the evidence for evolution is gathered from fossils, observation and DNA analysis				
explain how populations can diverge into new species by natural selection	11.3.3			
explain the importance of isolation for speciation and identify three types of isolation	11.3.3			
outline the importance of sterile hybrids to understanding reproductive isolation	11.3.3			
define a gene pool	11.3.4			
outline why evolution requires a change in allele frequencies in populations	11.3.4			
	11.3.4			

give examples of the mechanisms of geographic, temporal and behavioural isolation				
outline how changes in allele frequency in gene pool can arise as a result of natural selection	11.3.4			
summarise how speciation can be gradual or abrupt	11.3.4			
define a niche and a habitat	11.4.1			
recognise that all species have tolerance limits that define their niche	11.4.2			
outline how species distribution data and abiotic factors can be correlated using a transect	11.4.2, 11.4.7			
distinguish between a	11.4.3			

fundamental and realised niche				
distinguish between divergent and convergent evolution and name examples of each	11.4.4			
distinguish between homologous and analogous structures and give examples	11.4.4			
state that adaptive radiation increases biodiversity in a community	11.4.5			
describe why two species cannot survive together in identical niches.	11.4.6			

EXAM-STYLE QUESTIONS

You can find questions in the style of IB exams in the digital coursebook.

Chapter 12

Ecological relationships

C4.1, C4.2, A4.2, D4.2, D4.3

INTRODUCTION

Almost the entire surface of the Earth – the land, rivers, lakes, seas and oceans – is home to organisms of one kind or another. It has been estimated that there are as many as 10 million different species on Earth and understanding where and how they live and interact is a branch of biology known as ecology. Humans are not the most numerous species on Earth: there are many more bacteria and insects. But humankind is having a disproportionate effect on the world's ecosystems as damage is caused by pollution, rainforest destruction and global warming.

12.1 Modes of nutrition

LEARNING OBJECTIVES

In this section you will:

- recall that organisms need energy to drive their metabolism
- understand that organisms may be obligate anaerobes, facultative anaerobes or obligate aerobes
- distinguish between autotrophs that obtain energy from inorganic nutrients and heterotrophs that obtain energy and nutrients from other organisms
- learn that a few organisms obtain nutrition in both ways
- distinguish between consumers, detritivores and saprotrophs
- define the term trophic level as a way of classifying organisms by their feeding relationships
- learn that consumers may be primary, secondary or tertiary consumers or omnivores
- recognise that trophic feeding relationships simplify the complexity of an ecosystem
- learn that some autotrophs are chemosynthetic rather than photosynthetic
- understand that omnivores are species which feed at more than one trophic level

- identify some adaptations that herbivores, carnivores and plants have to feed

GUIDING QUESTIONS

- How do living organisms obtain the energy they need?
- How do modes of nutrition affect the interactions of organisms in ecosystems?

12.1.1 Feeding groups

All organisms need to acquire energy to drive their metabolism. This enables them to grow, reproduce and function in their environment. Species are divided into groups that are defined by their method of obtaining food. Different organisms feed in different ways and feeding interactions influence the growth, survival and reproduction of all species. A niche is the role a species has in an ecosystem, it includes all the biotic and abiotic interactions that influence a species (Chapter 11.4).

Autotrophs and heterotrophs

Autotrophs are species that are able to make their own food from basic inorganic materials. This group includes all plants that can photosynthesise, as well as mosses, ferns, seaweed, unicellular algae and purple and blue-green bacteria. Autotrophs (which means 'self feeding') use light energy to synthesise sugars, amino acids, lipids and vitamins, using simple inorganic substances such as water, carbon dioxide and minerals. Heterotrophs are consumer species that obtain their food from organic matter. **Heterotrophs** obtain both energy and nutrients such as minerals and vitamins from other organisms.

KEY POINTS

autotroph is an organism that produces complex organic compounds from simple inorganic molecules, usually by photosynthesis.

a heterotroph that feeds on living organisms by ingestion is a consumer.

a heterotroph that feeds on organic nutrients from dead organisms by internal digestion is a detritivore.

ecology is the study of the relationships between living organisms and their environment, including both the physical environment and the other organisms that live in it.

heterotroph is an organism that obtains energy and nutrients from other organisms.

a heterotroph that feeds on organic nutrients from dead organisms by external digestion and absorption is a saprotroph. Saprotrophs are also known as decomposers.

This group includes herbivorous and carnivorous animals, which feed on living organisms. Methods of feeding are used to explain the relationships of organisms within an ecosystem, as shown in Figure 12.1.1.

Two important groups of heterotrophs are detritivores and saprotrophs, which feed on dead organic matter. These organisms are vital to the well-being of any ecosystem because of their recycling role. When an organism dies, the remains of its body provide nutrients for detritivores and saprotrophs, which feed on them in different ways.

The two groups of heterotrophs are distinguished by their methods of digestion.

Consumers feed by **holozoic** nutrition which means their food is ingested (eaten), digested inside their bodies then absorbed, and assimilated. Undigested material is egested and leaves from the end of the gut.

Saprotrophic nutrition is the digestion of food outside the body followed by the absorption of already digested materials. Fungi and bacteria, together known as decomposers use this method to feed on dead and waste material. These organisms are important for the recycling of nutrients in an ecosystem.

Mixotrophic organisms such as *Euglena* (Figure 12.1.1) are both heterotrophic and autotrophic. *Euglena* has chloroplasts and photosynthesises when there is sufficient light but can also feed on small organisms by endocytosis. *Euglena* cannot be classified as a plant or an animal and is placed in the Kingdom Protista.

- Detritivores are organisms such as earthworms, woodlice and millipedes that ingest dead organic matter such as fallen leaves or the bodies of dead animals (Figure 12.1.2). They digest the organic matter inside their bodies.

- Saprotrophs – which include bacteria and fungi – secrete digestive enzymes onto organic matter and then absorb their nutrients in a digested form (Figure 12.1.3). Saprotrophs are responsible for the decomposition of organic matter and are sometimes referred to as decomposers. Saprotrophic bacteria and fungi are vital for most ecosystems and are crucial to the recycling of inorganic nutrients such as nitrogen compounds. Recycled inorganic compounds can be re-used over and over again by autotrophs, which in turn continue to grow and provide food for heterotrophic consumers.

If there is enough sunlight to provide energy for the autotrophs to photosynthesise, and the community itself can maintain the recycling of inorganic materials within the abiotic environment, an ecosystem like this has the potential to remain stable and self-sustaining for a long period of time. This happens for as long as there are no adverse interferences from outside. Catastrophic natural events and human interference are two factors that can disrupt otherwise stable ecosystems. It is important to remember that sustainable, stable systems are vital for the continued survival of all species, including our own.

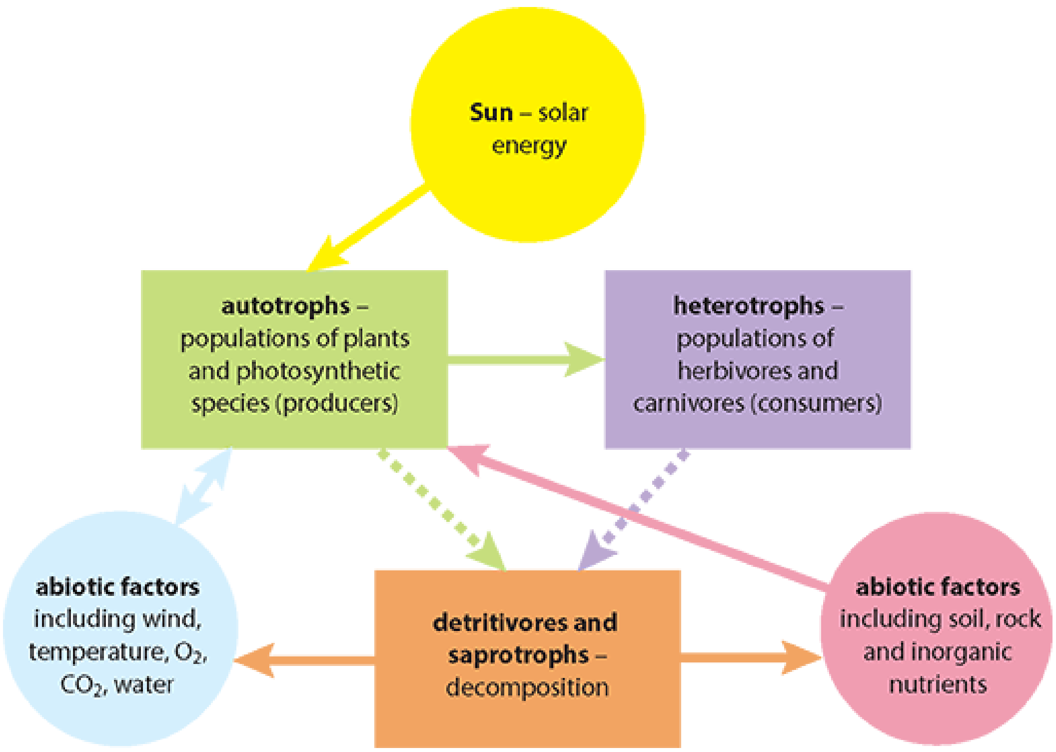


Figure 12.1.1: The feeding relationships in an ecosystem. A few organisms are both autotrophs and heterotrophs. One example is the aquatic species *Euglena*.

NATURE OF SCIENCE

Looking for trends and discrepancies: are all plants and algae autotrophic?

Autotrophs or ‘self-feeders’ are organisms that produce complex organic compounds from simple substances in their environment. In the majority of cases, autotrophs are plants and algae, which use light from the Sun as a source of energy.

One organism that is neither plant nor alga, but which was once classified with the plants because it can photosynthesise, is *Euglena*. *Euglena* is a unicellular organism with chloroplasts in its cell that enable it to feed autotrophically, like a plant. But *Euglena* can also feed heterotrophically, taking in organic materials as animals do. When *Euglena* was first discovered, organisms were classified into just two kingdoms – the plant kingdom and the animal kingdom – and *Euglena* was impossible to place. Then, in the 19th century, Ernst Haeckel added a third kingdom, which he called the Protista, to accommodate organisms like *Euglena* that display characteristics of both plants and animals.

Figure 12.1.2: Millipedes feed on dead leaves on the forest floor and recycle the nutrients they contain via their feces. They are detritivores.

Chemosynthetic autotrophs

Some autotrophs are chemosynthetic rather than photosynthetic. Like all autotrophs chemoautotrophs make their own food but need a source of energy to do so. They get this energy not from the sun, but from the chemical bonds of inorganic molecules. *Nitrosomonas* is a nitrogen-fixing bacterium found in soil. It obtains energy from the oxidation of ammonia. Using this energy, it can synthesise glucose from carbon dioxide. Many microorganisms in dark regions of the oceans, where light is unavailable, also use chemosynthesis to produce biomass from carbon molecules. In most cases the energy for chemosynthesis comes from the oxidation of hydrogen sulfide or ammonia.

Figure 12.1.3: Fungi secrete enzymes onto dead material and absorb digested material into their cells. They are saprotrophs.

Diversity of nutrition in Archaea

Archaea is a domain of single-celled organisms which have no cell nuclei and so are prokaryotes but they do share some characteristics with eukaryotes. Archaea were initially classified as bacteria but analysis of genetic material has identified that they are a separate domain. Archaea are metabolically diverse; some can photosynthesise but do not use chlorophyll to capture light. Others are chemoautotrophs and obtain their energy for ATP production by breaking down molecules in their environment. Archaea can live on a huge range of energy sources: ammonia, metal ions, even hydrogen gas. Some salt-tolerant types found in salt lakes use sunlight as an energy source, and others can fix carbon from the atmosphere. Some are adapted to life in hot springs and thermal vents. Table 12.1.1 summarises the range of nutritional types in this domain.

KEY POINT

chemoautotroph refers to an organism which uses energy from chemical reactions to generate ATP and produce organic compounds from inorganic substances.

Type of nutrition	Source of energy	Source of carbon
Phototrophs	Light	Organic compounds
Chemotrophs (Lithotrophs)	Oxidation of inorganic compounds, e.g. sulphur, ammonia, methane, iron	Organic compounds or carbon fixation
Heterotrophs	Oxidation of organic compounds from other organisms	Organic compounds or carbon fixation

Table 12.1.1: Modes of nutrition in Archaea.

Trophic levels and feeding relationships

Every organism needs food to survive but eventually it too will be eaten. In any ecosystem, there is a hierarchy of feeding relationships that influences how nutrients and energy pass through it. The sequence of organisms that provide food for one another is known as a **food chain**.

Green plants are autotrophs, which start food chains because they are able to capture light energy from the Sun. Plants are called sometimes called producers because they ‘produce’ organic compounds by photosynthesis. These organic compounds contain chemical energy that has been converted from light energy by the process of photosynthesis. Every other organism in a food chain obtains organic compounds from its food and so is called a heterotroph or consumer.

Every ecosystem has a structure that biologists divide into categories on the basis of the food sources of the different organisms. These categories are known as trophic levels. Trophic means ‘feeding’ and every organism in a food chain can be placed in a particular feeding category or trophic level.

Green plants are producers and are placed at the first trophic level. Primary production is the accumulation of carbon compounds in biomass by autotrophs. After them come all the consumer levels. The first consumers, or primary consumers, are always herbivores. Any organism that feeds on herbivores will be a carnivore and can be listed as secondary consumer, tertiary consumer and so on depending on its food source. Secondary production is the accumulation of biomass by heterotrophs who are secondary consumers. A food chain can therefore be summarised as shown in Figure 12.1.4.

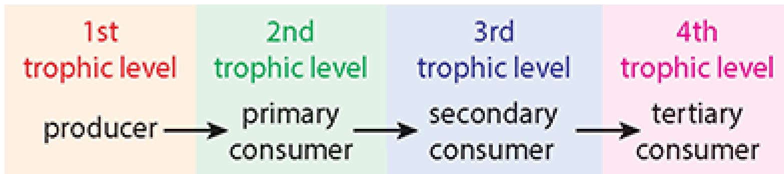


Figure 12.1.4: A food chain consists of a producer and consumers.

Every organism fits somewhere in a food chain, and although the organisms that make up the food chain will vary from place to place, almost every food chain starts with a green plant. It may be any part of the plant, for example the leaves, roots, stems, fruits, flowers or nectar.

