light speckled colour. The much less common dominant form gives rise to the black, melanic moth.

In the polluted areas of Britain, the speckled form was no longer camouflaged on the blackened tree bark, and was easily seen by birds that ate speckled moths. The black moths were better suited to the changed environment because they were camouflaged. Black moths survived and bred, and the proportion of black moths with the dominant allele grew in the population.

In 1956, the Clean Air Act became law in Britain and restricted air pollution. Lichen grew back on trees and their bark became lighter. As a consequence, the speckled form of the peppered moth has increased in numbers again in many areas, and the black form has become less frequent.

Antibiotic resistance

Antibiotics are drugs that kill or inhibit bacterial growth. Usually, treating a bacterial infection with an antibiotic kills every invading cell. But, because of variation within the population, there may be a few bacterial cells that can resist the antibiotic. These individuals will survive and reproduce. Because they reproduce asexually, all offspring of a resistant bacterium are also resistant, and will survive in the presence of the antibiotic. In these conditions, the resistant bacteria have enormous selective advantage over the normal susceptible strain, and quickly out-compete them.

Treating a disease caused by resistant strains of bacteria becomes very difficult. Doctors may have to prescribe stronger doses of antibiotic or try different antibiotics to kill the resistant bacteria.

The problem of antibiotic resistance is made more complex because bacteria frequently contain additional genetic information in the form of plasmids, which they can transfer or exchange with other bacteria, even those from different species. Genes for enzymes that can inactivate antibiotics are often found on plasmids, so potentially dangerous bacteria can become resistant to antibiotics by receiving a plasmid from a relatively harmless species. Many bacteria are now resistant to several antibiotics (Figure 11.2.2), so pharmaceutical companies are constantly trying to develop new antibiotics to treat infections caused by these multiply resistant forms of bacteria.

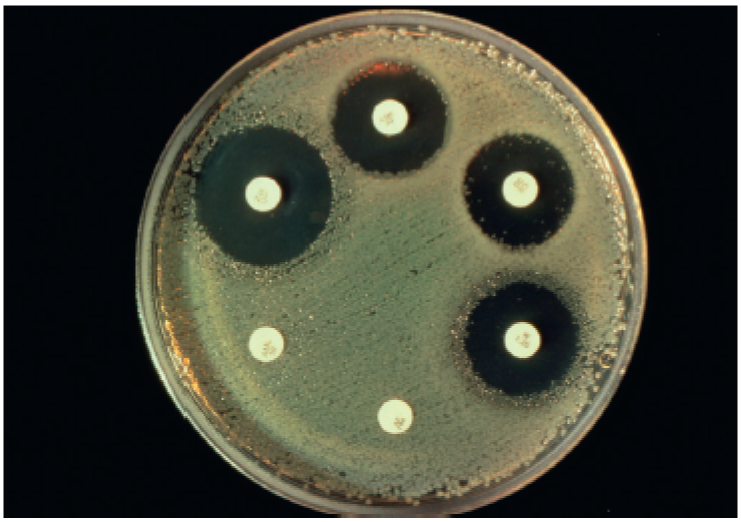

Figure 11.2.2: The grey–green areas on the agar jelly in this Petri dish are colonies of the bacterium *Escherichia coli*. The white card discs are impregnated with different antibiotics. This strain of *E. coli* is resistant to the antibiotics at the bottom left and has been able to grow right up to the discs. The other discs have a 'zone of inhibition' around them because those antibiotics kill the *E. coli* cells.

Resistance to pesticides

Pests including rodents, weeds and insects can develop resistance to pesticides that humans have developed to control them. Pest species develop resistance as a result of natural selection as the individuals that are most resistant to a pesticide survive and pass on their resistant genes to their offspring. Many pest species produce large numbers of offspring and this increases the probability of mutations and the rapid spread of resistant populations. Pesticide resistance is a serious problem for agriculture all over the world. Pests consume between 10 and 20% of all global crops either while they are growing or when they are stored.

Some examples of species that have become resistant to pesticides include rats which have developed resistance to the rodenticide warfarin. In Europe some resistant rat populations can still survive after eating five times more of this pesticide than normal rats. New pesticides now have to be used to kill them.

Plant pest species include many of the weeds that grow in maize, cotton and soybean farms. In the USA several species of these weeds are now resistant to the herbicide glyphosate. Resistant weeds can often survive application of herbicide at rates that are much greater than the recommended rate. While in Australia over 25 weed species now have populations that are resistant to at least one of the herbicides that are used there.

Insecticide resistance has also occurred as pesticides have been applied over large areas and resistant genes have spread rapidly through insect populations. One example of resistant insect species is the Colorado potato beetle which has developed populations resistant to all the commercially produced insecticides that have been used against them.

