanding

7 Distinguish between:
   a food chain and food web.
   b herbivore and carnivore.
   c second-order consumer and third-order consumer.

8 All systems are capable of transforming a source item to a product.
   a Draw an annotated diagram of a generalised system.
   b Summarise photosynthesis in terms of a system.

9 What is the difference between photosynthetic efficiency and trophic efficiency?

10 Predict what happens to the food web if a member at one trophic level is eliminated.

Quantitative modelling to predict change

Food webs are qualitative ways of showing energy pathways and associations in an ecosystem but they are not quantitative because they do not provide numerical data about feeding relationships.

Ecological pyramids can provide quantitative relationships between trophic levels of a community in terms of:

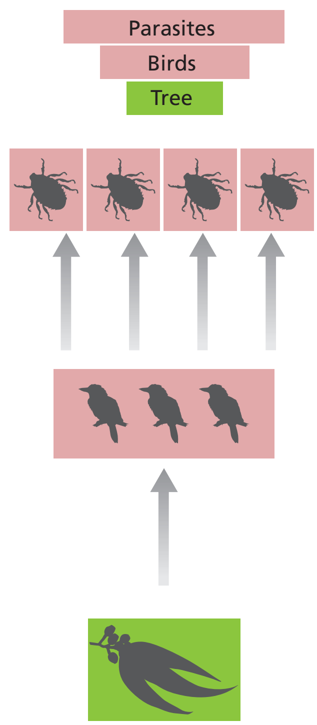
- *numbers* of organisms involved
- the biomass (the *amount* of organic matter)
- the *amount* of energy transferred from one trophic level to the next.

Pyramid of numbers

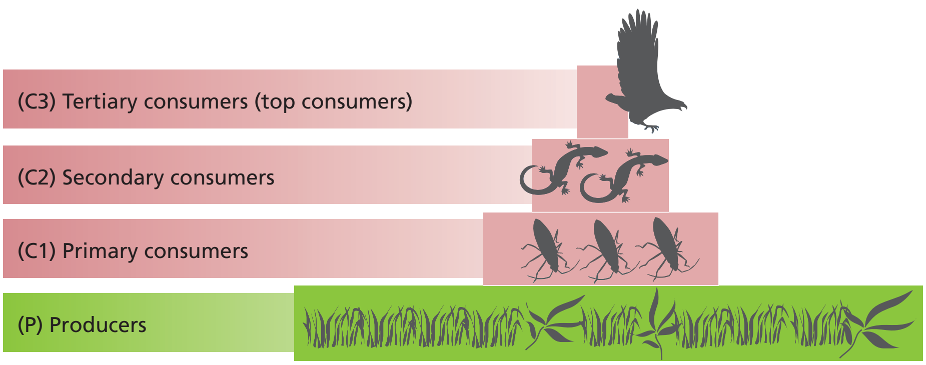
If we consider a so-called 'typical' food chain, there tends to be a progressive drop in the number of organisms found at each level. This is represented as a **pyramid of numbers**. Figure 4.13 shows the progressive fall in numbers at each trophic level.

Pyramids of numbers may not always have an apex representing higher trophic levels. For example, a single very large producer such as the eucalypt tree may support a large number of primary consumers. Numerous organisms along the food chain depend on the eucalypt, including the larvae of sawflies, cup moths and wattlebirds, which feed on nectar and pollen, fruits and insects. Beetles and silvereyes feed on native fruits and berries in addition to insects. In these cases, an inverted pyramid of numbers results.

Inverted pyramids of numbers can also result when communities contain parasites. Imagine a native mammal, such as a bandicoot or a wallaby, infested with ticks or fleas. These parasites are in the trophic level above these animals, yet their numbers are much greater. An example of an inverted pyramid of numbers is shown in Figure 4.14.



▲ **Figure 4.14**
An inverted pyramid of numbers results when more organisms occupy the trophic level above the preceding level.



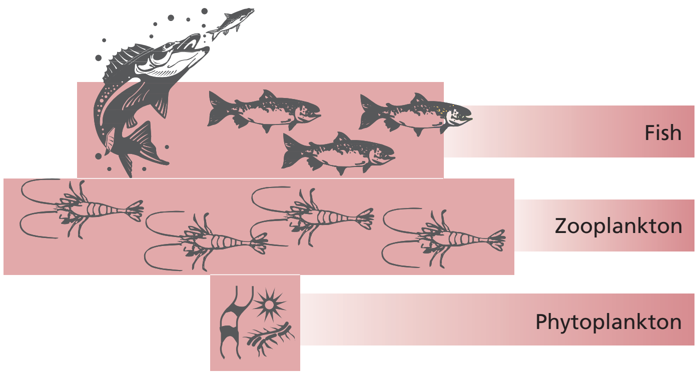
▲ **Figure 4.13**
Pyramid of numbers in a grassland. The width of each rectangle indicates the relative numbers of organisms at each trophic level.

Figure 4.15 ▼ Pyramids of biomass. Note that at each successive trophic level the amount of biomass decreases. The consumers must eat considerable amounts of food to fulfil their energy needs.

Pyramid of biomass

Whilst the pyramid of numbers is only concerned with the numbers of organisms at each trophic level and their dependence on each other, the **pyramid of biomass** is another type of ecological pyramid that can be constructed for a community. The total mass (amount of dry organic matter) of organisms at each level is measured. The measurement can be at one particular time or it can be calculated as a rate from measurement of dry mass in a given area for the duration of a year (e.g. $g\,m^{-2}\,year^{-1}$).

Figure 4.16 ▼ Inverted pyramid of biomass



Pyramids of biomass are almost always pyramidal in shape but, in certain circumstances, measurements may give an inverted pyramid. For instance, at particular times of the year, the biomass of the tiny herbivorous organisms that float in lakes and oceans (zooplankton) may exceed the biomass of the tiny photosynthetic organisms (phytoplankton) on which they feed. How can this be?

The organisms that make up the phytoplankton are smaller than the zooplankton that depend on them and they have shorter life cycles. As a result, at any one time point, the biomass of the phytoplankton may be less than that of the zooplankton. This loss is made up for by the tremendous turnover of phytoplankton as they rapidly live their lives, reproduce and die.

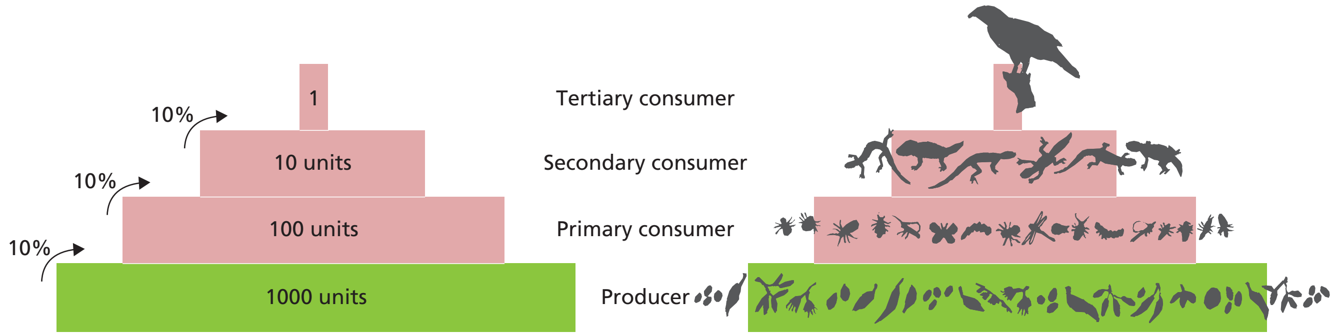
Pyramid of energy

Although pyramids of numbers and biomass provide ecologists with a certain amount of useful information, to get a fuller understanding of what happens to energy transfer along pathways in communities, **pyramids of energy** (or 'energy pyramids') are constructed (Figure 4.18).

Pyramids of energy are expressed in units of energy per area in a given time; for example, kilojoules per square metre per year ($kJ\,m^{-2}\,y^{-1}$). They show the *rate* at which energy is transferred from one trophic level to another. This dynamic view of a community contrasts with the 'snap shot' picture provided if energy is only taken at one particular time point. Pyramids of energy allow ecologists to describe the rate of energy transfer in a community. This allows them to make predictions about whether a community can be sustained or what impact changes to rates of energy transfer will have on the community.