Figure 12.1.5 shows three examples of food chains from different ecosystems. Notice that the arrows in a food chain always point in the direction in which the energy and nutrients flow. Each of these food chains contains an autotroph at the start of the chain, followed by primary, secondary and tertiary consumers.

KEY POINTS

primary consumer is an organism that feeds on autotrophs (plants).

secondary consumer is a heterotroph that feeds on primary consumers.

tertiary consumer is a heterotroph that feeds on secondary consumers.

trophic level is the position of an organism in a food chain.

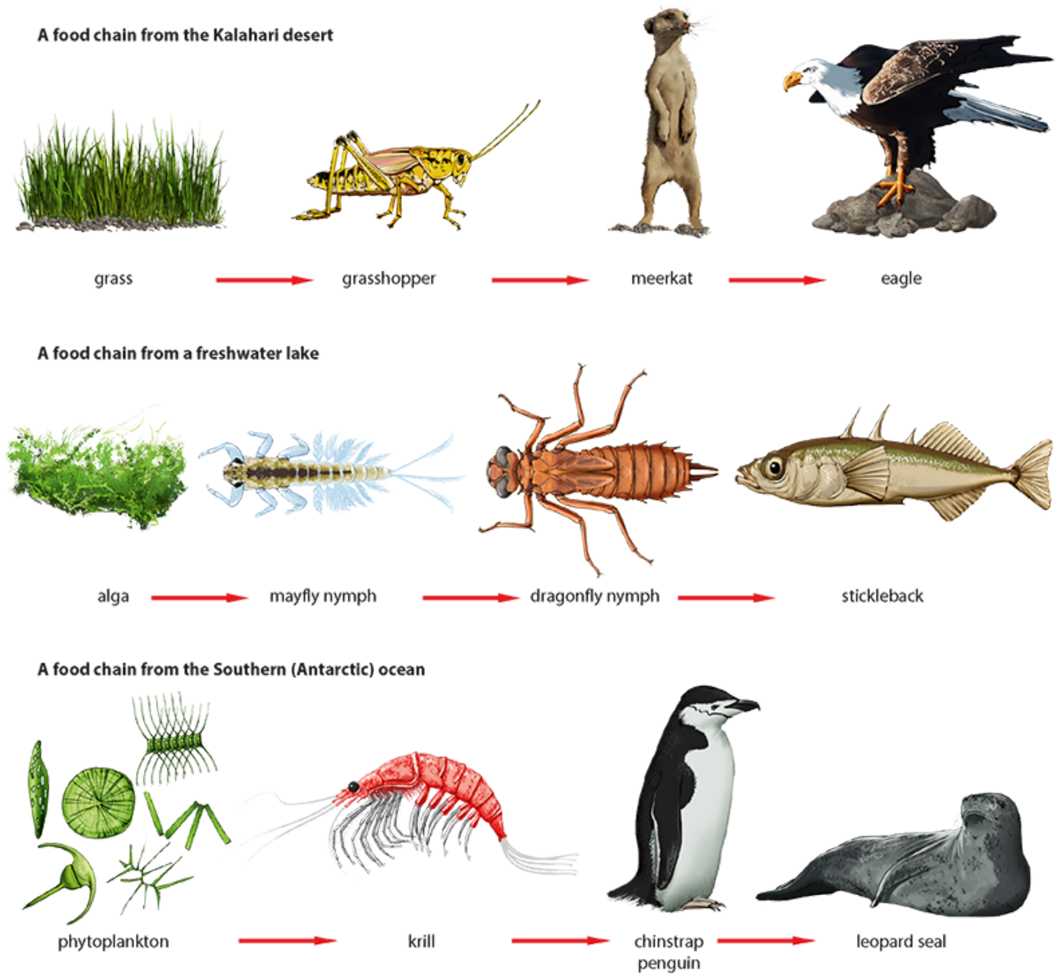


Figure 12.1.5: Grass, algae and phytoplankton are all examples of photosynthesising autotrophs, which use light as their source of energy. Almost all food chains start with light as the initial source of energy. Grasshoppers, mayfly nymphs and krill are primary consumers. Meerkats, dragonfly nymphs and chinstrap penguins are secondary consumers.

When these organisms die, they will provide nutrients for a series of detritivores and saprotrophs, which will return inorganic nutrients to the abiotic environment, so that they can be re-used by autotrophic organisms.

The food chains shown in Figure 12.1.5 are taken from different ecosystems and continents but you can construct some food chains using organisms in your local area. You might use your school campus, a garden or local park or nature reserve. Try to separate the organisms you can see into groups. Identify the autotrophs and heterotrophs and classify the consumers into primary, secondary or tertiary categories.

SCIENCE IN CONTEXT

Spraying with DDT insecticide: unintended consequences

In the 1950s the World Health Organization (WHO) sprayed parts of an island in Borneo with DDT insecticide to eradicate the malarial mosquito. The treatment was successful and a malaria epidemic was halted. But there were other results that no one had predicted.

The huts in the villages had thatched roofs which were eaten by a particular species of caterpillar. The caterpillar was not affected by DDT but the wasp that was its natural predator was wiped out. Soon the thatched roofs began to collapse. Insect-eating geckos and the local gecko-eating cats also died of DDT poisoning. The roofs of the huts were replaced with corrugated iron but there was soon a big increase in the number of rats which threatened to spread diseases in the village. The WHO solution was to airlift in new cats and drop them into the village by parachute.

To consider:

Use your knowledge of food chains to explain these events on the island.

1 Why did the thatched roof collapse?

2 DDT is an insecticide so what caused the death of the cats?

3 Why did the rat population increase and how did the new cats help the villagers?

4 You can read more about the effects of DDT on food chains in Section 12.4.

TEST YOUR UNDERSTANDING

1 Distinguish between autotrophs and heterotrophs.

2 Describe the feeding methods of a detritivore and a saprotroph.

3 How is the trophic level of an organism decided?

4 Divide these organisms into producers and consumers.

leaves snails grass pond algae

mice owl earthworm

5 Look at this diagram which shows feeding relationships on a seashore.

How many primary consumers are there?

How many secondary consumers are there?

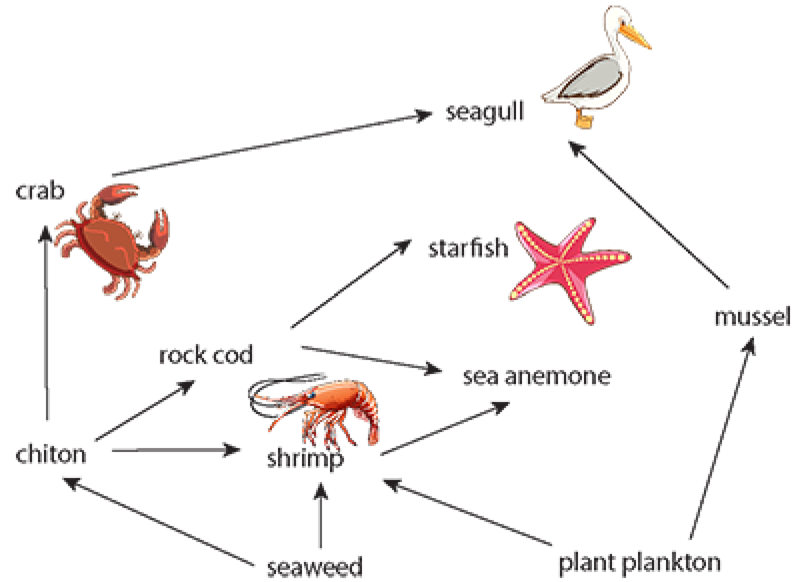


Figure 12.1.6: Feeding relationships on a seashore.

12.1.2 Complexities in feeding relationships

The concept of trophic levels is a quick and easy way to get an idea of relationships in an ecosystem but few consumers feed on only one source of food. For example, this food chain describes one set of feeding relationships:

grass → beetle → robin → sparrowhawk

But beetles eat a wide range of plants, robins eat other types of insect and sparrowhawks eat other birds. So this food chain could be interlinked with many others. A **food web** like the one shown in Figure 12.1.7 shows a much more realistic picture of the feeding relations of the organisms in a habitat. Notice how organisms change trophic levels depending on what they are eating at any particular time. In Figure 12.1.7, the fox is a primary consumer when it is eating a crab apple but a secondary consumer when it is eating a wood mouse.

KEY POINTS

omnivore an animal that is able to eat both plants and animals.

niche is the role a species has in an ecosystem, it includes all the biotic and abiotic interactions that influence a species.

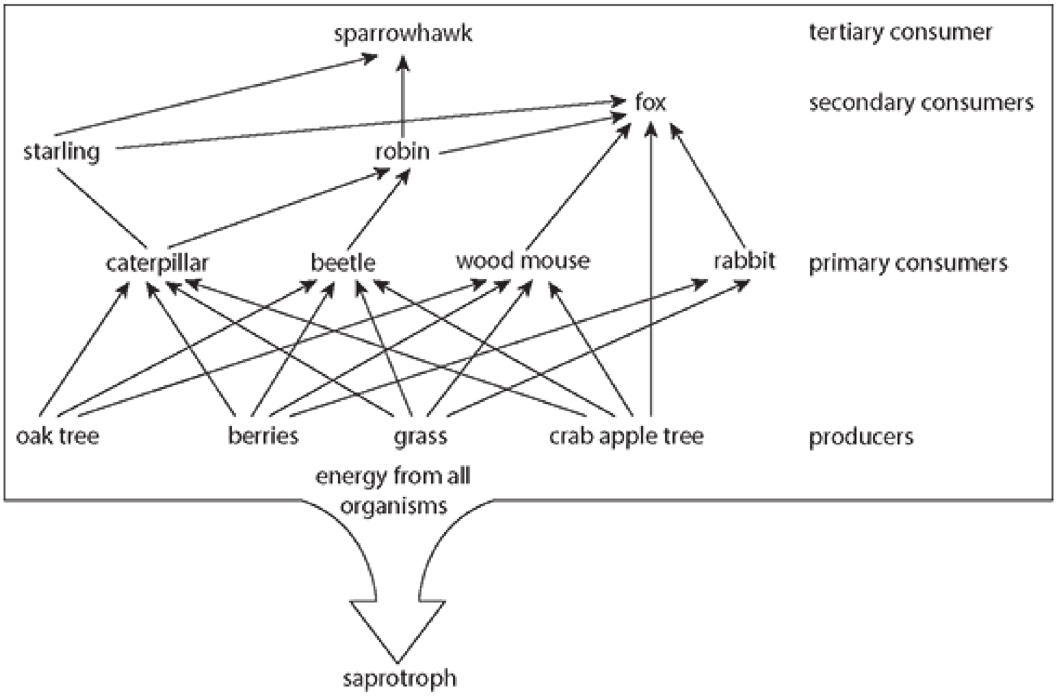


Figure 12.1.7: Many species can be defined as omnivores because they feed at more than one trophic level.

SCIENCE IN CONTEXT

Generalists and specialists

Classifying a species as a generalist or a specialist is a way to identify what kinds of food and habitat resources it relies on to survive. Generalists can eat a variety of foods and thrive in a range of habitats. Specialists, conversely, have a limited diet and habitat requirements.

Raccoons (*Procyon lotor*) are a good example of a generalist species. They live in a range of different environments in North America, including forests, mountains and large cities. They are omnivores and can eat fruit and nuts, insects, frogs, eggs and waste left by humans, and can adapt to whatever food source is available.

In contrast, the Australian koala (*Phascolarctos cinereus*) Figure 12.1.9 is a specialist. It is a herbivorous marsupial (pouched mammal) that feeds only on the leaves of the eucalyptus tree and so can only live in habitats where eucalyptus trees grow.

Figure 12.1.8: Koalas are specialists and feed exclusively on the leaves of eucalyptus trees.

Trophic feeding relationships do not take account of other complexities in ecosystems and they simplify interactions between species. An organism may feed at more than one trophic level, change its diet through its lifecycle or its interactions may be affected by abiotic factors or interference. All food chains and webs have two or three trophic levels but most do not have more than four.

The Canada lynx (*Lynx canadensis*), is a specialist secondary consumer which preys almost exclusively on snowshoe hares. Both these animals live in the forested, mountainous areas and tundra where lynx are very well-adapted to survive. Their padded paws enable them to walk in deep, soft snow as they hunt.

Specialist species like koalas and the lynx have evolved to fit a very specific **niche** and can easily be affected by environmental disturbances, such as climate change or habitat loss due to forest fires. Specialists are more likely to be affected by these disruptions because they cannot use other food sources or habitats in the way that generalists can. Some specialist species are in decline due to human activity and interference whereas the number of generalist species is increasing.

Other feeding relationships

Parasitism is a symbiotic feeding relationship between species, where one organism, the **parasite**, lives on or inside another organism, the **host**, causing it some harm, and is adapted structurally to this way of life.

Examples of internal parasites are tapeworms and *Plasmodium*.

- Tapeworms are segmented flatworms that attach themselves to the insides of the intestines of animals such as cows, pigs and humans. They get food by eating the host's partly digested food, depriving the host of nutrients.

- *Plasmodium* is a unicellular eukaryote that causes malaria in humans. It reproduces in liver cells and red blood cells. Part of the parasite's life cycle takes place in the *Anopheles* mosquito, which is the vector that transmits the parasite from one person to another as it feeds on blood.

Examples of external parasites are fleas and leeches.

- Fleas (Figure 12.1.9) feed on the blood of mammals and birds. Their bodies are adapted and flattened so they can move through fur and feathers of their hosts and claws prevent them being removed. They can be vectors of other diseases and cause localised infections where their bites cause irritation to their host.

Figure 12.1.9: A flea in the fur of a dog.

- Leeches live in ponds and feed on the blood of mammals. They puncture the skin of their host and secrete an enzyme that stops the blood from clotting. They may ingest more than their body weight in blood and leave bleeding wounds on their hosts' bodies.

12.1.3 Adaptations for feeding

Organisms are adapted for their modes of nutrition and their adaptations may either be for capturing their food, or for ingesting and digesting it. We can draw inferences about the diets of extinct species or newly discovered organisms by looking for these adaptations.