11.2.3 Artificial selection

People have altered certain domesticated species by breeding selected individuals in a process called artificial selection. Plants or animals with favourable characteristics are chosen and bred together, to increase the number of offspring in the next generation that have the favourable characteristics. Individuals that do not have the desired features are not allowed to breed. People have domesticated and bred plants and animals in this way for thousands of years and, over many generations, this has resulted in the evolution of numerous breeds and varieties, which differ from each other and from the original wild ancestors.

Modern varieties of wheat, barley, rice and potatoes produce higher yields and are more resistant to pests and disease than ever before. Wheat and rice plants are shorter and stronger than varieties from 100 years ago, so that they are less likely to be damaged by wind and rain and are easier to harvest. The plants of 100 years ago were also very different from the original grasses that wheat was bred from 10 000 years ago. Many plants are bred for their appearance, and ornamental varieties have different petal shapes and colours from the original parent stock.

Animals are chosen and bred by farmers and animal breeders for special characteristics such as high milk yield in a cow, or good-quality wool in a sheep. Individuals with these characteristics are selected to breed, so that more of the next generation have these useful features than if the parents had not been artificially selected (Figure 11.2.3).

Although the driving force for artificial selection is human intervention, which is quite different from natural evolution, selective or artificial breeding does show that species can change over generations.

But selective breeding can remove some genes from populations and lead to a limited gene pool (Sections 11.2.4 and 11.3). A population of selected plants or animals may have reduced genetic diversity and may become less healthy as a result.

We can see how this can happen in the breeding of certain animals where there have been negative effects on the health of animals. Pedigree dogs, like animals used in farming have particular characteristics such as height or type of fur that people select when breeding them. But some dog breeds such as bulldogs and labradors have a higher incidence of conditions such as heart disease or abnormal hip joints. Artificial selection has led to some genes being lost from the dogs' gene pool resulting in less healthy animals.

KEY POINTS

artificial selection selective breeding of domesticated organisms by humans.

gene pool all the genes and their alleles present in an interbreeding population.

Figure 11.2.3: Selective breeding of cows over many centuries has produced many breeds including the Guernsey, bred for the production of large quantities of fat-rich milk. Other breeds have been produced with flat backs to make giving birth easier, or thick fur to survive in colder regions.

11.2.4 Gene pools

Processes that increase or decrease variation in a population alter the proportions of alleles in a gene pool, which is all the genes and their alleles present in a population.

Natural populations can gain alleles when then are introduced from other gene pools, for example when new individuals immigrate, or move into an area. In a similar way, alleles can be lost from a gene pool if individuals leave, or emigrate, or if certain alleles are artificially bred out of a population. The examples of domestic farm animals and pedigree dogs show us that selective breeding for chosen characteristics runs the risk of losing some genes from the gene pool altogether and once they have been lost from a population, the loss cannot be reversed unless organisms from other populations are reintroduced. This can happen in natural populations as well as artificially bred plants and animals and lead to a problem known as inbreeding depression which reduces a population due to a lack of healthy mates and low genetic diversity.

KEY POINT

inbreeding depression reduction in the fitness of a population due to a lack of healthy mates and low genetic diversity.

One example of this was seen in Sweden where populations of adders became isolated from others due to farms that separated their territories. The snakes could only breed with members of their own small populations. As a result, the snakes not only gave birth to offspring with defects, but also suffered a decrease in breeding success. A loss of genes which leaves a limited gene pool can result in populations with many individuals with similar genes as they only breed with others who also have them. In Sweden new adders were taken to breed with the isolated snakes and the populations recovered and flourished. But for endangered species this solution cannot work because there are not enough individuals to replenish the population.

You can read more about the importance of changes in gene pools and their effect on evolution in Section 11.3.

NATURE OF SCIENCE

Scientific theories and evidence

Natural selection is a theory. In science, the term 'theory' has a very specific meaning. Scientific theories require a hypothesis that can be tested by gathering evidence. If any piece of evidence does not fit in with the theory, a new hypothesis must be put forward and more scientific evidence gathered. It is important to recognise the difference between a theory and a dogma, which is a statement of beliefs that are not subject to scientific tests. Since Darwin's time, a large amount of evidence has been collected to support his theory. With technologies such as DNA profiling and carbon dating, further evidence continues to accumulate and must be tested against the theory.

To consider:

1. How much evidence is needed to support a theory?
2. What kind of evidence is needed to refute a theory?
3. Will it ever be possible to prove that evolution has taken place?

TEST YOUR UNDERSTANDING

7 Explain why sexual reproduction is important for evolution.

8 Individuals in a population are often said to be ‘struggling for survival’. Name the key factor that causes this struggle.

9 If an environment changes, individuals with particular combinations of genes are more likely to survive. State the name given to this phenomenon.