Only some of the energy stored in a trophic level goes to the next trophic level, so pyramids of energy can never be inverted in the way that pyramids of numbers or biomass sometimes are.

The higher the trophic efficiency, the steeper the sides of the pyramid will be. This means that a pyramid of energy drawn to show an ocean ecosystem would have steeper sides than one drawn to show a terrestrial ecosystem that is dominated by birds or mammals.



▲ Figure 4.17
A pyramid of energy shows the rate of energy transfer through successive trophic levels. The organisms at the top of the food chain receive only a small amount of the total energy stored by producers. This ultimately limits the number of possible trophic levels.

QUESTION SET 4.4

Remembering

1 Describe a convenient way to quantify species within a food chain.
2 Describe the features of an inverted pyramid of biomass.

Understanding

3 Explain with an example how you would construct a pyramid of energy.
4 Explain why a pyramid of numbers is not always pyramidal in shape.
5 Explain why pyramids of energy can never be inverted.

Applying

6 A forest clearing has 1 km^2 of luscious grass and is home to a community of rabbits, foxes and hawks. In one year the grasses produce 150 000 $kJ\ m^{-2}\ y^{-1}$ of energy. This food is consumed by the rabbits that are in turn consumed by the foxes. The foxes are in turn food for hawks. Construct a pyramid of energy and calculate the energy extracted by the top consumer. Explain what happens to the energy as it is transferred to each level.
7 Grass → mouse and rabbit and grasshopper → snake → kookaburra → wedge-tailed eagle.
  a From the food chain depicted above, construct a pyramid of biomass.
  b Which consumer could be both a tertiary and quarternary consumer?

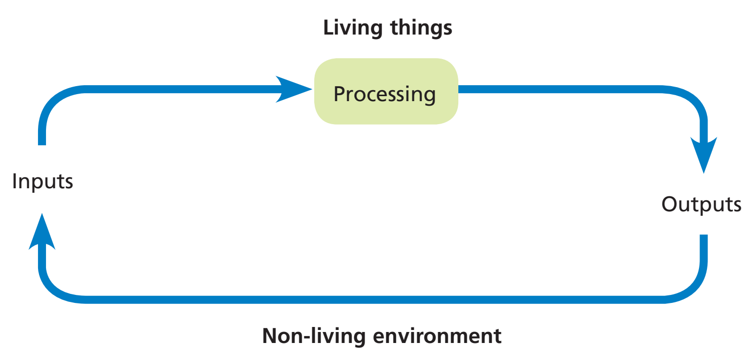
Full circle: how does matter get recycled?

The difference between energy and matter is that the Sun provides a constant, external supply of energy while the total matter that exists on our planet is a fixed resource and therefore must be recycled.

A matter of recycling

Fortunately, matter is cycled between the living (biotic) component and the non-living (abiotic) components of the ecosystem. We noted earlier that energy is lost along food chains through the production of organic wastes such as faeces and dead tissues. However, the matter comprising this detritus is not necessarily lost to the ecosystem. **Detritivores**, such as worms, feed on plant detritus and scavengers feed on the dead carcasses of animals. In this way, the organic matter re-enters the food chains.

▼ Figure 4.18
The relationship between the non-living environment and living things. Material from the non-living environment is taken up by living things and this material is then incorporated into the cells and tissues of the living organism.



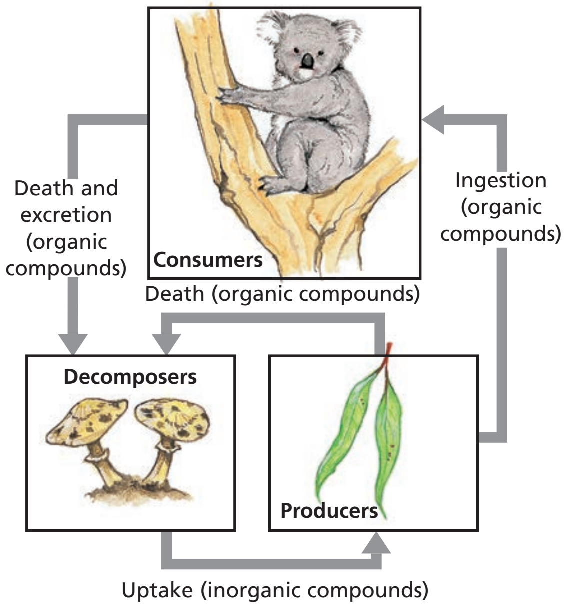


Figure 4.19 ▲ The relationship between producers, consumers and decomposers. Each member can absorb products produced as by-products or waste material from another.

In a forest ecosystem (such as the one shown in Figure 4.12), the tree (producer) absorbs mineral nutrients and water from the soil, and oxygen and carbon dioxide from the air. Consumers such as stick insects and insect larvae take in the complex organic materials in the form of plant foliage (leaf and soft branches) that the tree synthesises. The consumers take in air containing the oxygen produced as the leaves of the tree and other plants photosynthesise. In turn, consumers and non-photosynthesising producers release carbon dioxide as a waste product of cellular respiration. Micro-organisms decompose the organic wastes of the tree and the consumers. These simple products are recycled by the tree and by the micro-organism decomposers to provide nourishment. Figure 4.19 shows the relationship between producers, consumers and decomposers.

Material cycling models

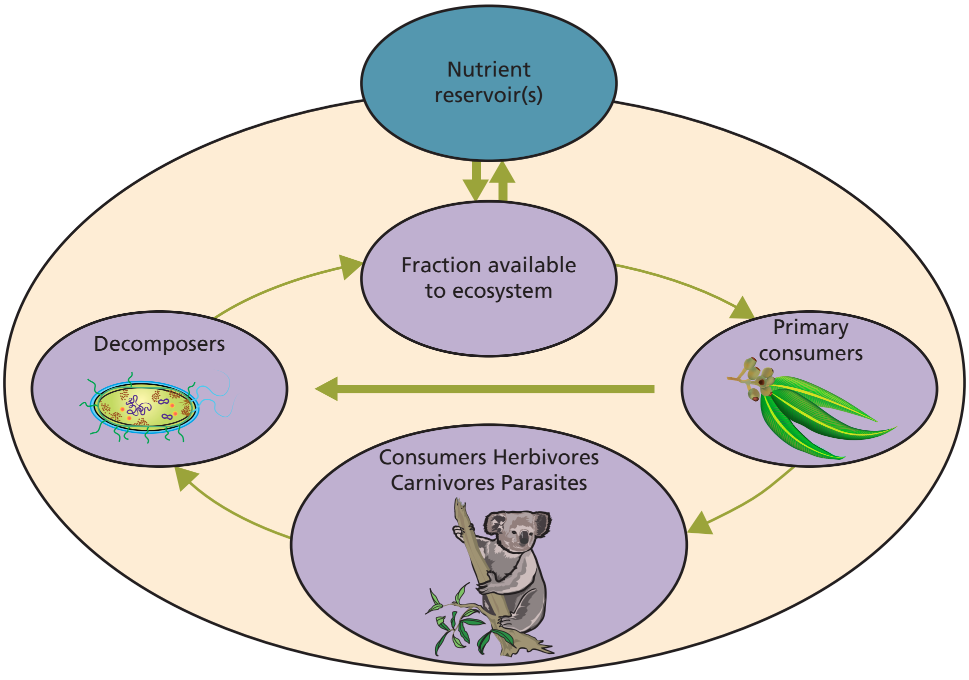
In living things, carbon is the most abundant chemical **element** closely followed by hydrogen, nitrogen and oxygen. Carbon is able to bond with many other elements giving an enormous variety of biological molecules essential for life. Carbon is a fundamental element of all organic matter including carbohydrates, lipids, proteins and nucleic acids that are the chemical building blocks of cells and the source of their energy. The continuous supply of key elements including carbon, nitrogen, oxygen and phosphorus are essential for life because these materials constitute most of the molecules in cells that give an organism their form and function. Without these key ingredients, life on Earth would cease. To replenish supplies, organic matter containing these elements must be recycled. All living organisms acquire these materials through the nutrients they consume.