1 Adaptations in the teeth of Hominidae

Hominidae is a group which includes all modern and extinct great apes which are modern humans, chimpanzees, gorillas and orang-utans plus all their ancestors. Some members of the group are herbivores while others are omnivores and have some meat in their diet. The teeth and skulls of living hominids, including ourselves and our extinct relatives, can give us clues to the diets that they ate. The teeth of our ancestors can also show us how our own diet has evolved. Herbivores tend to have large, flat grinding teeth to break apart plant material. Omnivores have several different kinds of teeth to tear at meat and grind plant food.

Different teeth are needed for herbivorous and carnivorous diets. (Table 12.1.2).

Hard, brittle foods such as seeds can be crushed between teeth with rounded cusps and shallow jaws. Tough foods, such as raw meat or leaves, need to be sliced or sheared by teeth with thinner, blade-like crests. The shape of teeth reveals what these primates are capable of eating. Their diets probably varied with seasons and availability of food. You can use digital images of skulls to examine other Hominid teeth and deduce what they may have eaten.

Hominid	***Pan troglodytes* Chimpanzee**	***Paranthropus robustus* (An ape that lived between 1 and 2 million years ago in South Africa)**	***Homo floriensis* (an extinct species of small human that lived in Indonesia about 50,000 years ago)**	***Homo sapiens* Human**
Cusps on molar teeth – provide more surface area for chewing. They help teeth grind and break down fibrous material	yes	yes	yes	yes
Enamel thickness – thick	thin	Very thick	Very thick	Very thick

enamel prevents teeth breaking as animals chew				
Size of canines – canine teeth may not be used for hunting but for social interaction	Very large	medium	medium	medium
Jaw and muscles – strong muscles and jaws indicate a low energy plant diet for at least part of the time.	Incisors cut and rip food from trees. Molars and premolars grind and crush.	Thick bones and powerful muscles, strong molars for grinding	Smaller premolars, similar to humans, not capable of forceful biting	Teeth that are similar to H. floriensis but are not always needed for the food we eat.
Diet	Primarily plant material:	Tree and shrub food: Nuts seeds	Probably plants and	High energy food and

	fruits, seeds, nuts, leaves and insects, Sometimes meat.	and hard fruits	uncooked meat.	a mixed diet which includes meat and plant sources

Table 12.1.2: The teeth and diets of some hominids.

2 Adaptations of herbivores

Herbivores range in size from tiny ants, termites and caterpillars to koalas, wildebeest, goats, horses and rhinos. Some herbivores such as flying foxes and fruit bats only eat fruit while others such as caterpillars and koalas only feed on leaves and termites only eat wood.

Small leaf eating insects have piercing and chewing mouthparts; aphids have a tube-like stylet which they use to pierce stems and drink plant sap, caterpillars have biting and cutting mouthparts which saw through leaves. (Figure 12.1.10).

Herbivores adapted to a high **cellulose** diet such as ruminants (goats and sheep) have specialised teeth. They do not have **incisors**, (the flat front teeth which carnivores use to tear flesh), instead, they have a dental pad that helps chew plants. Herbivores have broad, flat **molars** (back teeth) with rough surfaces, which are used for grinding up tough plant tissues. Many herbivores (like rabbits and squirrels) have chisel-like front teeth used for gnawing through wood or hard seeds. These teeth grow continually as they are worn down with use. Ruminants have a digestive system with a four chambered stomach. Their saliva is alkaline as they don't begin to digest food as soon as it enters their mouths.

Figure 12.1.10: The sawfly cuts circular holes in the leaves as it feeds

3 Adaptations of predators

Predators also have adaptations which help them catch and kill their prey. These may be physical, chemical or behavioural. Physical adaptations include good eyesight and hearing for locating prey. Sharp teeth and claws for holding and biting are also important. As well as physical adaptations, predators may use chemical signals to locate their prey. Great white sharks use sensory organs in their snouts to detect the tiny electrical impulses produced by their prey. Snakes and spiders produce venom and toxins to poison and kill their prey. Snake venom is toxic saliva that is injected by fangs into prey and spiders also produce venom which can immobilise prey before it is eaten. Predators may either be solitary hunters, like the lynx (Section 12.3) or hunt in packs or family groups like wolves and lions. Behavioural adaptations such as calls and scents ensure that the group works together.

4 Adaptations of plants

You can read about the adaptations plants use to transport and gather the substances they need for photosynthesis in Chapter 8.3 and about their adaptations to life in very dry or very wet environments. Some species in dense forests grow upward to reach sunlight which you can read about in Chapter 11.4 Other species, known as shade-tolerant plants, are adapted to living in the dimmer light on the forest floor. These plants can photosynthesise using far red light more efficiently than other plants. Red light tends to be absorbed in the forest canopy while far red light (730 nm) penetrates to the lower levels of the forest. Shade tolerant plants grow broader, thinner leaves to catch the maximum sunlight and they use nutrients more efficiently than other species. Some plants move their leaves to capture light at different times of day and others move their chloroplasts to the top of their palisade cells when most light is available.

5 Adaptations to avoid being eaten

Plants and animals have many strategies to protect themselves from being eaten or damaged by organisms which feed on them. These are discussed in section 12.3.3

Mutualism is a relationship where both species involved benefit from their interactions. In some cases, the species are entirely dependent on each other and in others, they both benefit but could survive without each other.

The relationship between aphids (small sap-sucking insects) and some species of ants is an example of mutualism. Aphids secrete sugary honeydew, a liquid that is the waste product of their diet. Ants feed on the honeydew and in return some ants will protect the aphids from predators and parasites., even carrying aphid eggs and young into their nests.

Coral and the zooxanthellae they contain are another example of a mutualistic relationship. Corals begin life as a tiny, free-swimming larvae which settle and develop into polyps. Polyps replicate to form a colonies of polyps, growing on top of each other and they produce a calcified skeleton around themselves. As corals grow, they take in single-celled zooxanthellae from the environment around them. The coral provides shelter and nutrients for the zooxanthellae to use for their photosynthesis, while the zooxanthellae produce sugars, and other substances, as well as oxygen as a by-product which the coral uses for respiration.

TEST YOUR UNDERSTANDING

6 List three adaptations of predatory species which assist with capturing prey.

7 How can a study of dentition (teeth) help identify an animal's diet?

8 Outline two examples of a parasitic relationship.

REFLECTION

Can I explain the importance of categorising organisms in an ecosystem even though the categories are only approximate?

12.2 Transfer of energy and matter

LEARNING OBJECTIVES

In this section you will:

- learn that most ecosystems rely on light energy from the sun
- recall that photosynthesis converts light energy into carbon compounds for metabolism, to increase biomass for growth and reproduction
- understand that energy flows through food chains as organisms feed and as it is used it is converted to heat
- learn that organisms cannot convert heat energy to other forms of energy
- recognise that energy is lost from trophic levels as dead organic material
- understand that because energy is lost at each trophic level, the length of food chains and accumulation of biomass is limited
- draw food webs to represent feeding relationships in a community and use them to construct pyramids of energy
- learn that organisms also acquire nutrients such as nitrogen as they feed and that nutrients are eventually recycled to the environment
- summarise the stages in the carbon cycle

- recognise that energy flows in a food web can be quantified and represented in diagrams.

GUIDING QUESTIONS

- How do feeding relationships between organisms show the flow of energy in an ecosystem?
- What patterns can we identify in the complex structure of an ecosystem?

12.2.1 Energy flow

Food chains

In Section 12.1 we discovered that every organism needs food to survive but eventually it too is eaten. There is a hierarchy of feeding relationships that influences how nutrients and energy pass through it producing a sequence of organisms known as a food chain.

Most ecosystems rely on a supply of energy from the Sun. This can be converted into chemical energy in carbon compounds, such as glucose, by photosynthesis. Only a few food chains begin with chemoautotrophs (Section 12.1), which do not need sunlight. All green plants are autotrophs and are able to capture light energy from the Sun and form the first link in different food chains.

Carbon compounds that plants produce are used

- as a source of energy in respiration
- to increase biomass in growth or reproduction.

As the chemical energy in stored carbon compounds passes from one organism to the next, the energy is used for similar processes in each organism.

autotroph → primary consumer → secondary consumer → tertiary consumer

TEST YOUR UNDERSTANDING

9 Use organisms from where you live to make a food chain which includes the four categories of feeding listed in the section on Food chains.

EXAM TIP

In an exam, do not say that plants 'make' energy for food chains. Remember that they only convert energy from one form to another.

Energy and food chains

Arrows in a food chain show the direction of flow of both the energy and nutrients that keep organisms alive. Energy flow through an ecosystem can be quantified and analysed. Studies reveal that, at each step in the food chain, energy is lost from the chain in various ways:

1. some energy is not consumed,
2. some energy leaves the food chain as waste, or when an organism dies, and
3. some is used by living organisms as they respire.

In all three cases, the lost energy cannot be passed to the next trophic level.

Consider an area of African savannah where grass, antelopes and cheetahs form a simple food chain.

grass → antelope → cheetah

- Energy loss 1: food not consumed. The grass stores energy from photosynthesis but the antelopes only eat some parts of the grass. So, they do not consume all the energy it has stored.

- Energy loss 2: not assimilated, or lost through death. The grass that is eaten passes through the digestive system of the antelope but not all of it is digested and absorbed, so some passes out in the feces. If an antelope dies and is not eaten by a predator, but decays and is eaten by detritivores and saprotrophs, the energy in its body is lost to this food chain.
- Energy loss 3: cell respiration. Antelopes use energy to move and to keep their body temperature constant. As a result, some energy is lost to the environment as heat.

Organisms cannot convert heat energy into any other form of energy and so it is lost from the ecosystem.

The assimilated energy that remains after respiration goes into building the antelope's body and this energy becomes available to the cheetah when it eats the antelope.

Food webs

Different food chains in an ecosystem are interconnected because it is unusual for an organism to have a single source of energy and nutrients. The organisms in the simple food chain in the 'food web below' will eat and be eaten by different organisms. For example, the antelope could be eaten by a lion or a wild dog, and the grass eaten by zebra and wildebeest (Figure 12.2.1). Linked food chains form a web of interactions known as a food web.

Pyramids of energy

We can represent the transfer of energy between trophic levels as an energy pyramid. Each trophic level is drawn as a rectangle and the width of each layer in the pyramid is proportional to the amount of energy it represents.

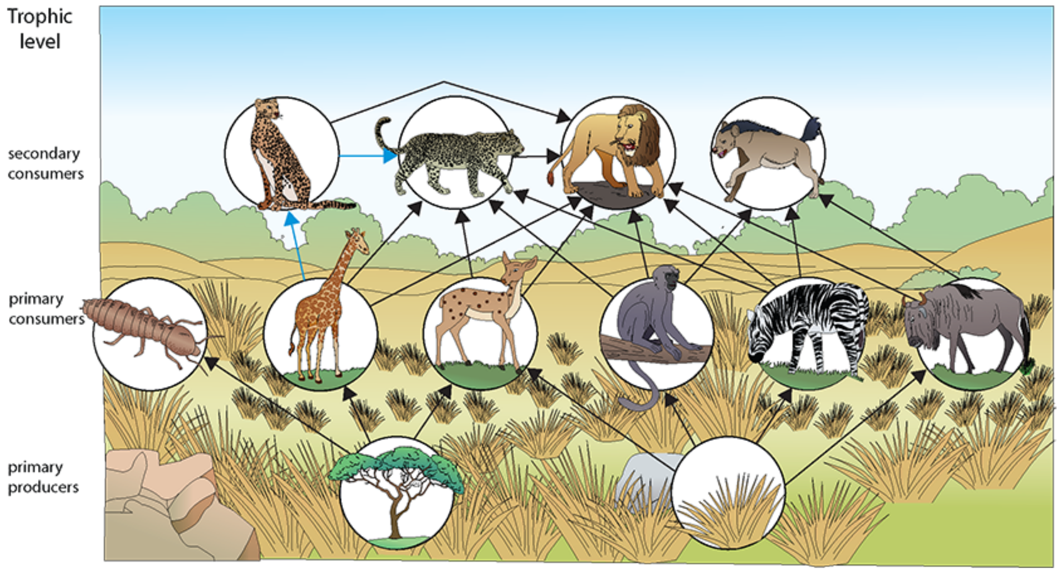


Figure 12.2.1: A food web from a grassland ecosystem.

NATURE OF SCIENCE

Using theories to explain natural phenomena: the concept of energy flow and food chains

Plants are the primary source of energy in nearly all ecosystems, but energy capture and photosynthesis are not efficient processes. So, not all of the energy of the sunlight is used. When herbivores feed, the energy transferred from plant to herbivore is also not 100% efficient. Not all of the plant material is eaten and absorbed, and some energy is lost in movement and respiration. The same is true for carnivores eating prey animals. Only about 10% of the energy in producers is passed to herbivores and a similar low percentage of energy is passed from herbivores to carnivores (Figure 12.2.2).

All along a food chain or food web, energy is lost at each trophic level through respiration and waste. This is why ecosystems rarely contain more than four or five trophic levels. There is simply not enough energy to support another level and understanding the concept of energy flow explains why food chains are limited in length.

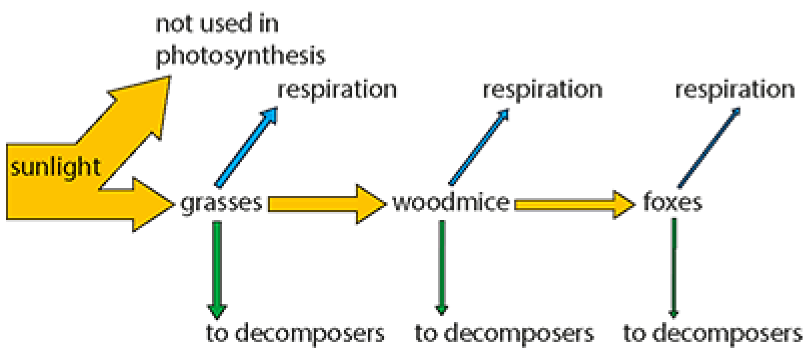


Figure 12.2.2: Energy losses in a food chain (not to scale). Energy is measured in kilojoules per square metre per year ($kJ \cdot m^{-2} \cdot year^{-1}$). Only a small percentage of the energy in each level is transferred to the next.

To consider:

1. How useful are diagrams such as food chains and pyramids of energy in helping us understand an ecosystem?
2. How can ecologists improve the quality of the data they collect in an ecosystem?