10 Define the term ‘speciation’.

11.2.5 Types of selection

Allele frequency and evolution

Evolution is defined as the cumulative change in the heritable characteristics of a population. The ‘heritable characteristics’ referred to in this definition are all the alleles in the gene pool of a population. So, if the frequencies of these alleles in the gene pool do not change, then the population is not evolving. Allele frequencies in a population are always fluctuating, in fact, because they depend on the reproductive success of individuals. But if just a single allele shows a change in frequency over a prolonged period of time, then we can say that the population has evolved. Any process that allows favourable alleles to be passed on or prevents the inheritance of unfavourable alleles can contribute to evolution.

Modes of natural selection and change

In any population, an individual can have any combination of the alleles present in the gene pool. This gives rise to variation in the population. In most cases, a population will be well adapted to its environment and so the same alleles will be selected, maintaining a stable population. This is known as **stabilising selection** (Figure 11.2.4).

If the environment, changes the population may also change. Some individuals may have alleles that are more favourable in the new conditions and these alleles will provide an advantage to those individuals, making them more likely to survive and reproduce successfully. This will result in a change in the population, known as **directional selection** and lead to the prevalence of new forms.

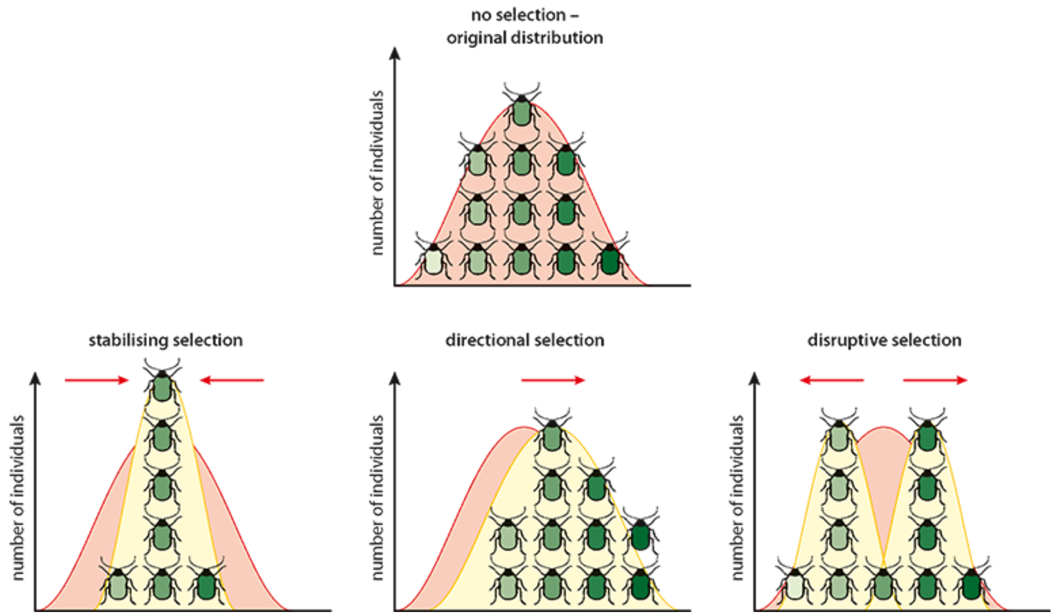

Figure 11.2.4: In these examples three kinds of selection change the colour of beetles – a feature that is controlled by several genes. Stabilising selection eliminates extreme forms, directional selection favours dark coloured beetles and disruptive selection eliminates the 'average' form and leads to two distinct forms.

A third possibility is that natural selection results in the formation of two new forms from a single existing population. This is known as **disruptive selection**.

Sexual selection

Sexual selection is a special example of natural selection. It affects an organism's ability to obtain a mate. As individuals select mates with characteristics that favour survival, the overall resilience of a population, that its ability to recover quickly from changes in the environment, will also be increased.

Many organisms have extreme features or behaviours to do this. Examples include the elaborate tails of male peacocks, battles between males over territories and growth of extremely large horns or antlers. But sexual selection can sometimes produce features that are harmful to an individual. For example, brightly coloured feathers may attract predators as well as mates.

KEY POINTS

allele frequency the percentage of a population that carries an allele at a particular locus. It is also sometimes referred to as gene frequency.

resilience the ability of a population to recover quickly from changes in the environment.

Sexual selection can come about because a characteristic such as the antlers of a stag increases its abilities in competition with members of the same sex. Stags, rams and bulls use antlers or horns in contests of strength and a male that is successful in battle usually secures more female mates.

The elaborate tail of the peacock (*Pavo cristatus*) has fascinated biologists for many years (Figure 11.2.5). Why did such an impractical structure evolve? Research in the 1990s revealed that females prefer not only males with long tails but also those with more eye spots on their tails. Females probably prefer these males because they are likely to produce attractive and therefore reproductively successful male offspring, or because a large tail is a sign of good health. Evidence also suggests that the number of eye spots on a tail can be correlated with the numbers of B and T cells the male produces, which is a sign of a well functioning immune system.