The way in which matter is cycled has a large effect on the availability of these nutrients. **Nutrient cycles** feature the following two main components.

1 A biological component that follows how the element cycles through organisms
2 A geochemical component showing how the element cycles through soils, rocks, water and the atmosphere.

Given the interdependent manner in which these components are related, nutrient cycles are also called **biogeochemical cycles** (Figure 4.20).

Figure 4.20 ▶ Generalised model of biogeochemical cycling



Biogeochemical cycles: carbon, nitrogen, phosphorous

WOW The worms of Mumbai

Mumbai in India generates more than 6000 tonnes of rubbish a day. The Green Cross Society uses a native species of earthworm to convert vegetable and slaughterhouse wastes into compost. Recycling organic matter not only helps to maintain the fertility of soils but also reduces the number of rats in towns and cities. This, in turn, reduces the chance of outbreaks of plague, which is transmitted by fleas carried by the rats.

Soil cycling

Nutrients essential for plant growth are taken in from the soil by a network of plant roots. Micro-organisms, fungi and insects present in the soil and on the surface contribute to the decay of plant matter such as leaf litter under trees. In this way, nutrients are returned to the soil and, in some ecosystems, can even accumulate. More than 90% of all the phosphorus, potassium and nitrogen (as nitrites and nitrates) in the Western Australian karri (*Eucalyptus diversicolor*) forests is in the top metre of the soil and provides a long-term storage reservoir of nutrients, replenishing what is used. The organic matter in the soil is called **humus**, which, apart from storing nutrients, contributes to the soil's texture and water-holding capacity. Soils with little nutrient-storage capacity can easily become depleted with changes or disturbances, such as fire, logging, ploughing, intensive cropping and removal of soil in run-off.

Nutrients also enter the soil in rainfall. Minute solid particles derived from windblown sands and top soil, fires, volcanic activity and storms are carried in the atmosphere or from the surface of forest foliage. These are washed down into the soils where they bond to soil particles, adding to the mineral nutrient store. Plants including banksias, waratahs and native grasses have adapted to thrive in their native Australian soils, changing over many hundreds of generations to cope with the soil deficiencies such as the lack of certain mineral nutrients. Introduced species are adapted to different soils in different countries and must be provided with additional nutrients to meet their needs (Figure 4.21).

An obstacle in the nutrient cycle is how quickly nutrients can be returned to the soil from the decomposition of dead organic matter. For example, different types of leaves decompose at different rates. If they are thin and soft, as in rainforests, they decompose fairly rapidly, but hard leathery leaves, such as those of eucalypt forests, can take several years. The rate of decomposition depends on how much moisture and air is present in the soil and organic material. These conditions favour the activity of decomposers. Woodlands in Victoria, and other regions such as North America and Europe, have deciduous trees that resorb nutrients and chlorophyll before dropping their leaves in autumn. This leaf litter provides a considerable pool of nutrients to be released to the soil by decomposers (Figure 4.21).

Shutterstock.com/Gucio_55

▲ **Figure 4.21**
The autumn woodland has an abundance of leaf litter. This material rapidly forms humus and enriches the soil with nutrients.

Carbon cycle

Carbon atoms circulate between the organic compounds of living things and their non-living surroundings through a number of pathways, and together these form the carbon cycle (Figure 4.22).

The carbon cycle is unique among nutrient cycles because it does not necessarily involve decomposers. How can this be? Autotrophs take in their carbon as carbon dioxide gas from the atmosphere and carbon dioxide is given out by all organisms as a result of cellular respiration.

Even in the absence of any decomposers, carbon would still be able to circulate for some time within an ecosystem. Not all dead material decays. In **anaerobic** or highly acidic conditions, decomposers may be unable to break down all the remains and waste products of organisms. In such situations and over long periods of time, these substances may accumulate to form fossil fuels, such as peat, coal, oil and gases derived from them. In nature, these deposits represent a **sink**, whereas **source** refers to the origin of materials deposited in the sink.

CARBON CYCLE

The ocean is a major sink for carbon and a critical component in the global balance of carbon dioxide. Visit this link to explore more about the role oceans play in the carbon cycle.

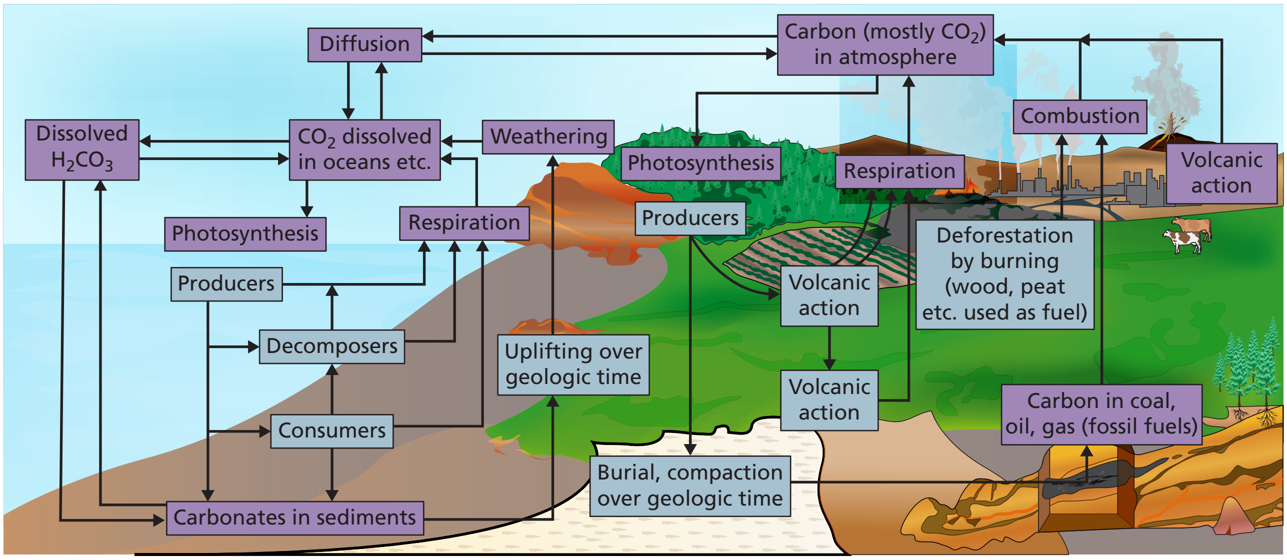


Figure 4.22 ▲ Atmospheric carbon dioxide is trapped by autotrophic organisms and incorporated into carbohydrates during photosynthesis. This carbon-rich biomass is consumed by members of the food chain as a source of energy and matter. Carbon is released into the atmosphere as CO_2 from cellular respiration and the combustion of fossil fuels.

The amount of carbon dioxide in the atmosphere is maintained largely by a balance between photosynthesis, which withdraws carbon dioxide from the atmosphere, and cellular respiration and combustion, which add carbon dioxide to the atmosphere. Unfortunately, due to a number of factors, the level of carbon dioxide in the atmosphere has risen considerably during the last 200 years. Humans use fossil fuels as a source of energy and the combustion of these fuels releases carbon dioxide, a surplus that disrupts the natural balance. Even though plants photosynthesise more rapidly with the increased availability of carbon dioxide, it is not being taken in at a sufficiently fast rate because of the removal of vast areas of forest over the last century. Changes to ocean temperatures have also affected the cycling of carbon.

Nitrogen cycle

The high percentage of nitrogen in the atmosphere is maintained by the interactions between the biotic conversion of gaseous nitrogen to nitrates and nitrites by specialised bacteria. This loss of gaseous nitrogen is compensated for by the return of nitrogen to the atmosphere by abiotic factors including volcanic activity and the bacterial conversion of nitrites to nitrogen gas. Nitrogen is an essential element along with other elements (e.g. carbon, hydrogen and oxygen) for living things including plants to make protein. These molecules are essential for plant structure and function. Proteins have many different roles in cells, and play an essential part in controlling cell activities and the growth of new cells. Even though the air has 80% nitrogen, plants are unable to absorb nitrogen directly from the atmosphere. Most plants can only absorb the dissolved form as nitrates (and sometimes as ammonium NH_4^+) from the soil. As heterotrophs, animals rely on plants for their source of nitrogen.