So the antelope → cheetah energy transfer would appear as in Figure 12.2.3. This section of an energy pyramid shows that only about 10% of the energy from the antelope passes to the cheetah and that about 90% is lost.

Energy losses of up to 90% occur at every step in a food chain, between one trophic level and the next.

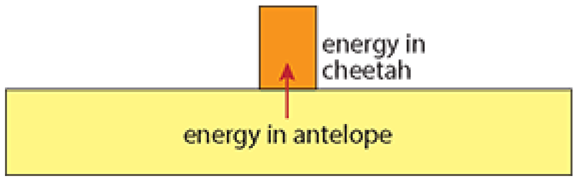


Figure 12.2.3: A simple energy pyramid for a single energy transfer.

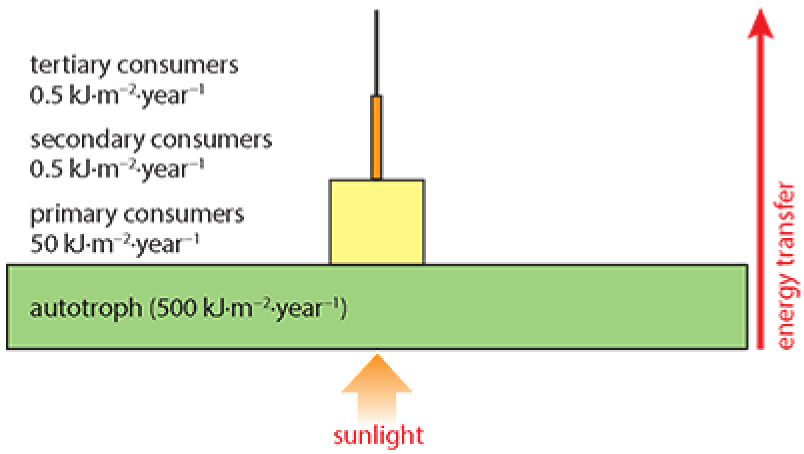


Figure 12.2.4: A generalised energy pyramid. It shows only 10% of available energy passing to the next trophic level.

The energy content of each trophic level can be calculated and used to construct an energy pyramid for an ecosystem (Figure 12.2.4).

Pyramids of energy show the amount of energy at each trophic level.

One consequence of the energy losses between one level and the next is that the quantity of biomass (biological material) at each level decreases due to the loss of waste products at each transfer of energy. Every link in the chain results in losses, so that eventually there will be insufficient energy to support any further trophic levels. Most food chains commonly contain between three and five species, and seldom more than six. The energy that enters an ecosystem as light is converted to stored chemical energy and finally lost as heat.

TEST YOUR UNDERSTANDING

10 Explain what the arrows represent in a food chain.

11 State the initial source of energy for most food chains.

12 List the three ways in which energy is lost when moving from one trophic level to the next.

INTERNATIONAL MINDEDNESS

Feeding the world

We can also draw pyramids of energy for different types of farming and food production and compare their trophic levels and efficiency of energy conservation. As we grow arable crops or farm animals, energy is used in the growth of biomass and production of offspring. In a terrestrial ecosystem, food is usually harvested at trophic levels 1 and 2 (autotrophs and herbivores). From an energy point of view, farming systems that produce crops are much more efficient than those that produce animals because the energy has passed through only one trophic level.

One hectare of land can produce approximately 7.5 tonnes of wheat (equivalent to 11 000 loaves of bread) or 0.3 tonnes of beef. Many more people can be provided with food from the wheat rather than the beef.

A steadily rising world population has increased the demand for food and led to environmental damage, as more land is needed for farming. Forests have been cut down and soil degraded. Also, as newly emerging economies worldwide have seen incomes rise, the demand for meat has also increased.

To consider:

1. Why is arable farming more efficient in energy terms than farming animals?
2. How important are other products that we get from farmed animals, for example milk, wool and leather?
3. Do you think that people should be encouraged to reduce their consumption of meat and to eat more vegetables?

12.2.2 Nutrient recycling

All the organic matter from an organism, including living or dead material and waste, is eventually consumed by other organisms, which include detritivores and saprotrophs (Section 12.1). All these organisms respire and release energy as heat, which is no longer available for use by living things.

Nutrients are continually recycled and the supply of nutrients is limited and finite. Nutrient cycles transfer chemical elements such as carbon, nitrogen and phosphorus through the biotic and abiotic parts of the ecosystem from one organism to the next. Organisms usually take in nutrients as ions and use them to construct cells or for respiration.

For example, nitrogen is absorbed as nitrate or ammonium ions. It is used to construct proteins and nucleic acids. Phosphorus may be absorbed as phosphate to construct nucleic acids or lipid molecules.

A nitrogen atom may be absorbed as nitrate by plant roots and used to make an amino acid. The amino acid may pass into an animal when the plant material is eaten, and then pass out of the animal's body in urine as urea during excretion. Soil bacteria may convert urea in the excreted material back into nitrate and the cycle begins again.

In the soil, the saprotrophic bacteria and fungi are essential for the recycling of nutrients. Relationships like this form part of biogeochemical cycles.

The carbon cycle

Carbon is one of the most important elements that is recycled in an ecosystem (Figure 12.2.5). Inorganic carbon dioxide in the atmosphere is trapped or ‘fixed’ as organic carbon compounds during photosynthesis. Carbon dioxide gas needed for photosynthesis passes by diffusion from the atmosphere into land-dwelling autotrophs and dissolved carbon dioxide diffuses from water into aquatic organisms. Some of this carbon is soon returned to the atmosphere or the water as the plants respire. The other steps in the carbon cycle follow the same path as food chains. As herbivores eat plants, and carnivores eat herbivores, the carbon compounds move from plants to animals. Respiration by any organism in this sequence returns carbon to the environment as carbon dioxide. When a plant or animal dies, carbon compounds in their bodies provide nutrition for detritivores and saprotrophs and may also be respired, returning carbon dioxide to the atmosphere. Aerobic respiration depends on the release of oxygen from photosynthesis and photosynthesis depends on the release of carbon dioxide from respiration.

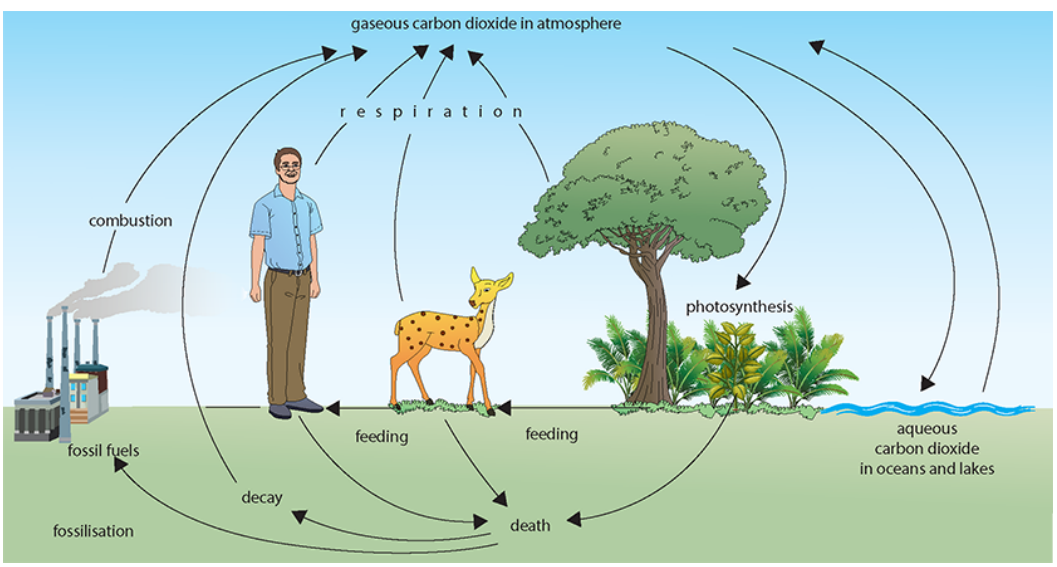


Figure 12.2.5: The carbon cycle.

This relationship forms a major interaction between autotrophs and heterotrophs.

EXAM TIP

Recall that energy *flows*, but that nutrients *cycle*.

Methane, peat and fossil fuels

In some conditions, plants and animals do not decay completely when they die and organic carbon in their bodies may not be released directly as carbon dioxide as they decompose. In wetlands, where the soil is waterlogged and the concentration of oxygen is very low, organic material is broken down by anaerobic **methanogenic** bacteria (Achaeans), which produce **methane** as a byproduct. Peat bogs represent the largest natural source of atmospheric methane, a greenhouse gas many times more harmful than carbon dioxide. A large proportion of this methane is recycled by methane-eating bacteria (methanotrophs) in the peat bog, which form a symbiotic relationship with peat-bog moss. The bacteria supply additional carbon dioxide to the moss, which in turn provides the bacteria with a habitat.

Methane is oxidised to carbon dioxide and water released into the atmosphere. Thus, eventually, carbon dioxide rejoins the carbon cycle and contributes to the carbon dioxide in the atmosphere, although some remains in the ground.

Peat is also produced in wetlands where partly decayed vegetation accumulates and flooding prevents oxygen flow in the soil, so that anaerobic and sometimes acidic conditions persist. For peat to form, the production of biomass must be greater than its chemical breakdown. The first stage in peat formation takes place when water levels are low and aerobic micro-organisms act on decaying vegetation in surface layers. As this layer becomes covered by further layers of vegetation and thus subjected to anaerobic conditions in wetter, deeper layers, it becomes preserved and changes very little with time. Depending on the local conditions, the types of peat from different areas can be quite different in their degree of decomposition. Areas where peat is found also have specific kinds of plants, such as heather, sphagnum moss and sedges. Since organic matter accumulates over thousands of years, peat deposits also provide records of past vegetation and climates.

KEY POINTS

methanogenic bacteria respire anaerobically and release methane

methane (CH_4) is a greenhouse gas released by animals as they digest food, by rice fields and some bacteria

Peat is harvested as a fuel in some parts of the world as it can be compressed into bricks and unlike coal, burns without producing smoke (Figure 12.2.6). But peat is not classified as a renewable energy resource because its rate of extraction is far greater than its very slow rate of formation which can take between 1000 and 5000 years.

Figure 12.2.6: Peat is cut to be used as a fuel. It can also be used as an additive improve soil structure.

Some partially decomposed organic matter from past geological eras has become compressed and fossilised in a process that has taken millions of years. Conditions on Earth at the time prevented decomposers from feeding on this material and over time it was fossilised to become **fossil fuels**. Vast coal, oil and natural gas deposits have been formed deep under the ground where they contain reserves of carbon that are locked in and excluded from the carbon cycle for very long periods of time. The carbon trapped in these fuels cannot return to the atmosphere unless the fuels are burned, when the carbon in them combines with oxygen in the air to form carbon dioxide. Over a very long period of geological time, fossil fuel formation has gradually lowered the carbon dioxide level of the Earth's atmosphere, but in more recent times this balance has been upset. As people burn wood, peat, coal, oil or gas, the carbon molecules locked up in them for thousands or millions of years are released back into the atmosphere as carbon dioxide. As carbon dioxide re-enters the carbon cycle it has the potential to cause global warming (Section 12.6).

NATURE OF SCIENCE

Obtaining evidence – how is reliable data on carbon dioxide and methane concentrations obtained?

The level of carbon dioxide in the atmosphere has been increasing since the end of the nineteenth century. The first measurements of the gas were made by Charles Keeling (1928–2005) who took careful measurement of samples from Mauna Loa in Hawaii and the Antarctica in 1957 and 1958. Since then records of the gas have been kept continuously and the Keeling curve (named after Charles Keeling) and additions to it are well recognised (Figure **12.2.7**). Today, many different types of data are collected about the Earth's climate (Figure **12.2.8**) and the concentrations of both carbon dioxide and methane are recorded.

Carbon dioxide has been measured using a weather satellite instrument called AIRS (Atmospheric Infrared Sounder) developed by a NASA scientist Moustafa Chahine (1935–2011). AIRS works by measuring the infrared light emitted by carbon dioxide molecules. Gas molecules absorb infrared rays emitted by the Earth's surface and then re-radiate them at a slightly lower energy level. The exact frequencies of the emissions depend on temperatures. About three million measurements are taken in this way every day and a computer processes the information that is collected. AIRS focuses on a section of the atmosphere known as the middle troposphere but a second satellite, NASA's Orbiting Carbon Observatory (OCO), collects data from the entire atmospheric column.

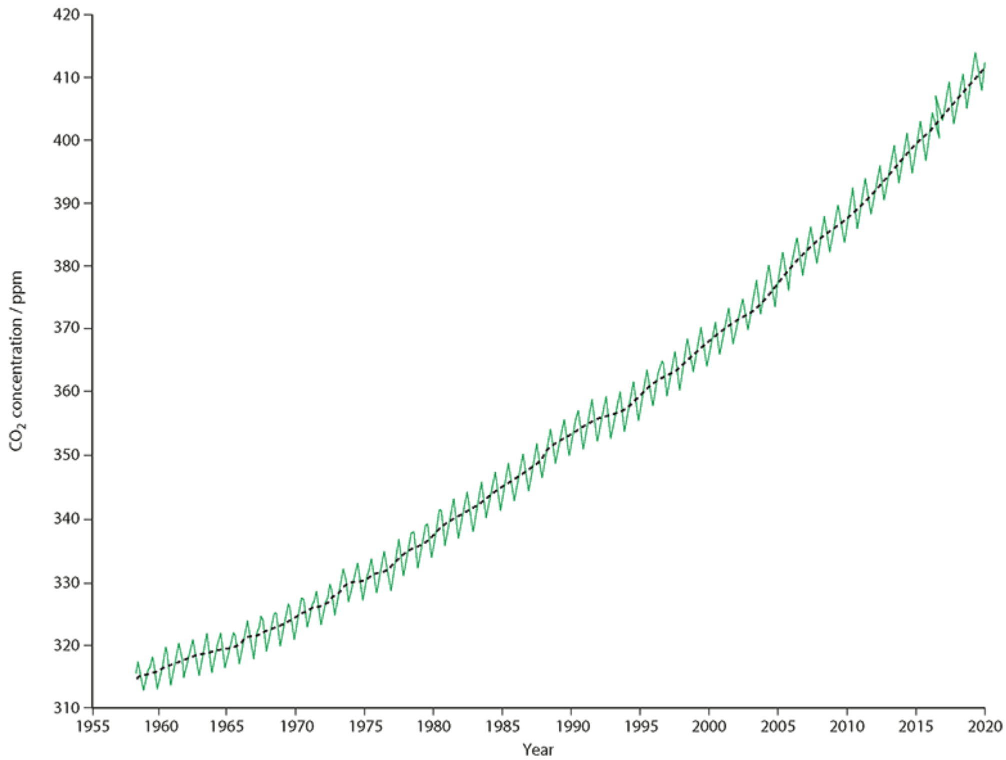


Figure 12.2.7: Atmospheric carbon dioxide concentrations measured at monthly intervals in Hawaii.