Figure 11.2.5: The tail of a male peacock produces a colourful display to attract female birds.

It seems that females choose mates for their appearance and that a large unwieldy tail does not reduce the male's survival chances.

Factors that affect allele frequencies in populations

Over a period of time, directional selection will lead to an increase the frequency of a favoured allele. For example, if three genotypes – **BB**, **Bb** and **bb** – vary so that **BB** individuals produce more offspring than the other genotypes, the **B allele** would become more common with each generation. The rate at which an advantageous allele approaches the point where it is 'fixed' and is the only variant of the allele in the population can be shown in a graph (Figure 11.2.6). The initial increase in frequency of an advantageous, dominant allele that is rare at first is more rapid than that of a rare, but advantageous, recessive allele. A recessive allele cannot become fixed until it is frequent enough to occur in homozygous organisms but a new dominant allele has an immediate effect on heterozygous individuals.

Another important factor in determining allele frequency is genetic drift. Genetic drift is defined as a change in allele frequency in a gene pool due to chance events.

KEY POINTS

fixed an allele that is the only variant of that gene that is present in a population. It is homozygous in all members of the population.

genetic drift a change in allele frequency in a gene pool due to chance events.

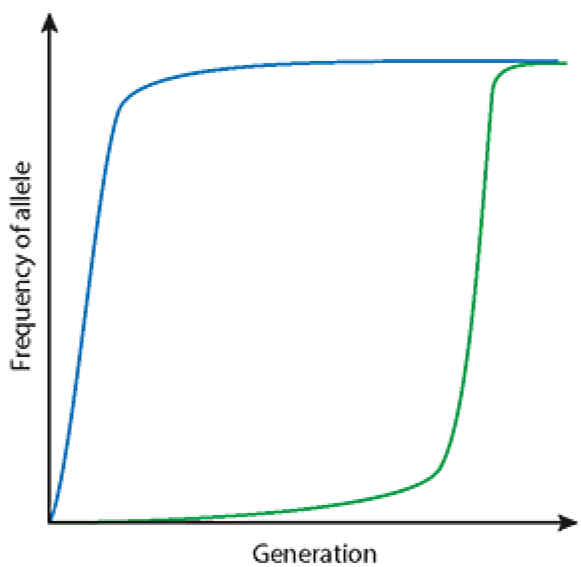

Figure 11.2.6: Graph to show how allele frequencies change under directional selection that favours a dominant advantageous allele (blue curve) and that which favours a recessive advantageous allele (green curve).

It can cause gene pools of two isolated populations to become dissimilar, as some alleles are lost and others become fixed. Genetic drift can occur when a small number of ‘founders’ (new colonisers) separate from a larger group and establish a new population. Founding individuals carry only a small part of the total diversity of original gene pool, and the alleles that they have is determined by chance alone, which means that rare alleles, or rare combinations of alleles, may occur in higher frequencies in the new isolated population than in the general population. This is called the ‘founder effect’.

Many island populations of species, such as Darwin’s finches on the Galápagos Islands, display founder effects and may have allele frequencies that are very different from those of the original population.

The finches living on the Galápagos Islands (Figure 11.2.7), about 900 km off the coast of Ecuador, were important in shaping Darwin’s ideas about natural selection. Studies of the birds, now known as Darwin’s finches, continue to this day and modern DNA analysis indicates that all 13 species now found on the islands probably evolved from a small flock of about 30 birds that became established there around 1 million years ago.

When the birds first arrived, the Galápagos Islands were probably free of predators and initially the resources were sufficient for all the individuals. As the population grew, the finches started to adapt their feeding habits to avoid competition and as each group selected different foods, they developed differently as gene and allele frequencies changed. Eventually a number of separate species were established. Today we recognise 13 different species including the cactus finch which has a long beak that reaches into blossoms, the ground finch with a short stubby beak adapted for eating seeds buried under the soil, and the tree finch with a parrot-shaped beak suited for stripping bark to find insects (Figure 11.2.8).