The nitrogen cycle (Figure 4.23) depends on the metabolic activities of specialised bacteria called fixers, the nitrifiers and the denitrifiers. Some of these bacteria have developed a special symbiotic relationship with plants so that instead of living free in the soil, plants accommodate them in special root organs called **nodules** (Figure 4.24). In exchange, plants have a ready source of nitrogen at their disposal.

Gaseous nitrogen (N_2) makes up about 80% of the atmosphere and can be removed from the atmosphere by lightning and by nitrogen fixation.

Ions are atoms that have either gained or lost a valence shell electron, acquiring a positive or negative charge. Polyatomic ions like nitrite (NO_2^-), nitrate (NO_3^-) and ammonium (NH_4^+) have more than one atom present in the ionic molecule.

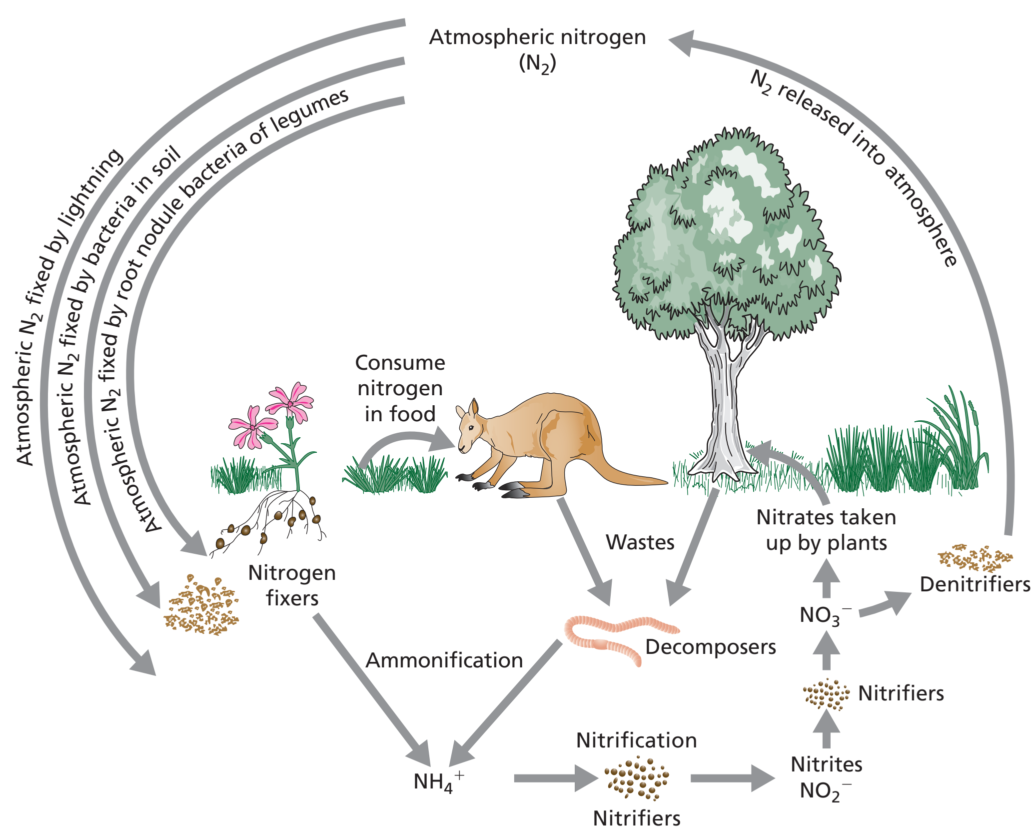


Figure 4.23
The nitrogen cycle. A balance is maintained between processes that withdraw nitrogen from the atmosphere (nitrogen fixation) and those that add nitrogen to the atmosphere (denitrification and volcanic emissions).

Nitrogen fixers

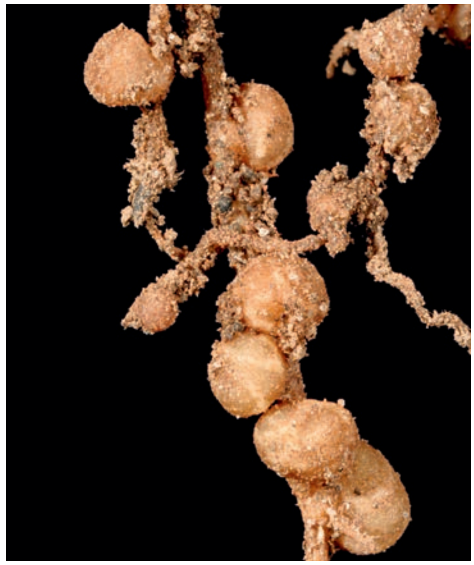
The process of **nitrogen fixation** can be carried out by certain prokaryotes, such as the bacteria *Azotobacter* and *Rhizobium*. These bacteria enter the fine root hairs of *Casuarinas*, *Acacias* and legumes, including clover, peas and beans. This invasion causes the host plant to form nodules on the roots that provide accommodation for the resident bacteria so that the fixed nitrogen can be rapidly transported by the plant.

Other nitrogen fixers live freely in the soil. These prokaryotes are able to absorb the nitrogen gas from the air spaces in the soil and build it up, quite remarkably, into amino acids, the building blocks of proteins.

Ammonifiers (bacteria and fungi)	waste	→	NH_3 ammonia
Nitrifiers (bacteria)	NH_3	→	NO_2^- nitrites
Nitrifiers (bacteria)	NO_2^-	→	NO_3^- nitrates
Denitrifying (bacteria)	NO_3^-	→	N_2
Nitrogen fixers (bacteria)	N_2	→	NH_4^+ ammonium ions

Figure 4.24 ▶ The nitrogen fixers live in soil and also in the nodules of specific plants. These bacteria specialise in the fixation of atmospheric nitrogen.

Corbis/Nigel Cattlin/Visuals Unlimited



Alamy/Custom Life Science Images

Nitrifiers convert decaying material into nitrites

Nitrifying bacteria convert the ammonia released in urine and from the decay of faeces, dead plants and animals to nitrites (NO_2^-). This takes place in a series of chemical steps during which energy is released as heat. The bacteria use this energy for building up their own organic compounds. Other bacteria convert the nitrites to nitrates that, only then, can be absorbed by plants.

WOW

Too much of a good thing

Too much nitrogen is affecting many of Europe's most precious heathlands and sphagnum bogs. These places are nutrient-poor habitats with low inputs of nitrogen and plants adapted to this. Besides airborne nitrogen oxides from power stations and cars, the largest source of this excessive nitrogen is evaporation from animal urine in run-off. A dairy cow produces 40 L of urine a day!