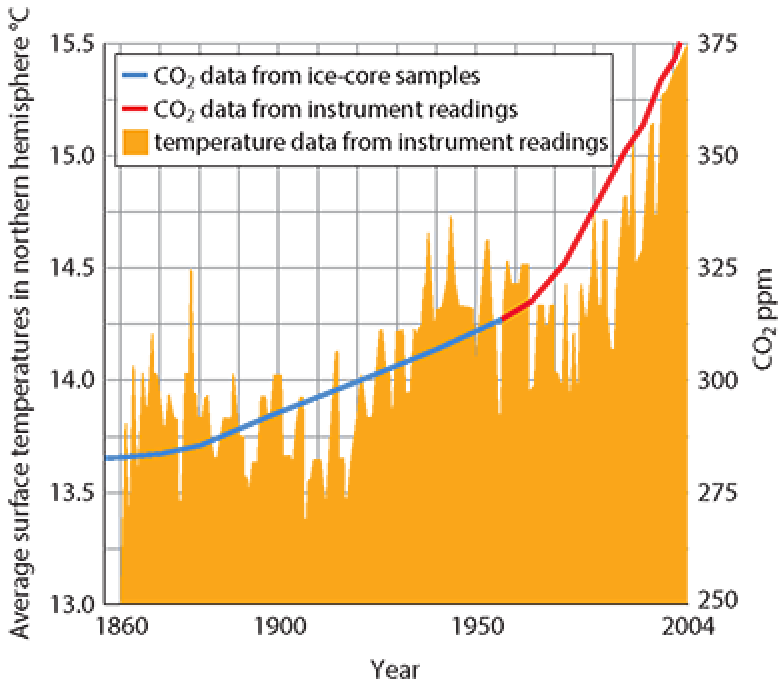


Figure 12.2.8: Graph showing carbon dioxide data from different sources and evidence of warming global temperatures.

The OCO uses optical properties of carbon dioxide to measure its presence using an AIRS. Carbon dioxide molecules vibrate at certain frequencies of light and this instrument uses the sunlight as a light source to monitor the vibrations. The satellite circles the Earth and collects light that has passed through the atmosphere and into three spectrometers, two of which respond to carbon dioxide. The spectra produced resemble bar codes, which can be analysed precisely back on Earth and provide data on areas as small as a square kilometre.

Question to consider

- Look at the curve shown in Figure **12.2.7**. The dotted line shows the trend of increasing carbon dioxide in the atmosphere but what do the peaks and troughs along the line indicate?

TEST YOUR UNDERSTANDING

13 The leaves of a tree store 20 000 $J \cdot m^{-2} \cdot year^{-1}$ of energy. Estimate the amount of energy that may be stored in caterpillars that feed on the leaves.

14 State the difference between energy movement and nutrient movement in an ecosystem.

15 Why is it important to understand the flow of energy in an ecosystem?

REFLECTION

Could I communicate the importance of understanding feeding relationships to someone else? Which ideas would I focus on?

Links

- Photosynthesis is essential to provide energy for organisms' metabolisms. What do organisms use this energy for? (Chapter 2.3)
- How does understanding ecosystem stability help us understand the importance of biogeochemical cycles? (Chapter 12.4)

12.3 Ecological relationships and populations

LEARNING OBJECTIVES

In this section you will:

- define the terms populations and community in an ecosystem
- discover that organisms and populations in a community interact in many ways
- recognise that when overall effects are limited, organisms can coexist and biodiversity can increase
- recall that ecological relationships can be intraspecific and interspecific and can affect the distribution and population sizes of species
- learn that population size can be estimated using random sampling methods which include quadrats and the Lincoln index
- understand that competition occurs when different organisms require the same resources, and may be inter- or intraspecific
- discover that the chi-squared test can be used to investigate evidence for interspecific competition
- investigate predation including quantifying predator–prey relationships and adaptations that prey animals have for defence

- consider herbivory and the defence mechanisms plants use to protect themselves
- understand the importance of keystone species in an ecosystem

- understand the interspecific interaction mutualism
- understand that cooperative intraspecific relationships can have advantages and some disadvantages
- learn how new populations in suitable environments grow in size, and define the terms lag phase, log phase and stationary phases
- define the carrying capacity of an ecosystem
- understand how numbers in a population may fluctuate around the carrying capacity due to density-dependent and -independent factors
- learn that in some cases a population may enter a phase of decline
- recall that plants, fungi and bacteria may release chemicals that are detrimental to other species close to them.

GUIDING QUESTIONS

- What interactions occur between organisms and populations?

- Why are organisms and population in communities interdependent?
- What effect do ecological relationships have on the population size of different species?

12.3.1 Interactions between populations

A **population** of organisms is a group of the same species living in the same place at the same time and interacting with each other. The *number* of individuals is known as the population size and is only one aspect of any population.

A **community** is the biotic (living) component of an ecosystem. It consists of populations of different species that live in the same area and interact with one another. In any ecosystem there will be communities of organisms – that is, groups of different populations of all the different species – that are present that **coexist** and interact with each other. Some of these species will have overlapping habitats and niches (Section 11.4). Interactions in communities are important factors in natural selection. The interactions help shape the ecosystem and evolution of the interacting species within it. Three major types of community interactions are predation, competition and symbiosis. **Symbiosis** means 'living together' and includes **commensalism**, mutualism and parasitism. These interactions are explained in Section 12.2.

Interactions, population size and distribution

The size of a population and the distribution of organisms in an ecosystem is dependent upon biotic and abiotic factors. Every organism has an ideal living space that it requires, its fundamental niche, but the space it actually inhabits is its realised niche (Section 11.4). Abiotic factors such as soil type, shelter, weather and climatic conditions are key to determining an organism's distribution but the size of a population and its distribution are also influenced by interactions between members of its own species and of other species. A distribution pattern may be explained if one species excludes another through competition or limits the range of a species by feeding on it, or affecting its health.

The availability of food is a major factor in how many organisms can live in an ecosystem. Rainforests with rich food supplies can support more species that are more evenly distributed than deserts and the polar regions where there is less food. Both interspecific and intraspecific competition influence the number of organisms that can survive. In most situations predators and prey have evolved together and a balance is achieved but the arrival of new predators can upset this balance, for example the red fox was introduced to Australia in the mid 1800s and their numbers increased rapidly. Foxes have been blamed for the decline in native species such as quokkas, numbats and bettongs. They also reduce the food available to native predators whose populations are reduced.

Pathogens and parasites also influence the abundance of a species, and interactions with new pathogens can limit population size and distribution. For example, a new pathogen, the fungus *Hymenoscyphus pseudoalbidus* which causes ash die back disease has spread across Europe since the start of this century. This chronic fungal disease of ash trees causes loss of leaves and death of upper parts of infected trees. The fungus has killed many ash trees and the number and distribution of ash trees has been severely reduced in many parts of Europe.

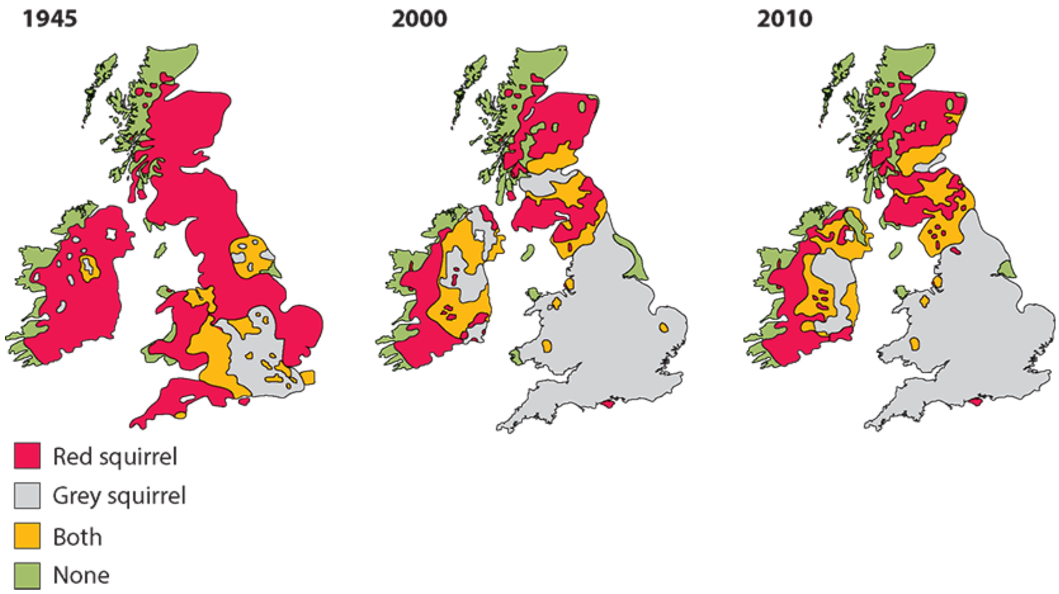


Figure 12.3.1: The distribution of red and grey squirrels in the United Kingdom and Ireland over a 65 year period.

Competition between species can lead to one being excluded by another. This can occur between existing species or because a new species has arrived or been introduced. Examples of out-competition of native species by newly introduced species include the Canada goose in Europe. In the 1990s there were only a few hundred Canada geese (*Branta canadensis*) in France but now their numbers have increased so much that they are limiting the population size and distribution of ducks, coots and other goose species. The cane toad in Australia (Section 11.4) and the invasive Himalayan balsam, now growing in many countries, are also affecting the populations and distribution of native species that they compete with.

Figure 12.3.1 shows how the distribution and population size of squirrels in the United Kingdom and Ireland has changed over a period of 65 years. Red squirrels (*Sciurus vulgaris*) are the native species in the British Isles. The grey squirrel (*Sciurus carolinensis*) species was introduced around 100 years ago from

America. The grey squirrel is larger and heavier, with a typical weight of 550 g, compared to 300 g for native red squirrels. Greys compete with reds for food and also carry a virus known as squirrelpox. Grey squirrels are immune to the disease but they transmit it to red squirrels, for whom it is fatal. Populations of red squirrels are now only found in places where greys are rare or absent. Grey squirrels can also affect the composition of native woodland by removing bark from trees bark and selecting the seeds of certain trees to eat. The population size and distribution of the red squirrel has reduced as a result of this interspecific interaction while those of grey squirrels have increased.

The abundance and distribution of species are estimated using techniques such as transects and quadrats described in Section 12.3.2. Distribution–abundance relationships give an insight into the relationship between the local abundance of species and the size of their ranges within a region and these can be related to both abiotic factors and interactions between species.

TEST YOUR UNDERSTANDING

16 Suggest two abiotic factors that might affect the distribution of a species.

17 Why can a newly arrived species reduce the population of an existing species in a habitat?

18 Why is the distribution of species more even and plentiful in a rainforest than a desert?

12.3.2 Estimating population sizes

Investigating distribution of species: random sampling

A population is a group of individuals of the same species that live in the same area.

Population numbers can and do change over time and are affected by a number of factors in the environment. When ecologists want to understand the distribution of a species, or to compare the distribution of one species with that of another in a different location, it is usually impossible to do so by a direct counting method. In most cases, ecologists take a sample of the population and, if the sample is chosen at random, it should provide a good representation of the whole population. Random sampling is used if the area under investigation is large or if time is limited, and it assumes that every organism has an equal chance of being sampled (that is, of being selected as part of the sample). There are a number of sampling methods used by ecologists to collect data on the distribution of species in relation to one another and to abiotic factors in their environment.

Two common methods used for stationary organisms are quadrats and transects (transects are described in Section 11.4.2). Quadrats can show the population number (abundance), the distribution of organisms, their density and the frequency of occurrence. Mobile organisms are estimated using the capture–mark–release–recapture method.

Population density is calculated using the equation:

$$\text{Density} = \frac{\text{total number in all quadrats}}{\text{number of quadrat samples} \times \text{area of quadrat}}$$

KEY POINT

random sampling a technique in which each sample has an equal probability of being chosen to provide an unbiased representation of the total population.

Quadrats: to sample sessile (non-moving) species

One of the simplest and easiest sampling techniques involves using a quadrat (Figure 12.3.2). A quadrat is a square made of metal or wood divided into smaller squares. The quadrat is placed on the ground so that the organisms inside the square can be counted. The size of the quadrat will largely be decided by what is being measured. To estimate the number of different trees in a wood may require quadrats of 10 m by 10 m, but a 1 m quadrat would be the best size for studying wild flowers in grassland. Very small 10 cm quadrats might be used for sampling lichens on walls or tree trunks.

Figure 12.3.2: Using a quadrat to sample an area of grassland.

To use quadrat sampling you should:

- Use the correct number quadrats to get enough data to get a representation of the population.
- Identify the species in the quadrats so they can be distinguished from one another.
- Use a random number generator or table to select the squares to sample.

THEORY OF KNOWLEDGE

Sampling bias

Placing quadrats to collect data on the distribution of a species may not always be a truly random process. Researchers can introduce personal bias, even without meaning to, by placing a quadrat in a spot that they think will be more interesting or easier to work in. To ensure that the samples within a survey area are made completely randomly, a numbered grid of the area may be drawn up, and random number tables or generators used to select squares on the grid where a quadrat should be placed (Figure 12.3.3). Random number tables and random number generators are lists of numbers selected by a computer without any human bias.

To consider:

1. Is random sampling a useful tool for scientists?
2. How significant is the potential for sampling bias and can this ever be completely avoided?