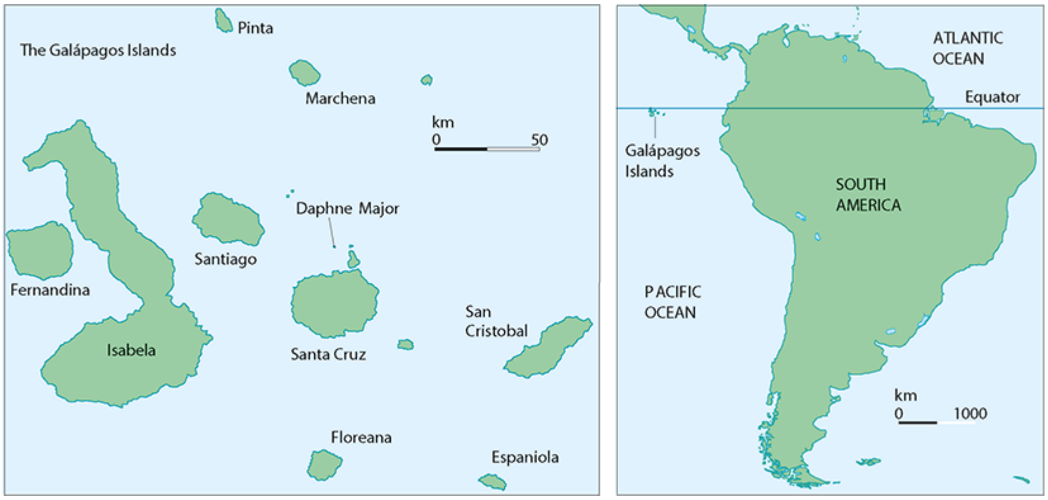

Figure 11.2.7: The Galápagos islands.

Figure 11.2.8: The tree finch, the ground finch and the cactus finch all have very different alleles from the original population of finches that arrived on the Galápagos Islands about 1 million years ago.

One human example of the founder effect is that of the German immigrants who first arrived in present-day Pennsylvania, USA, from Europe in the 16th century, and formed the Amish community. This group of new colonisers did not have all the genetic variation of the human species, or even of the European population, so the allele frequencies in their gene pool were different from those in the wider human population. For instance, a condition called Ellis–Van Creveld syndrome (a form of dwarfism with polydactyly, or additional fingers and toes) can be traced back to Samuel King and his wife, who arrived in Pennsylvania in 1744. Today, the gene causing the syndrome is many times more common among the Amish people, who tend to marry within their own community, and demonstrates how the genes of the 'founders' of a new community are disproportionately frequent in the population from that point on.

11.2.6 The Hardy–Weinberg principle

Godfrey Hardy, an English mathematician, and Wilhelm Weinberg, a German doctor, were two scientists who worked at the start of the 20th century and produced mathematical models of the frequencies of alleles in the gene pool. They concluded that if allele frequencies were stable, they could be calculated with a simple equation based on Mendelian genetics. As a species changes, the frequency of alleles in the population changes. The Hardy–Weinberg equation is used to calculate and model allele frequencies.

The formula is
$p^2 + 2pq + q^2 = 1$

where p = frequency of the dominant allele and q = frequency of recessive allele. If the frequencies of the alleles at a specific locus are considered, then $p + q = 1$ because chromosomes that do not have the dominant allele must have the recessive one.

Using the Hardy–Weinberg equation

If a gene has two alleles, **A** and **a**, the frequency of the dominant allele **A** is represented by p and the frequency of the recessive allele a is represented by q.

In a population of 100 individuals there will be 200 alleles. If 170 of these are the dominant allele then the remainder must be the recessive allele.

$$= \frac{170}{200} \times 100 = 85\% \text{ and } q = \frac{30}{200} \times 100 = 15\%$$

Populations are always represented by 1 so in this example p would be 0.85 and q would be 0.15.

In a randomly mating population, the possible combinations of alleles can be determined from a Punnett grid:

		Male allele	
		A	**a**
Female allele	**A**	**AA**	**Aa**
	a	**Aa**	**aa**

If the alleles are replaced with their frequencies:

		Male allele	
		Frequency of dominant allele **A** (p)	Frequency of recessive allele **a** (q)
Female allele	Frequency of dominant allele **A** (p)	p^2	pq
	Frequency of recessive allele **a** (q)	pq	q^2

The four genotypes represent the total population, which is always 1. So the equation becomes:
$p^2 + 2pq + q^2 = 1$

Conditions for using the Hardy–Weinberg equation

Mathematical models like the Hardy–Weinberg equation are used to predict what happens in nature. Any model can only work if certain assumptions are made. This is because all natural systems are very complex and have many factors that affect them. A model is a simplified version of a complex system.

Evolution is the change in frequency of an allele in a gene pool, so if the frequency remains constant then the population is not evolving. But populations do evolve as a result of selection pressures on them so Hardy and Weinberg outlined seven assumptions. They allow the equation to be used and applied to allele frequencies in a population that is not evolving:

1 There is no mutation that affects allele frequencies.

2 There is no natural selection: the frequency of alleles over time should not vary.

3 The population is large, because the equation is based on proportions and percentages, and larger numbers increase the reliability of the model.

4 All members of the population breed.

5 Mating is random between individuals who have the alleles and the equation does not work for alleles on the sex chromosomes.

6 Each mating produces the same number of offspring.

7 There is no immigration or emigration to alter allele frequencies.

WORKED EXAMPLE 11.2.1

Phenylthiocarbamide (PTC) is a substance that to some people tastes very bitter and to others is tasteless. The ability to taste PTC is controlled by a dominant allele (T).

Two populations of people were sampled: indigenous Aborigine population in Australia and the Quechua people of Peru. Both sample sizes were 500. In the Australian sample, 245 people were non-tasters and in the Quechua sample 20 people were non-tasters. Calculate the allele frequencies in these two groups.