Denitrifiers convert nitrites into atmospheric nitrogen

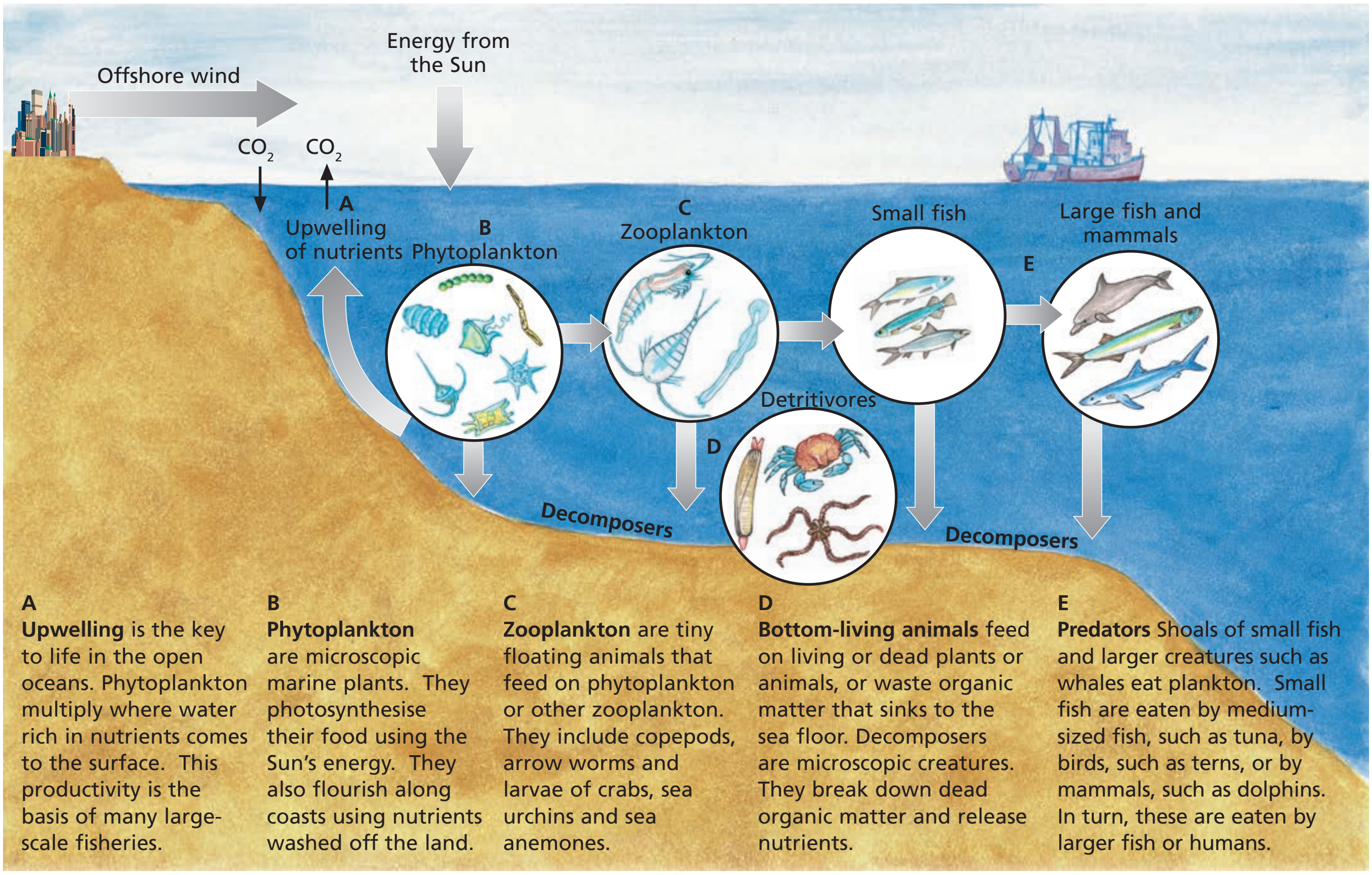
Plants growing in waterlogged soils have a particular problem to overcome. There is a shortage of available oxygen in the waterlogged soil so denitrifying bacteria convert nitrates in the soil into gaseous nitrogen. This process releases oxygen required for their metabolic processes. The combined action of nitrifiers and denitrifiers results in the recycling of nitrogen between plants and the atmosphere.

How does nitrogen reach the ocean?

In the oceans, some of the available nitrogen (such as nitrate and ammonium compounds) is brought in by rain and the activities of nitrogen-fixing organisms. This **nitrogenous** material circulates through the plants and animals found there. Some of the available nitrogen, however, descends beneath the upper 100 m of the surface beneath which photosynthetic organisms are absent. It may then descend all the way through to the sediments at the bottom of the ocean. Here the nitrogen compounds are unavailable to most organisms unless eventually returned to the atmosphere by volcanic emissions and other processes. This loss of nitrate and other nutrients makes the ocean a relatively poor environment in terms of available nutrients overall.

Nutrient cycling in the ocean

Reduced productivity in the oceans (i.e. reduced quantity of harvested seafood) has been attributed to both human impact and to changes in the natural ocean environment. Offshore, overfishing has had a catastrophic impact on the world's stocks of most of the sought after fish including flake (shark), bluefin, orange roughy and Chilean bass. Scientific reports have estimated that industrial fishing has reduced fish stocks by 90%. In contrast, closer to the shore and in estuaries, powerful natural uprising currents bring nutrients to the surface. In the latter regions, plant and animal life is more abundant, contributing to the success of fishing industries.



▲ **Figure 4.25**
Cycling of nutrients in the ocean

See Chapter 9 for more on the biological reactions of cells.

The water cycle

Water is considered a food although it has no nutritional value. Water provides a habitat for a diverse range of living things and it provides the environment in which all living cells are bathed. The wet mass of cells is 70% water and so forms the matrix in which most of the biological reactions takes place. The **water cycle** (Figure 4.26) is also known as the hydrological cycle and is driven by two energy sources: solar energy and gravity.

The phosphorus cycle

The phosphorous cycle (Figure 4.27) is also essential for life on Earth. Without phosphorous, diversity could not exist. It participates in key biological molecules because of its ability to transfer energy through bonding configurations. DNA, RNA and ATP are a few of these complex molecules.

How does inorganic phosphorous find its way into such molecular diversity? Volcanic action and earthquakes introduce buried reservoirs of phosphates as sediments and rocks to the environment. Mechanical weathering from wind and rain release phosphates to the soil and water, making phosphate available as an essential nutrient to plants and entering the food chain for consumption by consumers. After cycling through the food chain, phosphorous will again be returned to abiotic reservoirs as calcium phosphates of bones, shells, hard parts of aquatic animals and detritus in the oceans.

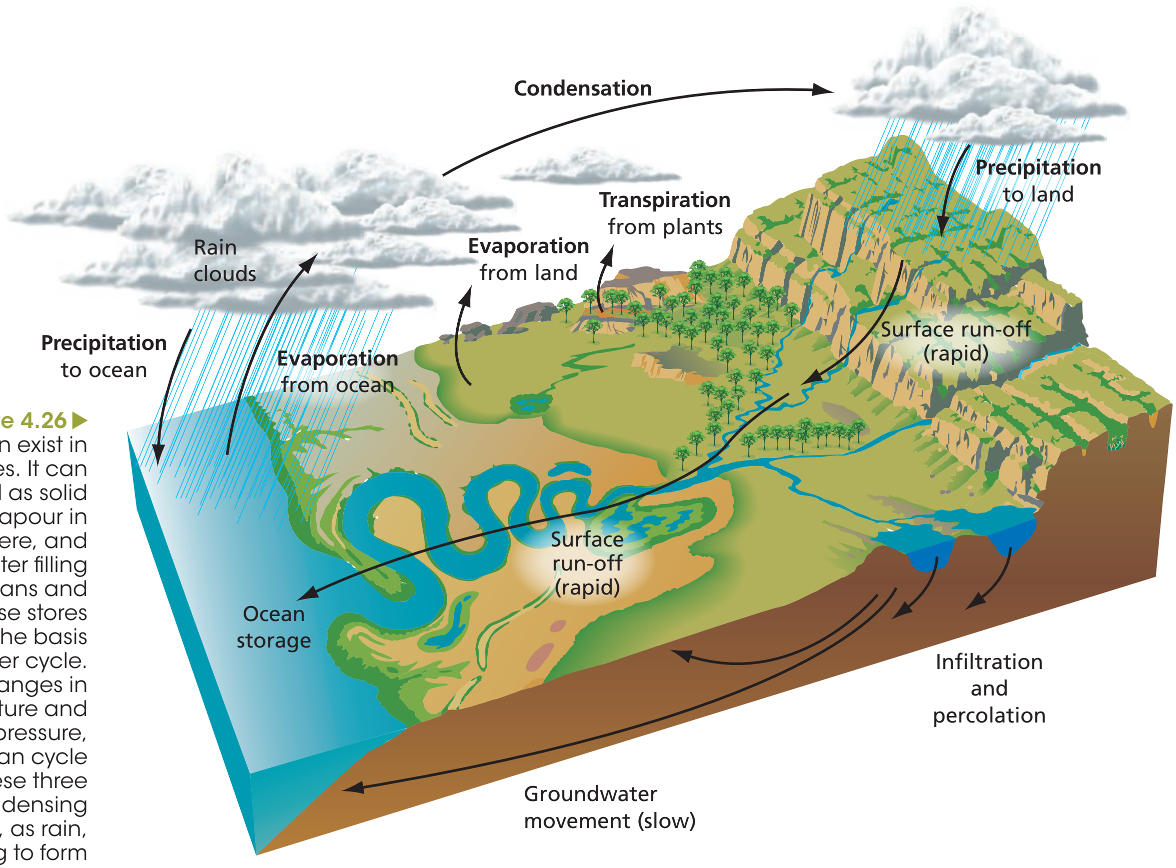


Figure 4.26 ▶ Water can exist in three states. It can be stored as solid ice, water vapour in the atmosphere, and liquid water filling rivers, oceans and lakes. These stores provide the basis for the water cycle. Due to changes in temperature and atmospheric pressure, water can cycle between these three states, condensing from vapour, as rain, or freezing to form solid ice.