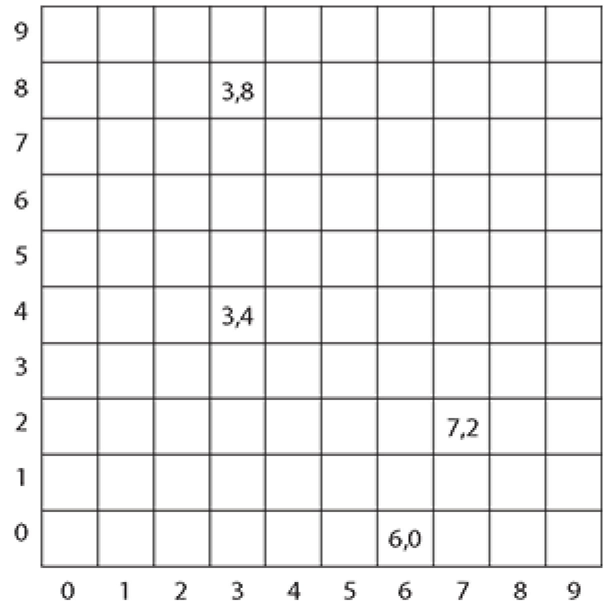


Figure 12.3.3: To select a part of an area to sample with a quadrat, divide the area into a grid of squares and then select a row and a column using randomly generated numbers.

Mark–release–recapture method: to estimate numbers of a motile (moving) species

The most common method of estimating population size of animals that can move is the capture–mark–release–recapture technique (Figure 12.3.4). It is used for populations where individuals are mobile and move freely in their habitat.

1 A sample of the population is collected by netting, trapping or another suitable method. The sample must be as large as possible and the trapping method must not harm the animals.

2 The number of organisms in the sample is counted and recorded.

3 Each of the captured animals is inconspicuously marked in some way; for example, with non-toxic paint for invertebrates or by trimming a concealed area of fur for small mammals.

4 The animals are returned to the wild and left for long enough to interact freely with the rest of their population.

5 A second sample of the population is collected after this time.

6 The number of marked and unmarked individuals in the second sample is counted.

The population size is calculated using the Lincoln index formula:

$$P = \frac{M \times N}{R}$$

where:

P is the total population

M is the number of organisms caught and marked originally

N is the number caught in the second sample (with and without marks)

R is the number of marked individuals in the second sample.

This method depends on a number of factors, which need to be taken into account.

- Marking the organisms must not harm them or cause them to be conspicuous to predators. That is, the marking itself must have no effect on the population size.

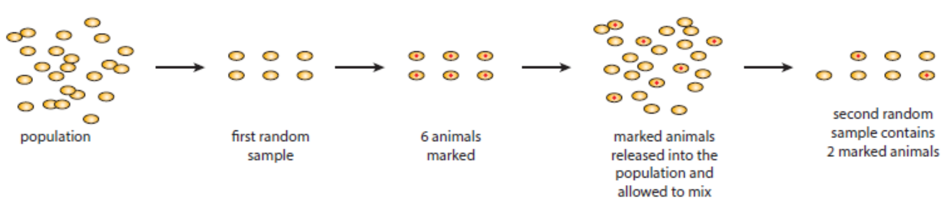
- There should be minimal immigration into or emigration from the population.
- The measurements must be conducted within a single life cycle, so there are no significant changes to the population through births or deaths.

The capture–mark–release–recapture technique is most appropriate for invertebrates such as woodlice, snails and ladybirds or small mammals, such as mice, with a limited territory. Sampling organisms with a large territory, or those where the population is small, is not accurate using this method

WORKED EXAMPLE 12.3.1

Here is a calculation using the Lincoln index for a theoretical population of small organisms that mix freely and live in the same area.

Answer



$$\text{estimated population size} = \frac{\text{number in first sample} \times \text{number in second sample}}{\text{number of marked animals in second sample}}$$

$$\text{estimated population size} = \frac{6 \times 7}{2}$$

$$\text{estimated population size} = 21$$

Note : This method only produces results of acceptable accuracy if the numbers in the samples are larger than shown here. At least 20 animals should be sampled.

Figure 12.3.4: Capture–mark–release–recapture technique for estimating population size.

Testing for the association between two species: the chi-squared test

Interspecific competition occurs when two different species need the same resource and one species is more successful when the other is not present.

You can read about examples of this type of competition in the example in which lions, hyenas and wild dogs are competing for a prey species, the zebra. Laboratory experiments can show us more about the effects of interspecific competition on a smaller scale. The work of G.F. Gause (1910–1986) on two species of single-celled *Paramecium* is described in Section 11.4.3.

We can use the chi-squared (χ^2) test to compare sets of data and evaluate if the differences between them are statistically significant or due to chance. To use this test in ecology we must:

- Use precise categorical data, for example species and counts of the numbers present.
- The test can be used to test for the association between species in an ecosystem. If the presence or absence of two species is recorded in quadrats during sampling it is possible to test whether:
  - the two species are distributed independently of one another (the null hypothesis), or
  - the two species are associated either positively or negatively, so they tend to occur either together or apart.

1 Draw up a table of results like this and enter the observed numbers of the two organisms in each quadrat:

	Species A present	Species A absent	Total for rows
Species B present			
Species B absent			
Total for columns			

2 Calculate the expected values, assuming the two species are independently distributed:

$$\text{Expected frequency} = \frac{\text{row total} \times \text{column total}}{\text{grand total}}$$

3 Calculate the value of chi-squared (χ^2):

$$\chi^2 = \sum \frac{(O - E)^2}{E}$$

where χ^2 is the test statistic, Σ means 'the sum of', O is the observed frequencies and E is the expected frequencies.

4 Calculate the degrees of freedom:

$$\begin{aligned}\text{The degrees of freedom} &= (\text{rows} - 1) \times (\text{columns} - 1) \\ &= (2 - 1) \times (2 - 1) \\ &= 1\end{aligned}$$

5 Use a chi-squared table to find the critical value at 1 degree of freedom for the chi-squared value you calculate. If the value you calculated (step 3) is greater than the chi-squared value at the 5% level then the null hypothesis can be rejected and we can accept that the two species are associated.

If the calculated value is less than the chi-squared value we accept the null hypothesis that the two species are distributed independently of one another (check the table of chi-squared values in Table 4.2.2).

EXAM TIP

Biologists use statistics when testing hypotheses. In biology we set the significance level (the cut off) for the probability of rejecting the null hypothesis at the 5% level. Put another way, we can reject a null hypothesis with 95% certainty of being correct.

TEST YOUR UNDERSTANDING

19 List three conditions that must be met to make the capture–mark–release–recapture method suitable to measure population size.

20 Which sampling method is used to measure populations of sessile organisms?

WORKED EXAMPLE 12.3.2

Two species of plantain, *Plantago major* and *Plantago minor*, grow in the same field. The field was surveyed using quadrats and random sampling and the following data are collected.

The null hypothesis is that there is no association between the two species and no significant difference between the observed and expected frequencies.

Answer

Step 1 Tabulate the data collected.

	***P. major* present**	***P. major* absent**	**TOTAL**
***P. minor* present**	22	46	68
***P. minor* absent**	33	49	82
TOTAL	55	95	150

Step 2 Calculate the expected frequencies.

	***P. major* present**	***P. major* absent**	**TOTAL**
***P. minor* present**	$(68 \times 55) \div 150$ $= 24.9$	$(68 \times 95) \div 150$ $= 43.1$	68
***P. minor* absent**	$(82 \times 55) \div 150$ $= 30.1$	$(82 \times 95) \div 150$ $= 51.9$	82
TOTAL	55	95	150

		***P. major* present**	***P. major* absent**
***P. minor* present**	*O*	22	46
	E	24.9	43.1
		0.34	0.19

	$\frac{(O-E)^2}{E}$		
***P. minor* absent**	O	33	49
	E	24.9	51.9
	$\frac{(O-E)^2}{E}$	2.6	0.16

Step 3 Calculate the value of chi-squared.

$$\chi^2 = \sum \frac{(O-E)^2}{E} = 0.34 + 0.19 + 2.6 + 0.16 = 3.29$$

Step 4 Check the chi-squared table on page 176.

Degrees of freedom = (2 − 1) = 1 as there are two species in the sample.

Compare the calculated value of chi-squared against the critical value at the confidence level of 95% (or $p = 0.05$) at 1 degree of freedom. As the chi-squared value is less than the critical value, we *accept* the null hypothesis. There is no significant difference between the observed and expected values for the two species of plantain.

NATURE OF SCIENCE

Assessing the risks and benefits of scientific research

As ecologists study organisms in their natural habitats they make observations and measurements to assess the numbers and distributions of species that are present. Sometimes it is necessary to disturb or even remove organisms from their habitats in order to discover the relationships that they have with other species. Joseph Connell (1923–2020) who worked on two species of barnacle (Figure 11.4.9) removed one species from an area of rocky shore as he investigated the niches that the two species occupied. When carrying out surveys using the capture–mark–release–recapture method of estimating populations, organisms are trapped, counted and released. In both cases, ecologists inevitably cause some damage to the ecosystem that is being studied.

In the same way, when you carry out field studies you will trample and disturb the areas you are studying and remove organisms to investigate. It is important to carry out studies of the natural world so that we can understand relationships that may be vital to conservation of ecosystems or species. It is also important to keep in mind that we must do all we can to prevent harm to organisms as we study them and ensure that we minimise the damage and disturbance we cause.

To consider:

1 Which of these approaches to the study of competition do you think would cause least harm to organisms being investigated?

- **a** Field observations of interspecific competition between two predators.
- **b** Manipulation of animals in the natural world, for example removing one species to assess its effect on another.
- **c** Laboratory experiments, for example in an artificial ecosystem such as a tank of fish.

2 How have you tried to minimise disturbance in field studies you have carried out?

12.3.3 Growth of new populations

New populations can start to establish themselves when a few individuals of a species enter an unoccupied area. Perhaps a few rabbits arrive on an uninhabited island covered by lush grassland, or some fish are washed into a newly established pond, or bacteria land on a fresh plate of agar jelly. Assuming there is enough food and there are few predators, the newcomers will reproduce and the population will increase rapidly. After a time, when there are large numbers of individuals, the food supply will start to be used up faster than it can be replaced. The population will be unable to increase any further and the population numbers will stabilise. We can observe these changes taking place and plot the numbers present in the population as a graph.

The typical pattern of growth for a newly established population is shown in Figure 12.3.5.

It is possible to follow the development of a population as it grows and changes over a period of time. All new populations produce similar growth curves as their numbers increase as a result of reproduction, then stabilise and, in some cases, later decline. The phases of population growth can be identified and described as follows:

1 During the lag phase, the new population settles into its new environment and slowly begins to reproduce so that numbers increase.

2 The log phase (or exponential growth phase) occurs as more individuals reproduce and the population shows exponential growth (the steepest part of the curve). At this time, the population inhabits an ideal, unlimited environment: there is abundant food, little competition for space and the effects of predation and disease are minimal.

3 After a time, the exponential phase ceases as one or more resources that individuals need become limited. The shape of the curve at this stage resembles a letter S, and it is called the S-phase. It shows that the rate of population growth is slowing down. The population is said to be in transition. Individuals must compete with one another for resources such as space, light, food, nutrients and water. This intraspecific competition increases as population numbers increase. When the rate of demand for a particular resource is greater than the rate of supply we say that the resource has become a limiting factor. Predation, disease and, in some cases, the accumulation of toxic wastes products such as carbon dioxide can also limit some populations.

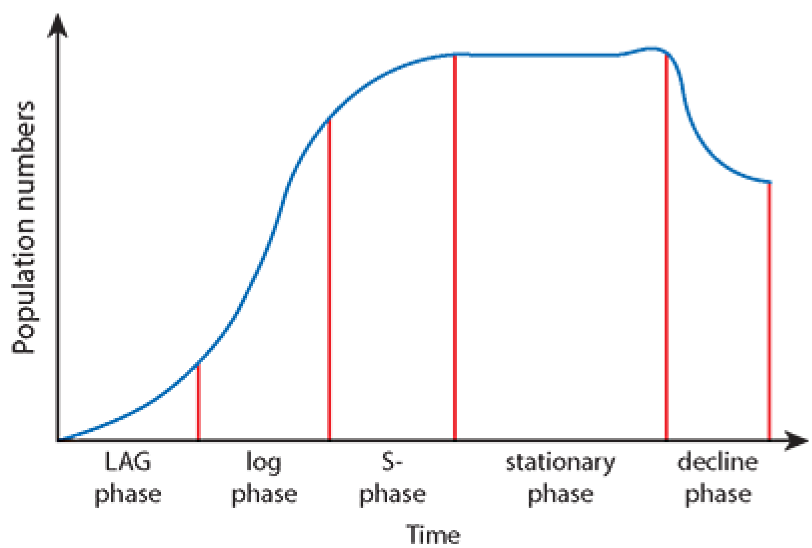


Figure 12.3.5: This graph shows the rate of growth for a new population as it becomes established and matures.

4 In the stationary phase population numbers become more or less constant and the curve on the graph levels off. The ecosystem has reached its carrying capacity, which is the number of individuals in a population that the resources in the environment can support for an extended period of time. At this time the population growth rate will slow down, either because organisms die through lack of an essential resource, or because they fail to breed and their birth rate falls. The number of individuals in the population fluctuates around the carrying capacity due to density-dependent factors and density-independent factors. The population remains more or less stable because rates of both natality (birth) and mortality (death) are balanced, and so are rates of **emigration** and **immigration**.

5 In some species a population may enter a phase of decline. This is caused by events such as disease or starvation. There may also be longer-term effects such as low birth rates or low fertility in the reproducing population. There may also be high mortality rates and high emigration rates as individuals move away from a difficult environment.

Why do population sizes vary?

We have identified a number of important reasons why a population may change in size:

- natality – the birth rate may change (the number of new individuals joining the population due to reproduction)

KEY POINTS

carrying capacity is the maximum average number of individuals of a species that an ecosystem can support.

lag phase is a period of time when a new population arrives in a new environment and begins to reproduce.

log phase (or exponential growth phase) is period of maximum population growth.

limiting factor is in populations, a resource that prevents the growth of a population above a certain level.

phase of decline is period of time during which a population size decreases.

stationary phase is period of time during which a population size remains unchanged.

- mortality – the number of deaths may change
- emigration – members of the population may move away to new habitats
- immigration – new members of the species may arrive from elsewhere.