Answer

Step 1 Non-tasters must be homozygous recessives (**tt**) and are therefore represented by q^2.

Step 2 For the Australian sample the proportion of people who are non-tasters is calculated as:

$$\frac{245}{500} = 0.49$$

So, $q^2 = 0.49$

Therefore, $q = 0.7$

The frequency of the non-tasting allele among the indigenous Aborigine population in Australia is 0.7.

Step 3 Since $p + q = 1$

$p = 0.3$

The frequency of the tasting allele in the Australian sample is 0.3.

Step 4 In the sample of the Quechua people, 20 were non-tasters so the proportion of Quechua people who are non-tasters is:

$$\frac{20}{500} = 0.04$$

So, $q^2 = 0.04$

Therefore, $q = 0.2$

The frequency of the non-tasting allele among the Quechua people is 0.2.

Step 5 Since $p + q = 1$

$p = 0.8$

The frequency of the tasting allele among the Quechua people is 0.8.

TEST YOUR UNDERSTANDING

11 Suggest why a changing environment is likely to favour disruptive selection.

12 Outline an example of sexual selection and how it benefits the species that you name.

REFLECTION

Reflect on the most important things you have learnt in this section.

Links

- How can climate change influence the survival of species? (Chapter 12.6)

11.3 Evolution

LEARNING OBJECTIVES

In this section you will:

- define a species as a group of organisms that share common characteristics and can interbreed to produce fertile offspring
- learn that all species have originated from a common ancestor by evolution
- define evolution as cumulative change in the heritable characteristics of a population
- describe the evidence for evolution from fossils, observation of phenotypes, selective breeding and comparisons of DNA sequences
- learn that population can diverge into separate species and define speciation as the process which forms new species
- learn that speciation occurs when two populations of a species are isolated by geography, behaviour or time and evolve differently
- recognise how infertile hybrids isolate evolving populations and prevent mixing of alleles between them

> define a gene pool as all the genes and alleles in an interbreeding population

- learn that evolution requires allele frequencies to change with time in populations
- learn that reproductive isolation can be temporal, behavioural or geographic
- discover that speciation of isolated populations can be gradual or occur abruptly.

GUIDING QUESTIONS

- How is evolution driven by natural selection?
- How do new species arise?

11.3.1 What is evolution?

Over long periods of time and many generations, the genetic make-up of species may change as they become adapted to new surroundings or altered conditions. One result of these changes may be the evolution of new varieties and species. There is strong evidence for the evolution of life of Earth, both from fossils and from organisms that are alive today. Natural selection provides an explanation of how evolution might have occurred.

KEY POINTS

evolution cumulative change in the heritable characteristics of a population.

species a group of organisms that share common characteristics and can interbreed to produce fertile offspring.

Life on Earth is always changing. Just by looking at any group of individuals of any species – whether humans, cats or sunflowers – you can see that individuals are not all the same. For example, the people in Figure 11.3.1 vary in height, hair colour, skin tone and many other ways. How do the differences within a species occur? How do different species arise?

A species is defined as a group of organisms that share common characteristics and can interbreed to produce fertile offspring. Variation within a species is a result of both genetic and environmental factors. We say that selection pressures act on individuals and because of variation, some may be better suited to their environment than others. These are likely to survive longer and have more offspring.

Figure 11.3.1: Most of the variation between humans is continuous variation and is influenced by the environment as well as genes.

The characteristics of a species that are determined by the genes are inherited and passed on to succeeding generations (Section 4.3). The cumulative change in these heritable characteristics over generations is called evolution. If we go back in time, then existing species must have evolved by divergence from pre-existing ones. All life forms can therefore be said to be linked in one vast family tree with a common origin that has changed and developed over time. You can read more about convergent and divergent evolution of the forms and functions of organisms in section 11.4.3.

11.3.2 Evidence for evolution

Evidence for evolution can be gathered from a number of different sources including evidence from fossils, observations of organisms alive today and studies of DNA base sequences. Evidence like this can enable us to build up a picture of how the organisms we see today have evolved.

The fossil record

Fossils, such as the one shown in Figure 11.3.2, are the preserved remains of organisms that lived a long time ago. They are often formed from the hard parts of organisms, such as shell, bone or wood. Minerals seep into these tissues and become hardened over time. As the living tissue decays, the minerals form a replica that remains behind. Soft tissue can sometimes be preserved in the same way, as can footprints and animal droppings. Most fossils become damaged over time or are crushed through land or sea movement, but some are discovered remarkably well preserved. The earliest fossils found date from over 3 billion years ago, so the time scale of the fossil record is immense. Most fossils are of species that died out long ago, because they did not adapt to new environmental conditions.

KEY POINT

fossil record a history of life found in the fossil remains of organisms from long ago preserved in sedimentary rock.