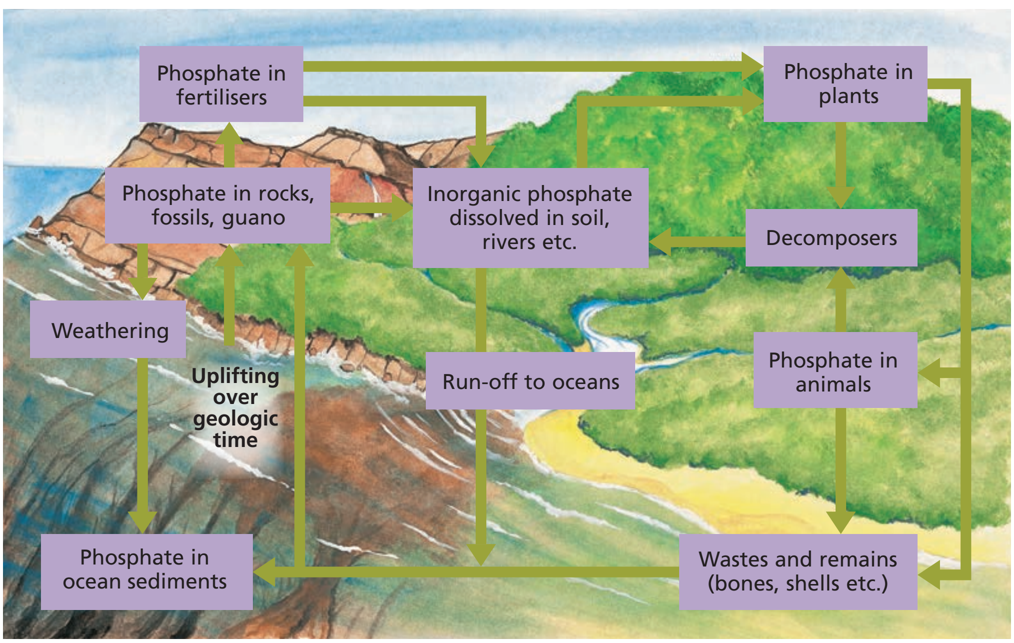


Figure 4.27 ▶ The phosphorus cycle

QUESTION SET 4.5

Remembering

1 How do biogeochemical cycles derive their names?

2 What are the basic components of a biogeochemical cycle?

Understanding

3 Which processes or activities:

  a contribute to nitrogen in the atmosphere?

  b withdraw nitrogen from the atmosphere?

  (Note: 'Atmosphere' also refers to air spaces between soil grains.)

4 Using the carbon cycle as an example, distinguish between a sink and a source.

Applying

5 Explain what happens to carbon sinks when atmospheric CO_2 increases.

6 Identify the points in the carbon, nitrogen and water cycles where interconnections occur.

Analysing

7 a Draw an annotated circle to represent cycling of matter in a woodland ecosystem in summer.

  b Describe the consequences to the woodland ecosystem of little or no activity by decomposers.

  c Describe the same woodland in autumn. Assume the majority of trees in the woodland are deciduous trees.

8 a Draw a simple annotated diagram that summarises the water cycle.

  b Why is water essential to living things?

  c Identify at least two points where there could be interruptions in the water cycle.

9 Predict what would happen at each step in the carbon cycle if:

  a large quantities of fossil fuels continue to be consumed.

  b there is a global increase in diatom activity in the ocean.

  c major deforestation occurred.

Biological magnification

The concentrations of **non-biodegradable** substances, such as dicholorodiphenyltrichloroethane (DDT) and mercury can increase as they get passed from one trophic level to the next along a food chain. This process of amplifying the amount of substance is referred to as **biological magnification**. While the toxicity of these compounds may not affect organisms lower in the food chain, their effects at the top of the food chain can be disastrous. For example, reproductive rates could decline and death rates could rise. It is generally well known now that the thinning of egg shells occurred in some species of birds due to a cumulative intake of toxic substances.

Populations of brown pelicans and peregrine falcons in Australia declined sharply during the 1950s. In North America and in northern Europe, the pattern for bald eagles, sparrowhawks and peregrine falcons was similar. In 1958, ornithologist Derek Ratcliffe made the link between broken eggshells, population decline and the use of organochlorine compounds, including DDT. Campaigners such as Rachel Carson drew public attention to the prolific use of these pesticides on crops and the damage to adult birds and other wildlife.

In 1942, the Australian armed forces introduced DDT in a limited way to control mosquitoes. It was used in agriculture extensively as an insecticide from 1947 to the 1960s and early 1970s. Given the relative isolation of each of the areas where there was maximum use, scientists were able to analyse the relationship between the use of DDT and the decline in numbers of peregrine falcons. Figure 4.28 shows the level of the pesticide use in the states and territories of Australia. The regions of heavy and medium use agree well with the percentages of eggshell thinning as the result of DDT toxicity in the peregrine falcon.

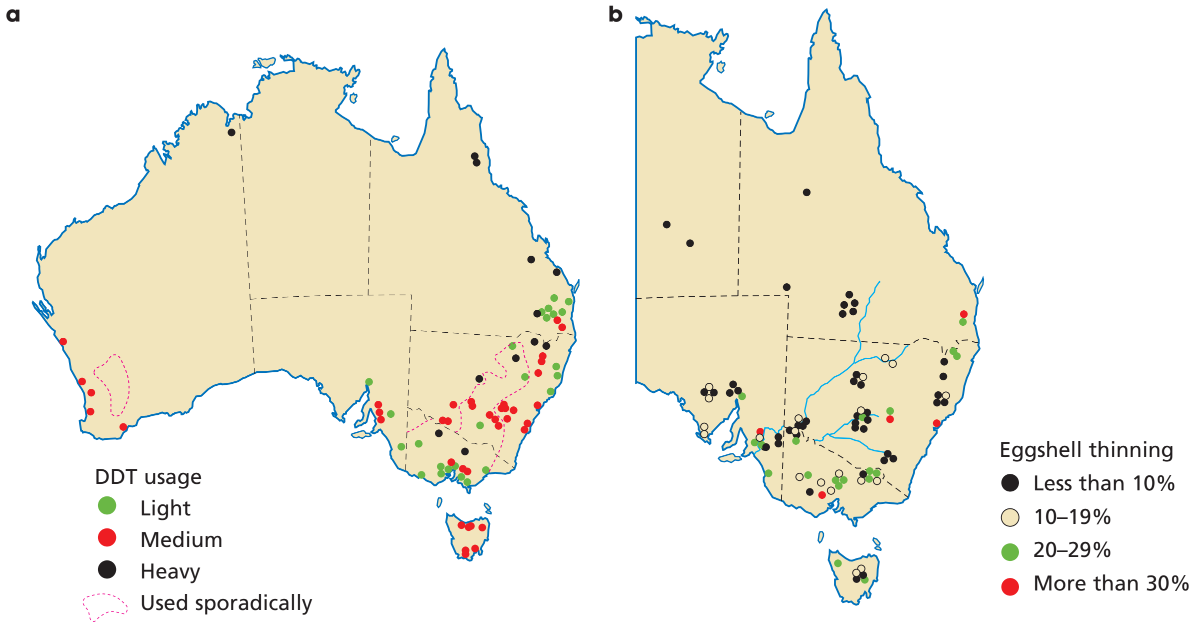


Figure 4.28 ▲
a) DDT usage and b) amount of eggshell thinning in peregrine falcons

Accumulation of other 'industrial' pollutants, such as heavy metals including mercury and 'natural' toxic substances produced by some species of cyanobacteria, can cause problems along food chains.