Some factors limit an increase in population numbers, no matter what species is considered. These include:

- availability of key resources such as food, water, oxygen, light, space,
- mates and shelter
- levels of waste products, such as carbon dioxide or nitrogenous waste
- disease
- predation or herbivory.

Density-dependent and density-independent factors

Density-dependent factors affect populations and their effects are related to the size and density of the population. Disease, migration and availability of resources are all density-dependent. If the population is small, individuals are less likely to compete for resources such as food, and are less likely to move away if conditions are favourable.

Figure 12.3.6: The common orange lichen (*Xanthoria parietina*) is an association between a fungus and an alga.

Density-independent factors also affect populations, but they are not related to population size or density. Density-independent factors include environmental factors such as light, temperature and rainfall, which may vary with the seasons.

KEY POINTS

density-dependent factor is a factor that influences a population and varies with population size.

density-independent factor is a factor such as light intensity or temperature which affects a population, whatever its size.

12.3.4 Competition

Competition is an interaction between organisms that require the same limited resources. The resources might be food, mates, nesting sites or territory. Two different types of competition are intraspecific and interspecific competition.

Intraspecific competition occurs between members of the same species. One example is competition between two male animals for mates (Figure 12.3.7). Competition has negative effects on both and leads to a reduction in fitness for both individuals, but the fitter individual survives and is able to reproduce. Intraspecific competition is a necessary factor in natural selection. It leads to adaptive changes in a species through time.

Plants, which cannot move, use the same resources as other members of their species that grow in the same area. For example young oak trees must compete for light, much of which will be blocked out by taller trees. Young oaks find themselves in competition with larger members of their own species. Acorns which germinate close to the parent plant are likely to be outcompeted and the young trees may die. This is one of the reasons why seeds of most plants are dispersed as far as possible from the parent plant so that competition is avoided.

Figure 12.3.7: Male bighorn sheep fighting for the right to mate.

Interspecific competition occurs between members of different species.

For example, two predator species might compete for the same prey. Interspecific competition takes place in communities of interacting species (Figure 12.3.8).

Interactions in communities and populations

Ecological interactions by one organism or population on another can have positive , negative or limited effects. Examples of these interactions are outlined in the next sections.

Mutualism: both organisms benefit

Mutualism is an interaction in which both species benefit. Lichen (Figure 12.3.6) is an example of a mutualistic relationship. A lichen is an association between a fungus and an alga. Lichens such as common orange lichen (*Xanthoria parietina*), which grows on rocks and walls, twigs and branches, consist of fungal filaments that surround cells of a green alga. The fungus absorbs water from the air and minerals from rocks or soil and protects the alga from intense sunlight and drying out. The alga uses the water and minerals, and photosynthesises to makes carbohydrate for itself and the fungus. Both gain from this mutualistic relationship.

KEY POINT

mutualism a cooperative interspecific interaction; sometimes called a mutual symbiosis.

Figure 12.3.8: Lions, hyenas and vultures compete for the carcass of a zebra.

Other mutualistic relationships include;

- the Egyptian plover (*Pluvianus aegyptius*), and the Nile crocodile. The bird feeds on parasites and food particles left around the crocodile's mouth, keeping its teeth clean and healthy. The crocodile openly invites the birds to hunt on its body, even allowing them to enter its mouth.
- coral polyps and the zooxanthellae which live inside them. Zooxanthellae photosynthesise to provide the organic

products to the coral, while the coral provides a sheltered location and access to sunshine.(Section 12.6)

- Root nodules found on the roots of legumes (peas, beans and clover). Nodules contain Rhizobium bacteria which fix nitrogen from the air and supply nitrogen compounds to the plants. The bacteria receive nutrients in return.

Predation: one species benefits, the other does not

When a lion, a hyena or a vulture feeds on a zebra they will benefit but the zebra population does not. **Predation** benefits the predator but not the prey species. Adaptations of predators and their prey are discussed later in this chapter.

Herbivory: one species benefits, the other does not

Herbivory is the process of an animal feeding on a plant. Different herbivores may feed on the same plant species at different times. For example, deer or moose may browse on the branches or bark of a tree in the autumn and winter but insect caterpillars attack the leaves in spring. In both cases the effect on the tree is a negative one.

KEY POINTS

herbivory refers to consumption of plant tissue for the purposes of nutrition.

predation is the process of an animal catching killing and eating a prey species.

Parasitism and pathogenic relationships: one species benefits, the other is harmed

Parasitism is a symbiotic interaction in which the parasite benefits while the host is harmed. Some parasites, such as fleas and lice, live on the surface of their host, while others live inside their host's body. The roundworm (*Ascaris* spp.) is an internal parasite that lives and feeds in the human intestine. The worms produce huge numbers of eggs, which pass out in the host's feces to the environment. People may be infected by swallowing the eggs in contaminated food or water. Some parasites eventually kill their host but most do not, as it would also result in the death of the parasite. More examples of parasites are described in Section 12.1.

Pathogens are any biological agent that causes disease or illness to its host. Human pathogens include strains of bacteria like *Salmonella*, *Listeria* and *Escherichia* coli which cause infections of the digestive system. Pathogens reproduce and thrive in their hosts' bodies but disrupt the normal physiology of the animal or plant they infect, causing them harm.

12.3.5 Chemical inhibition: allelopathy

Allelopathy is the chemical inhibition of one species by another and is important to plants, fungi and bacteria, which use it as a competitive strategy.

Plants release chemicals which inhibit the growth of other plants or prevent their seeds from germinating.

One example of this is the black walnut tree and butternut tree. The roots of these trees release a chemical called juglone which affects the roots and stems of other plants attempting to grow nearby. It also inhibits the other plants' seed germination (Section 12.1). The chemical is also found in all green and growing parts of the trees and in the unripe outer shells of their nuts. Juglone has been shown to inhibit respiration in plants that are sensitive to it and these affected plants cannot obtain energy for their metabolic activity.

Many plants also have germination-inhibiting substances in a wide variety of parts including fruits, leaves, bulbs and roots. These are usually non-specific in their effects and prevent the growth of their own seeds until conditions are favourable and may affect other seeds. For example, there is evidence that *Rhododendron ponticum* inhibits germination and growth of seeds and seedlings nearby. The main inhibitors are hydrogen cyanide, ammonia and ethylene, although the sap or extracts of some plants affect the local pH of the soil and inhibit seed germination.

Fungi and bacteria also release substances that kill or restrict the growth of other microorganisms. We use many of these substances as antibiotics to treat human bacterial infections because they are chemicals that kill or inhibit the growth of bacteria. All such chemicals are produced naturally by soil bacteria and fungi to enable them to compete with other microbes in their habitats. Penicillin is produced by a fungus *Penicillium*, and the antibiotics streptomycin, chloramphenicol and tetracycline are all derived from substances produced by soil organisms (Figure 12.3.9).

Figure 12.3.9: Four different antibiotic tablets have been placed on a petri dish in which bacteria are growing. Each has established a zone of inhibition around it as it releases antibiotic and kills bacteria.

Actinomycetes are fungi found in the soil that produce streptomycin and many of the antibiotics used in medicine today. Fungi also produce important inhibitors including cephalosporins, a class of antibiotics originally derived from the fungus *Acremonium*, and griseofulvin, which is produced by *Penicillium griseofulvum* to kill competing fungi. We use griseofulvin to treat fungal infections such as ringworm and athlete's foot.

No overall effect

Sometimes organisms or populations have no overall effect on one another. If there are no interactions or if direct influence is avoided then the organisms will coexist. This type of interaction enables the biodiversity of the ecosystem to increase.

Ecological relationships like these all affect the way organisms are distributed in an ecosystem and how many organisms can survive.

12.3.6 Features of relationships between predators, prey and plants

Predators catch, kill and eat other animals, known as their prey, to obtain energy and nutrients. The number of predators and their prey in an ecosystem will fluctuate (that is, increase and decrease) in relation to each other. If there are large numbers of predators the prey species will decrease in number. Likewise, if there are too few predators the population of the prey species may grow in size and could have the potential to damage or overgraze other areas of the ecosystem.

The relationship between the numbers of predators and their prey can be modelled mathematically. Data can also be collected from observations of predators and their prey in their habitats over long periods of time.

Predator–prey relationships

A well studied example of the effects of predation is that of the Canadian lynx, which feeds on the Arctic hare. Data were collected over a period of almost 100 years in the undisturbed cold, northern forests of Canada. The numbers of predator and prey fluctuated over the years with changes in the hare population being followed by corresponding changes in the numbers of lynx (Figure 12.3.10).

Snowshoe hare is the primary food of the lynx so the two population cycles are closely linked. When the hare population is high, lynx will eat about two hares every 3 days. Hare populations across the forest fluctuate in a cycle that ecologists have followed and which lasts 8–11 years. When their numbers are highest, snowshoe hares can reach a density of up to 1500 animals per km^2 and the habitat cannot support this many animals. With more hares in the forest, more are eaten as predation increases and starvation sets in as the hares overgraze the area. As this happens the hare population starts to decline.

When the hare population reaches its lowest level, it will remain stable for several years. The food plants slowly recover and the hare population starts to increase again. Since hares have several litters each year, the population increases rapidly. After 1 or 2 years at high densities, the hare population cycle repeats itself.

When the snowshoe hare population declines, the lynx population also declines after a lag of 1 or 2 years. At first as hare numbers start to decline, lynx continue to feed well because they can easily catch the starving hares.

But when hares become scarce, lynx numbers fall. Lynx do not have big reserves of fat and they starve in the freezing temperatures. Malnourishment significantly affects lynx reproduction and population levels. Females in poor condition are less likely to breed and produce litters.

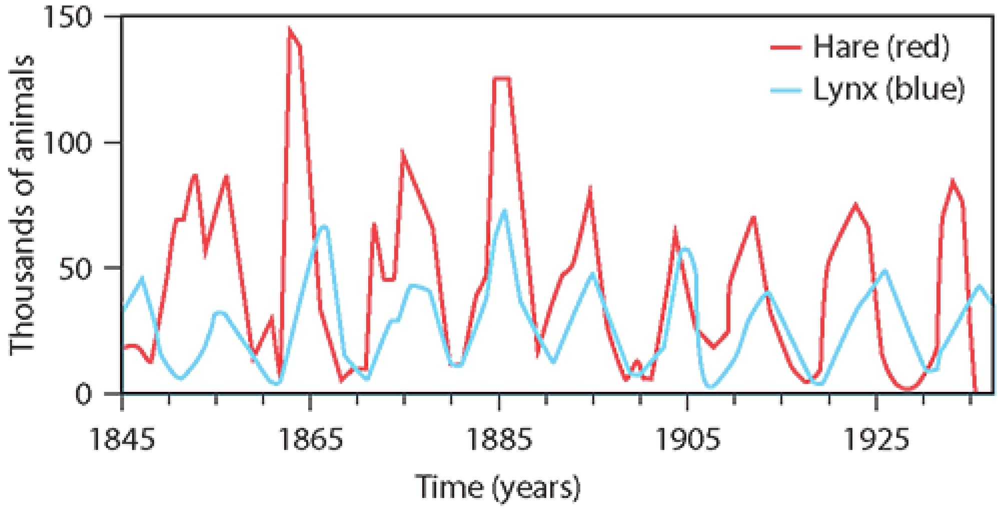


Figure 12.3.10: Changes in the populations of the Canadian lynx and the Arctic hare over time.

Their litters are smaller and many kittens die soon after birth. For a period of up to 5 years, few kittens survive to adulthood.

Avoiding predation

Prey animals do all they can to avoid being eaten and have a range of different defence mechanisms to protect themselves. Some of these defences are physical and some are chemical. Others are behavioural, such as hiding or running away.

Some examples of physical defences are outlined here**.**

- A porcupine's quills are used to deter leopards or other large predators (Figure 12.3.11).
- The crown-of-thorns starfish has venomous spines which give it physical and chemical protection.
- The shells of snails and other molluscs protect their soft bodies inside.
- Camouflage allows prey species to conceal themselves from passing predators.

Chemical defences are equally variable.

- The slow loris (Figure 12.3.12) is too slow to avoid predators by moving, so it coats its fur in poison which tastes unpleasant and discourages any predator that tries to eat it.

Figure 12.3.11: A porcupine can raise its quills to fend off large predators.

Figure 12.3.12: The slow-moving slow loris coats its own fur in a foul-tasting poison to protect itself from predators.

Figure 12.3.13: The bombardier beetle shoots a spray of hot chemicals into the path of approaching predators.

- Bombardier beetles (Figure 12.3.13) release a noxious spray of hydrogen peroxide and enzymes from their anus in an explosive burst. This is a mixture of hydrogen peroxide and enzymes that reaches a temperature of 100°C.

- Skunks release foul-smelling, foamy spray from their anal glands to drive away any animal that might threaten them.
- Millipedes can release hydrochloric acid, which can cause burns and irritation and has a bad odour.

Avoiding herbivory

Herbivory is the process of feeding on plants. Plants are food providers and parts of a plant will be lost as herbivores feed on them to grow and thrive. A single plant may provide leaves for browsing animals, fruits and seeds for birds, and roots for burrowing animals. Some plants have defence mechanisms against herbivores to protect themselves and stop or deter herbivores that try to eat them. These defences include spines, thorns and thick woody tissue. Many plants produce toxins that have a bad taste or contain substances that will harm a herbivore.

- Bougainvillea and roses both have thorns, which are modified stems.
- Spines are modified leaves or parts of leaves, such as extensions of leaf veins, and protect many types of cacti.
- Trichomes are much smaller structures formed from the outer layers of plant epidermis. Examples include the stinging structures of nettles which defend them against small insects and people.
- Some of the strategies which are used by coniferous trees are shown in Figure 12.3.14.

EXAM TIP

Remember that if an examination question asks you to ‘discuss’, it is important to present alternative points of view.

If you are asked to 'explain' a concept or situation, remember to include the steps in the process and write about them in some detail.