The study of fossils is called palaeontology. Palaeontologists have been collecting and classifying fossils for over 200 years, but they have only been able to work out how old they are since the 1940s. Scientists can estimate when a fossilised organism might have lived by studying the amount of natural radioactivity in the fossils they find. This process is called radiometric dating. Over time the amount of radioactivity decreases because radioactive elements decay. The rate of decay is fixed for each element, so it is possible to date a fossil by measuring the amount of radioactivity present in it and so determine the time that has passed since it was formed. Carbon-14 is used to study material up to 60 000 years old. For older material, other elements are used.

Figure 11.3.2: A fossil of *Archaeopteryx*, which is seen as an evolutionary link between reptiles and birds. It looked like a small dinosaur, but it had feathers and could fly.

Although the fossil record is incomplete and fossils are very rare, it is possible to show how modern plants and animals might have evolved from previous species that existed hundreds or thousands of millions of years ago. It is important to recognise that we can never say that ‘this species evolved into that species’, based on a fossil sequence, even when we have many fossils. All that we can say is that species appear to be related, that they probably share a common ancestor. Other species may have existed too, for which no fossils have ever been found.

A few organisms seem to have changed very little. The horseshoe crab we see today is very similar to fossil specimens that are 1 million years old. This suggests that there has been little selection pressure on these crabs.

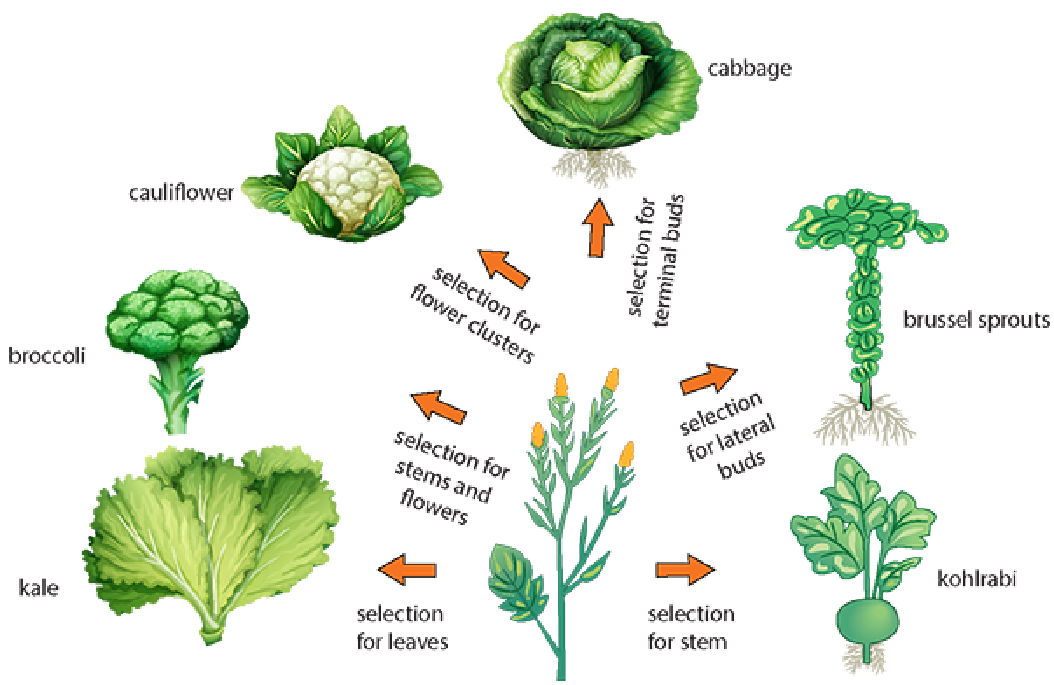

Figure 11.3.3: Selective breeding of the wild mustard plant *Brassica oleracea* has produced a variety of different food plants.

Observations of fossils provide evidence that life on Earth changes and that many of the changes occur over millions of years.

Selective breeding

Further evidence for the way evolution occurs comes from observations of selective breeding. People have altered the balance of alleles and the characteristics of domesticated species by breeding selected individuals in a process called artificial selection (Section 11.2). Plants or animals with desirable characteristics are chosen and bred together so that the numbers of offspring in the next generation with these characteristics increase. Individuals that do not have the desired features are not allowed to breed. People have selected plants and animals in this way for thousands of years and, over many generations, this has resulted in the evolution of numerous breeds and varieties, which differ from each other and from their original wild ancestors (Figure 11.3.3).

Direct observations of phenotypes: the work of John Endler

Canadian biologist John Endler studied wild guppies (*Poecilia reticulata*) in Trinidad in the 1970s. He noticed that there was a wide variation in colour among guppies from different streams and even among guppies living in different parts of the same stream. Males from one area could be bright blue with orange patches along their sides, while those further downstream were less brightly coloured with fewer patches. Endler recorded differences in the distribution of guppies and their predators, and also the background colours of the gravel in the different streams. He discovered a clear correlation between location and colouration in the fish and carried out experiments to test his hypothesis. His experiments show how selection can work to increase desirable characteristics and remove those which are not favourable for survival.