Organochlorines that have been eaten by birds are non-biodegradable because they cannot be metabolised (processed) by the liver into harmless substances. By applying the concept or idea of pyramids of biomass, you can see how these chemicals become concentrated along food chains to such an extent that damage occurs to the top consumers. For some time following the banning of organochlorine pesticides, tests on the tissues of the Eastern barred bandicoot, a rare marsupial in Victoria, Australia, showed high levels of dieldrin. A remarkable success story is the recovery of the North American sparrowhawk with the declining use of organochlorine defoliants (Figure 4.29).

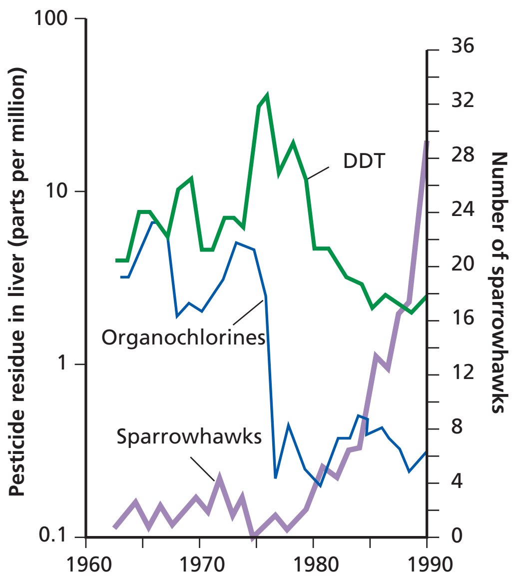


Figure 4.29 ▲
Sparrowhawks beat the pesticides. The number of birds has increased with the decline in pesticide use.

Case study

A forest fed on fish

Grizzly bears make the forests of British Columbia, Canada their home. Bear populations living by the rivers have a distinct advantage over other bears in the region – they can catch and eat fish. In autumn, large numbers of salmon travel up the river from the ocean to their spawning areas to produce their young and are in plentiful supply for hungry bears. The bears can eat 40 kg of fish per day for several weeks, gaining considerable weight. This is essential for them to survive over the long winter hibernation. Bears are key to the success of the forest ecosystem and occupy a crucial link in the food web connecting the river and the forest. The fish carcasses are discarded along the river banks and forest floor, which provides a breeding ground for insects and nutrients for their larvae. Decomposers finish the job of breaking down the carcasses to recycle all the nutrients to the soil. Scientists have estimated that 80% of the bears' composition is derived from the ocean. How can this be when the only source of ocean food is the salmon they consumed for a few weeks?

In spring, the bears emerge from hibernation very hungry and consume large amounts of the new grasses that have grown. Scientific tests on these grasses reveal high levels of a rare nitrogen isotope predominantly found in the ocean, nitrogen-15 (^{15}N). It was the fish fertiliser scattered on the forest floor by the bears in autumn that provided the nutrients for the grasses to flourish and the bears to eat in spring. This accounts for the seemingly large amount of ocean material in the bears' bodies.

The larvae that were incubated in the fish carcasses have matured into insects and are food for birds, which then carry this ocean-fed material further into the forest through their droppings. Scientists have removed samples of wood from established trees and have measured the amounts of ^{15}N, relating it to the growth rings. This data has shown that the presence of ^{15}N, and therefore salmon fertiliser, is dating back several decades. It is the diet of bears that has sustained an entire ecosystem.

Corbis/Thomas Kitchin & Victoria Hurst/All Canada Photos

▲ **Figure 4.30**
A grizzly bear hunting for salmon near a forest in British Columbia, Canada

Questions

1 Draw a diagram of this food web and identify the primary, secondary and tertiary consumers.
2 What is the main feature that has allowed this ecosystem to succeed in a region that would have otherwise looked very different?
3 Explain the source of the large amount of ^{15}N in the bodies of the bears.
4 In this ecosystem, bears are at the top of the food chain and have large amounts of ^{15}N. What ecological process explains the large amount of this isotope in the bears' tissues?
5 Find out where salmon appear in the food chain and then draw a biomass pyramid to include bears.
6 Predict what would happen to this food chain if the bears all died from disease. You may construct a diagram to show this.
7 Write two or three paragraphs about the text and draw your own conclusions about the sustainability of an ecosystem.

BROWN BEARS
View live webcam vision at Brooks Falls, Katami National Park, Canada, where brown bears hunt salmon. When the webcam is offline, it shows video footage of previous recordings.

QUESTION SET 4.6

Remembering

1 Define 'biological magnification'.

Understanding

2 Using a food chain model, illustrate your definition from question 1.

Applying

3 Toxic substances are non-biodegradable, which means they remain toxic in the environment and cannot be broken down. Consider a grassy area contaminated with an industrial toxin. The grass supports a food chain consisting of insects, caterpillars, small rodents, weasels and owls. Each grass has 1 unit of toxin. Each insect and caterpillar consumes 100 grasses over its lifetime. Assume the small rodent consumes 100 insects in its life time and the weasel eats 100 rodents in its life. Finally, the owl eats 100 weasels in its life.

a Draw a pyramid of biomass to represent the food chain.

b Calculate the units of toxin accumulated at each level.

c Compare the level of toxicity experienced by the producers and the owl.

CHAPTER SUMMARY

- Sunlight is the original source of energy for ecosystems.
- Matter is a finite resource on our planet and must be recycled.
- Systems such as an ecosystem are a set of interacting biotic and abiotic components that together form a larger entity. A simple system consists of a process that acts on an input and forms an output or product.
- Producers (autotrophs) transfer the energy from sunlight in a reaction that uses carbon dioxide and water to form glucose. Consumers (heterotrophs) cannot make their own energy and must acquire it by eating producers or other heterotrophs.
- Ecologists try to mimic complex systems by constructing simplified models such as food chains and food webs.
- Energy from producers can support whole communities of different animals. The size of the food chain is limited by how efficiently energy is transferred to each trophic level.
- Matter is transferred between trophic levels and does not run out.
- Energy is lost during each transfer so the number of trophic levels is limited.
- The efficiency of energy transferred to each trophic level can be modelled using biomass pyramids and calculations of gross and net primary productivity.
- All matter is recycled through biogeochemical processes. Carbon, oxygen, water, phosphorous and nitrogen are essential for life and are recycled through ecosystems.
- A self-sustaining ecosystem depends on detritivores to recycle detritus into a form that the producers can use as nutrients.

CHAPTER GLOSSARY

abiotic the non-living components of an ecosystem

anaerobic without oxygen

autotroph an organism capable of making its own food from inorganic substances using light (through photosynthesis) or chemical energy (through chemosynthesis); green plants, algae and certain bacteria

biogeochemical cycle the cycling of matter through the living component of an ecosystem, soils, rocks, water and the atmosphere

biological magnification the accumulation of non-biodegradable matter in the tissues of one organism, passed along from the previous one in the food chain

biomass the total amount of matter (mass) of living material in an ecosystem at a particular time

biotic the living components of an ecosystem

carbohydrate an organic compound that serves as a structural component and a major energy source in the diet of animals; includes sugars, starches, celluloses and gums

carnivore an organism that feeds on other animals

cellular respiration a series of cellular biochemical reactions and processes using glucose and oxygen and producing carbon dioxide and water; the energy released is used to convert ADP to ATP

consumer see *heterotroph*

decomposer an organism such as a bacterium and fungus that breaks down complex organic matter into simpler matter

detritivore an organism that feeds on small pieces of dead plant or animal matter

detritus organic wastes, including faeces and dead tissues

element a pure substance, the atoms of which are of one kind

emit to give or send out (light)

first-order consumer a consumer that feeds directly on producers; also known as a herbivore

food chain one organism occupying a trophic level is consumed by the next organism in a higher trophic level, creating a chain whereby energy and matter are passed to progressively higher levels

food web a diagram that shows how different organisms feed on each other, thereby transferring energy through an ecosystem; interconnecting food chains in an ecosystem

gross primary production (GPP) the total organic matter in an ecosystem (or specified area) made via photosynthesis

herbivore a first-order consumer that feeds on plant organisms

heterotroph an organism that cannot synthesise its own organic compounds from simple inorganic material; it depends on other organisms for nutrients and energy requirements

humus the dark brown organic matter in soil, derived from decomposed plant and animal remains (detritus)