TEST YOUR UNDERSTANDING

21 List three different prey species and outline their methods of avoiding predation.

22 Define herbivory.

23 Suggest a defence strategy a plant might use to avoid being eaten.

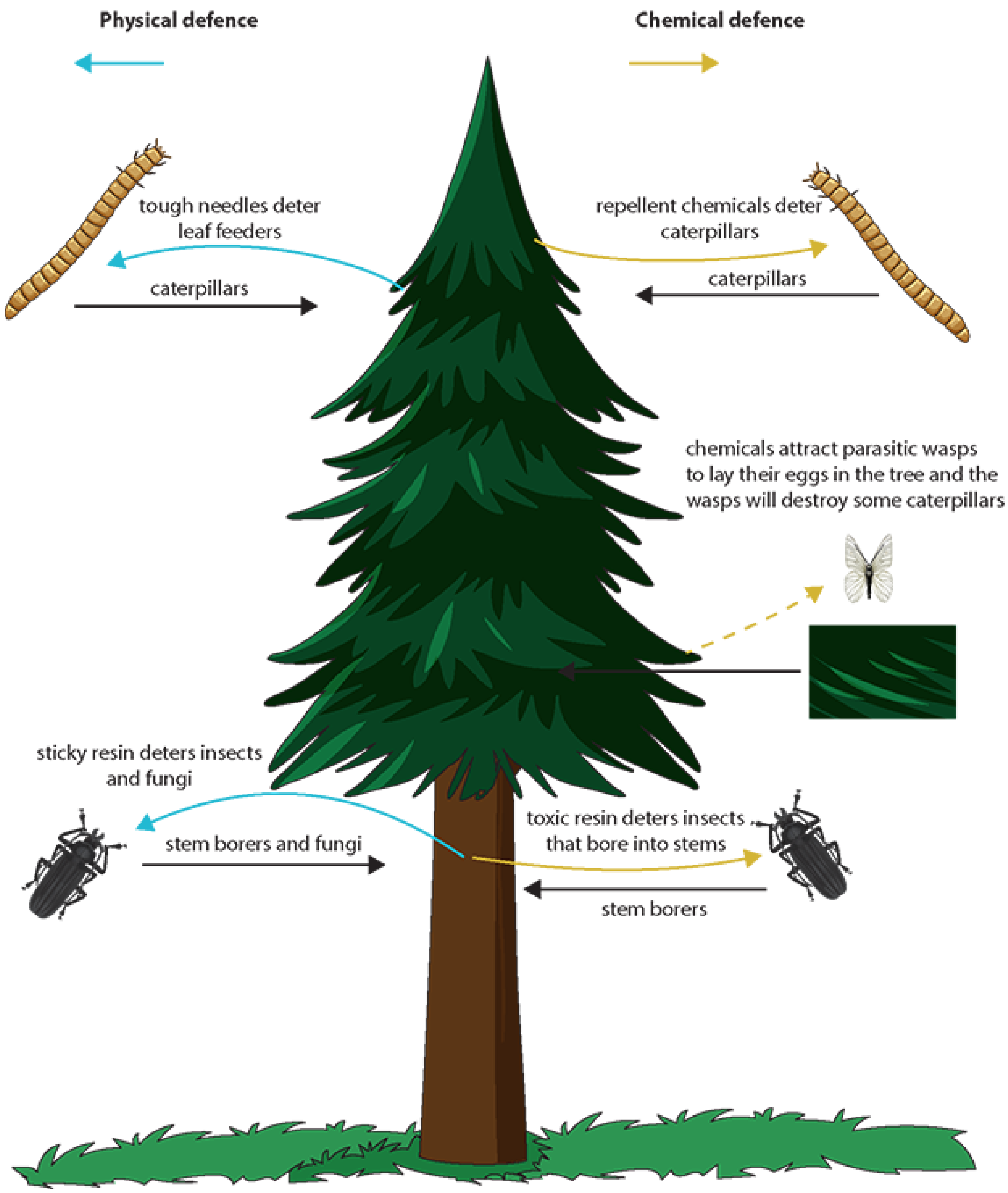


Figure 12.3.14: Some of the many strategies that plants, such as this pine tree, may have to deter herbivores that feed on them.

12.3.7 Cooperative interactions

Interspecific interactions

One type of cooperation between species is cooperative interspecific interaction, usually referred to as mutualism or mutualistic symbiosis. Earlier in this chapter we considered the cases of lichens and of plovers which feed on parasites on the body of crocodiles. Mutualism benefits both partners in an interaction, and there are many more examples of this type of relationship.

Plants form mutualistic relationships with fungi, forming **mycorrhizae**. A fungus will live either in or around the plant's root system and form part of that system (Figure 12.3.15). Mycorrhizae are important in providing the plant with nutrition and also affect the condition of the soil. As the plant photosynthesises it supplies the fungus with organic molecules such as sugars, while the fungus provides the plant with water and minerals from the soil.

Around 70% of plants have mycorrhizae with fungal hyphae (long branching filaments of the fungus, collectively called a mycelium) that penetrate the cells of the plants' roots. Inside the cells the hyphae branch to form arbuscules where nutrient exchange can take place (see Figure 12.3.15, right-hand side). In other plant species the mycorrhizae form a mycelium over the surface of the root and penetrate between the root cells (see Figure 12.3.15, left-hand side).

Both the plant and the fungus benefit from these arrangements. Plants with mycorrhizae can resist pathogens in the soil more effectively and some mycorrhizae release enzymes that combat soil pests such as nematode worms.

Bees and other pollinators of flowering plants also have mutualistic relationships in which both species benefit. Flowers provide bees with nectar and pollen, which worker bees collect to feed their colonies. Bees provide flowers with the means to reproduce by pollinating them as they spread pollen from flower to flower.

The majority of pollinators are insects – bees, butterflies, moths, flies, wasps and beetles – but many birds and bats are also important for some species of plant.

Plants always receive pollination services through the interaction, but the benefits received by the animal pollinators vary. Most receive food in the form of pollen or nectar, but some bees also use waxes and resins from flowers to build their hives.

Intraspecific interactions

Cooperative intraspecific relationships form between members of the same species. This may mean living together in small groups, such as lions living in families (prides), or in larger groups, such as zebra or wildebeest living together in a herd.

These relationships have both advantages and disadvantages for species that form such groups.

Advantages

There are many advantages to living with members of your own species. As well as social interactions, being a member of a herd or group allows protection from predators and the environment. It also gives access to information from other members of the group.

KEY POINT

cooperative interspecific interaction refers to the interaction between two species in which both species benefit, also known as mutualism.

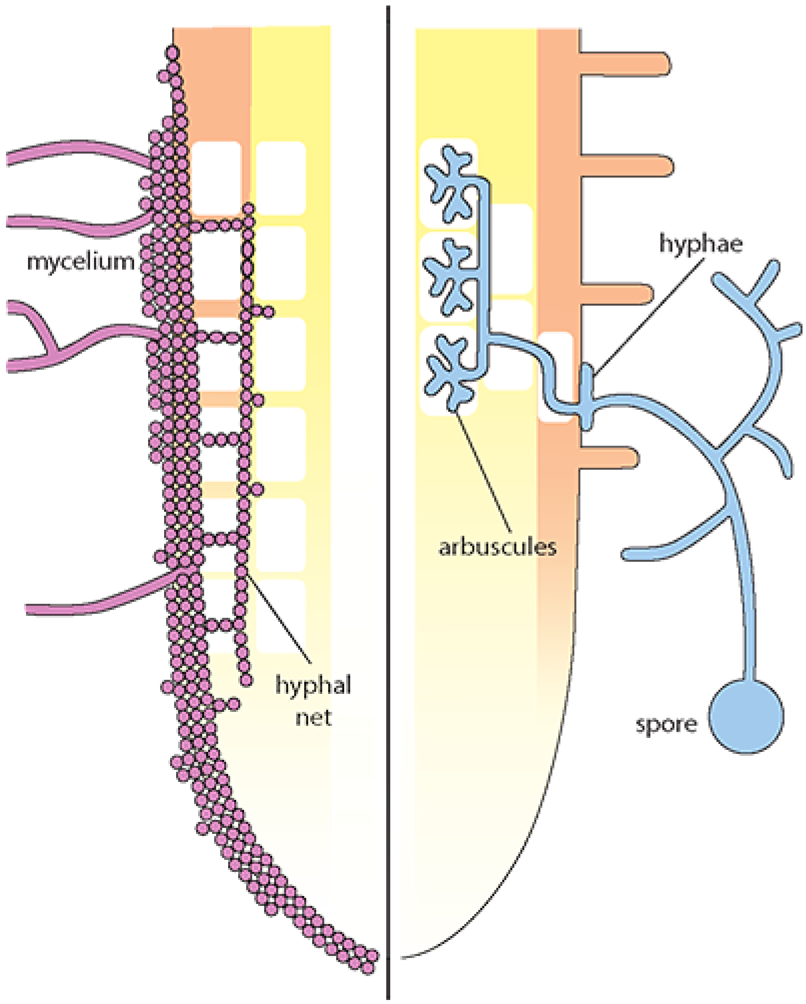


Figure 12.3.15: This diagram shows two ways in which fungi can form mycorrhizae. Some types of fungi have hyphae which penetrate root cells (right-hand side) others grow between the cells (left-hand side).

All these factors can increase the chances of survival for an individual in the group.

- **Protection from predation:** an individual in a group may be better protected from predation. Some members of the group can act as lookouts and watch for approaching predators. Herd animals such as zebra run together and confuse approaching predators by scattering in different directions. Some bird species use similar tactics. For example, a murmuration is a large group of starlings which form flocks and fly together in complex formations. In the largest, most densely packed groups, starlings are well protected from attacks by predatory hawks. This effect is known as the confusion effect and predators are less likely to succeed in catching prey as the prey group size increases.
- **Protection from extreme environments:** groups of emperor penguins huddle together in freezing conditions, protecting the individuals at the centre of the group. Penguins take turns on the outer edges of the huddle before moving to take their place in the warmer central area (Section 11.4).
- **Reproduction advantages:** animals living in groups are always closer to other members of their species, which are likely to be suitable mates for breeding. Once young are born other members of the group can assist with caring for them. Bats will suckle the young of other females from their roost if mothers are absent, and female lions often live in groups with their sisters who collectively guard and feed all the cubs in the pride.

Disadvantages

Living with members of your own species also has some disadvantages. There will be more competition for food and greater vulnerability to diseases that spread rapidly between organisms that are close together. Some of these factors can be detrimental to an individual’s survival.

- **Availability of resources:** if many members of the same species live together they will all require similar food, space and access to mates. Intraspecific competition will occur and decrease the availability of these resources. For example, in the case of the snowshoe hare, described in the section on predator – prey relationships, there will be insufficient food for all members of the group if population numbers rise too much.
- **Risk of infections:** living closely together will increase the likelihood that disease can pass quickly between individuals. Pneumonia can spread among populations of bighorn sheep as well as animals such as goats. Tuberculosis occurs and spreads through herds of buffalo, bison and deer, and many other intraspecific interactions cause the spread of parasites such as tapeworms, fleas and ticks.
- **Attracting consumers:** herbivores are more likely to feed where there is an abundance of their preferred food plants growing together. For example, small birds are more likely to visit bushes that are covered in berries, if the bushes are growing in dense clumps. Similarly predatory animals will be attracted to feed where there are many of their prey species living closely together.

Limiting factors and populations

Top-down limiting factors

Top-down limiting factors are those that involve an organism higher up the food chain limiting the numbers of a species at a lower trophic level, usually through predation or herbivory. One example of this is the control of the small algae (Fucus spp.) on a rocky shore by grazing limpets (Section 11.4 Nature of Science). Another example is the control of kelp forests due to the impact of sea otters. Otters feed on sea urchins, which use kelp as a source of food so if sea otter numbers fall, the sea urchin populations expand and reduce the kelp forest. Ecosystems such as those where sea otters and limpets are found are not controlled by the productivity of the primary producer but rather by a top predator or major herbivore acting as a keystone species.

Bottom-up limiting factors

Bottom-up control by limiting factors occurs where the nutrient supply and productivity of primary producers (plants and phytoplankton) control the structure of the ecosystem. In marine coastal ecosystems, plankton populations depend on and are controlled by the availability of nutrients. Phytoplankton populations increase so that large growths known as algal blooms appear when nutrients are abundant. This happens when sea currents cause upwelling, which brings nutrients to the surface where they are accessible to phytoplankton. The abundant growth of phytoplankton is then controlled by top-down control by herbivores, which use it as food. Algal blooms are also controlled by bottom-up control at times when nutrients are in short supply or in places where currents do not bring nutrients to the surface.

Limiting factors and ecosystem stability

Bottom-up and top-down control tends to keep a stable population at the carrying capacity of the ecosystem. The bottom-up resources set the limit for the maximum sustainable population, while top-down control removes individuals from a large population, with the result that resources are not over-exploited. The concept of internal control of populations by interactions between them is a key argument for the conservation of ecosystems.

12.3.8 Keystone species

A keystone species is one which has a disproportionate impact on an ecosystem and strongly affects community structure. Examples of keystone species include the sea otter, elephants and the prairie dog.

Keystone species are an example of top-down limiting factors. These factors involve an organism higher up the food chain limiting the numbers of a species at a lower trophic level, usually through predation or herbivory. One example is the control of kelp forests by the feeding activities of sea otters. Kelp forests are underwater areas found around many coastal areas. A high density of kelp plants results in a productive and dynamic ecosystem that is an important source of nourishment and shelter for fish and other sea animals. Kelp is eaten by sea urchins and sea otters that then feed on sea urchins.

But sea otters have thick, rich fur and became a target for hunters who, by the 1900 s, had brought the animal close to extinction. In the end, an international ban on sea otter hunting was imposed in 1911, saving the animal from complete extinction. Researchers discovered that around coastal islands that lacked sea otters, sea urchins had increased in size and in numbers with devastating consequences. The forests of kelp had disappeared, and large sea urchins were found on the empty sea floor, having consumed all the kelp plants in the area. Close to islands where sea otters had survived, or had been reintroduced, the kelp forests were alive and healthy.

Figure 12.3.16: Sea otters (*Enhydra lutris*) feed on sea urchins and are a keystone species

Sea otters are keystone species because if sea otter numbers fall, the sea urchin populations expand and reduce the kelp forest. The ecosystem is not controlled by the productivity of the autotrophic organisms but rather by a top predator acting as a keystone species. By almost wiping out sea otters, humans upset vital feeding relationships. Sea otters remain an endangered species but now we realise that high otter numbers mean fewer sea urchins, which in turn mean abundant healthy kelp forests, and a more diverse ecosystem.

INTERNATIONAL MINDEDNESS