model the artificial conceptual or abstract simulation of a real-world process or system, developed by simplifying key steps that produce reliable and consistent agreement as verified by field studies; a model may be mathematical equations, a computer simulation, a physical object, words or other form

net primary productivity (NPP) the amount of organic matter actually available to herbivores; the GPP less the energy required by the producers themselves

nitrogen fixation the process by which free nitrogen is 'fixed' or combined to form ammonium (NH_4^+) or nitrate (NO_3^-) ions before living things can make use of it for growth; all nitrogen-fixing organisms are prokaryotes (bacteria)

nitrogenous describes nitrogen-bearing compounds

nodule a local enlargement on the root of a plant containing nitrogen-fixing bacteria

non-biodegradable describes something that is unable to be broken down by the activity of decomposers

nutrient cycle the way in which nutrients are cycled between the living and non-living components of an ecosystem

omnivore an organism that feeds on a range of foods, including plant and animal matter

photosynthetic efficiency describes how well a producer converts light energy into the chemical energy of carbohydrates

phytoplankton the collective term for the tiny photosynthetic organisms present in bodies of water

producer see *autotroph*

pyramid of biomass a representation that shows the relationship between the total amount of (dry) organic matter at each trophic level in a given area of an ecosystem

pyramid of energy a representation that shows the rate at which energy is transferred from one trophic level to another in a given area of an ecosystem

pyramid of numbers a representation that shows the number of individual organisms at each trophic level in a given area of an ecosystem

radiant energy the transfer of heat from a hot object by infrared waves

scavenger a consumer that feeds on dead and decaying flesh or remains

second-order consumer a consumer that feeds on first-order consumers (also known as herbivores)

sink a reservoir of material or energy; often used in relation to atmospheric CO_2

source the place of origin of material or energy; often used in relation to atmospheric CO_2

top consumer the last link in the food chain

trophic efficiency relates to the percentage of energy at one trophic level that ends up in the next trophic level

trophic level a feeding level in the food chain of an ecosystem

water cycle the continuous exchange of water between living things and their non-living surroundings

zooplankton a collective term for the tiny heterotrophic organisms present in bodies of water

CHAPTER REVIEW QUESTIONS

Remembering

1 Identify the key role of photosynthesis.
2 Define 'autotroph'.
3 Describe a pyramid of energy.
4 State each of the links in a general food chain and describe how they relate to one another.
5 Distinguish between a food chain and a food web.
6 Describe trophic efficiency.
7 Draw a food web that you have studied in this chapter and name each trophic level.
8 In a marine ecosystem, a food chain consists of phytoplankton, zooplankton, lantern fish and tuna. Name the primary consumer.
9 List two major ways nitrogen is provided to soil-based organisms.

Understanding

10 Under what circumstances would an ecologist encounter an inverted pyramid? Provide an example.
11 Why does a herbivore depend on producers for its energy requirements?
12 A rocky shore consists of rocky ledges and pools containing salt water. Living in this habitat is a community of plants and animals. These plants and animals interact with each other and the environment to form an ecosystem. Phytoplankton and zooplankton are consumed by barnacles, which are in turn eaten by the common dog whelk sea snails, which are eaten by crabs. Crabs are consumed by gulls.

Assuming a trophic efficiency of 10%, what percentage of biomass and energy does the crab represent in this food chain?

Applying

13 There are many types of communities. Energy enters most of them in the form of sunlight. Some of the organisms in a community are able to convert light energy into chemical energy, which is needed so that cellular processes can maintain life. Describe how:
   a environmental factors may determine the type of community.
   b chemical energy is made available for cellular processes.
14 A farmer grows grain that is fed to cattle. Humans eat the meat of the cattle. If the amount of energy available in the harvested crop is 800 kJ, how much energy is available for the human population? Show your calculations as annotations to the food chain.
15 Explain the advantages of being an omnivore such as a fox.
16 Explain, using examples, why it is often difficult to assign trophic levels to organisms.
17 What effect does the migration of organisms have on pathways of transfer of energy and matter in ecosystems?

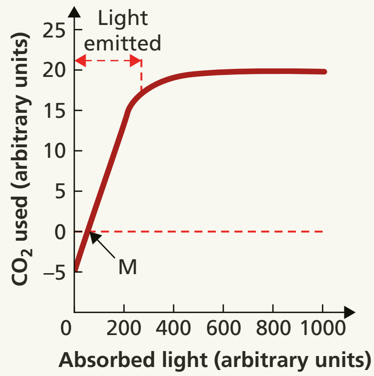
Analysing

18 Explain why there is a limit to the number of trophic levels in a food chain.
19 Is the Sun part of a food chain? Explain your answer.
20 Explain how energy is 'lost' from food chains and the significance to ecosystems of this loss.
21 Refer to Figure 4.12, which shows a forest ecosystem.
   a Draw up two food chains using an arrow between each link.
   b Identify an organism that is a second-order consumer in one chain but a third-order consumer in another. The chains do not have to be those of your answer to part a.
22 Based on knowledge gained from this chapter, explain whether the population sizes of certain species in the oceans should be monitored.

23 Figure 4.31 shows the rate of exchange between the cells of a leaf and its external environment as the light intensity is increased. All other variables are kept constant throughout the experiment.

a Describe what is occurring at point M in terms of the chemical reaction.

b Explain why the graph line becomes nearly horizontal from about 600 units of absorbed light.



▲ **Figure 4.31**
Carbon dioxide exchange between leaves and the environment with increasing light intensity

24 The Galapagos Rift, which receives no light, is a deep-sea boundary between oceanic plates. Sulfate in the sea water is converted into hydrogen sulfide at high temperatures. Chemosynthetic bacteria obtain energy from the hydrogen sulfide; they use this energy to convert carbon dioxide dissolved in the water into organic molecules. In the same area, clams that feed on the chemosynthetic bacteria are an energy source for crabs and octopods. Chemoheterotrophic bacteria return resources to the community.

Which one of the following combinations identifies the producer, the first-order consumer, the second-order consumer and the decomposer for the community described above?

	Producer	First-order consumer	Second-order consumer	Decomposer
a	Photosynthetic bacteria	Clams	Octopods	Chemosynthetic bacteria
b	Chemosynthetic bacteria	Clams	Crabs	Chemoheterotrophic bacteria
c	Photosynthetic bacteria	Octopods	Crabs	Chemosynthetic bacteria
d	Chemosynthetic bacteria	Crabs	Octopods	Chemoheterotrophic bacteria

25 An experiment was conducted to investigate the effect of temperature on the rate of photosynthesis in aquatic plants. The rate of photosynthesis was measured at 25°C and then at 15°C. Explain the most likely effect that this change in temperature would have on the rate of photosynthesis.

Evaluating

26 Table 4.4 shows estimates of the primary productivity of different ecosystems in $kJ\,m^{-2}year^{-1}$. Copy and complete the table that compares the value of 'food' energy available at different trophic levels in the four ecosystems.

Table 4.4 Estimates of the primary productivity of different ecosystems.

Type of ecosystem	Primary productivity ($kJ\,m^{-2}year^{-1}$)	Energy available to primary consumers ($kJ\,m^{-2}year^{-1}$)	Energy available to secondary consumers ($kJ\,m^{-2}year^{-1}$)
Grassland	8400		
Ocean	3350		
Tropical rainforest	3800		
Desert	<840		

a Define GPP and NPP using the information given above.

b Which ecosystem is least productive? Explain why.

27 Explain why the production of organic matter in deserts and cold climates is about 1 kg m^{-2} whereas in tropical forests and grasslands it is about 5 kg m^{-2}.

Creating

28 Show how the pesticide DDT becomes concentrated within a food chain. Explain your answer using your knowledge of trophic efficiency.

29 An ecosystem is maintained by the constant supply of energy derived from sunlight and the recycling of material. Create a summary diagram of a simple ecosystem of your choice that demonstrates energy transfer along a food chain and recycling of matter via the carbon cycle, water cycle and nitrogen cycle.

Reflecting

30 What have you found difficult to understand in this chapter? What strategies could you put into practice to make the content easier to understand?

31 You have been shown that beef is one of the most energy intensive foods to produce. How could this influence your food choices in the future?