Figure 11.3.4: *Poecilia reticulata* is a species of guppy that is found in Trinidad. Male coloration depends on the presence or absence of predators.

cow	A T G - - - A C T A A C A T T C G A A A G T C C C A C C C A C T A A T A A A A A T T G T A A A C
sheep	A T G - - - A T C A A C A T C C G A A A A A C C C A C C C A C T A A T A A A A A T T G T A A A C
goat	A T G - - - A C C A A C A T C C G A A A G A C C C A C C C A T T A A T A A A A A T T G T A A A C
horse	A T G - - - A C A A A C A T C C G G A A A T C T C A C C C A C T A A T T A A A A T C A T C A A T
donkey	A T G - - - A C A A A C A T C C G A A A A T C C C A C C C G C T A A T T A A A A T C A T C A A T
ostrich	A T G G C C C C C A A C A T T C G A A A A T C G C A C C C C C T G C T C A A A A T T A T C A A C
emu	A T G G C C C C T A A C A T C C G A A A A T C C C A C C C T C T A C T C A A A A T C A T C A A C
turkey	A T G G C A C C C A A T A T C C G A A A A T C A C A C C C C C T A T T A A A A A C A A T C A A C

Figure 11.3.5: DNA base sequences from eight vertebrate organisms.

Endler's hypothesis was that female guppies prefer colourful males for mating. But predators can also spot colourful fish more easily. In locations where the numbers of predators are low, males are more colourful. If there are more predators, males are less colourful.

Endler transferred predatory fish to the areas with brightly coloured male guppies and he found that, after about 10 years, selection had acted to produce a population of duller males.

Brighter males had been eaten and their genes removed from the population. His experiments show that variation within a population provides the basis for rapid evolution when the environmental conditions change and that we can directly observe changes taking place.

Comparing DNA base sequences

Over the course of millions of years, mutations accumulate in any given segment of DNA. The number of differences between comparable base sequences can be used to demonstrate the degree of evolutionary divergence. Figure 11.3.5 shows sequences of bases in DNA of eight vertebrate species. The degree of similarity indicates how closely related the species are and how they may have evolved. Non-coding regions of DNA (Chapter 4) provide the best way to compare DNA sequences because mutations that occur in them are likely to remain over many generations. This is because selection pressure on these sequences is less than on sequences that code for proteins (exons). From information carried in DNA we can construct cladograms that show the relatedness of different species (Section 11.1). DNA sequences that make up specific genes and code for proteins mutate at a similar rate to non-coding regions, but changes in these areas are selected against more strongly. This is because changes to base sequences in genes can have detrimental effects on protein structure.

Species can also be compared for relatedness using similarities in their proteins, based on amino acid sequences. But this method will demonstrate a slower rate of change because degeneracy in the genetic code means that different **codons** can be used to insert the same amino acid into a protein. So some mutations in the DNA will not lead to a change in amino acid.

TEST YOUR UNDERSTANDING

13 The table shows the sequence of amino acids in part of a hemoglobin molecule of five different species. Use the information to work out the most closely related species in the list.

Species	Amino acid sequence in the same section of hemoglobin molecules
human	Lys–Glu–His–Iso
horse	Arg–Lys–His–Lys
gorilla	Lys–Glu–His–Lys
chimpanzee	Lys–Glu–His–Iso
zebra	Arg–Lys–His–Arg

14 State why the analysis of repeated DNA sequences is a useful way of searching for evolutionary relationships.

SCIENCE IN CONTEXT

Using mitochondrial DNA to investigate human evolution

DNA found in mitochondria is also used for examining evolutionary relationships *within* one species. A fertilised egg cell contains mitochondria from an offspring's mother but none from its father as only the sperm nucleus enters the egg at fertilisation. This means that mitochondrial DNA is only inherited from the mother of an offspring and can give a more direct indication of an evolutionary relationship.
Recombination does not occur in mitochondrial DNA and it also mutates more quickly than nuclear DNA so that changes

can easily be spotted. Every cell in the body has many mitochondria so it is also easier to collect more DNA for analysis. This type of analysis is most useful for looking at relationships between organisms that have evolved relatively recently in evolutionary history. Analysis of human mitochondrial DNA has been used to trace the origins of present-day human populations. All humans are thought to be related to one woman, known as ‘mitochondrial Eve’. This woman lived between 100 000 and 200 000 years ago in southern Africa. She was not the first human, but other female lines disappeared or had no female offspring and did not pass on their mitochondrial DNA. As a result, all humans today can trace their mitochondrial DNA back to Eve. In the years since she was alive, different populations of humans have drifted apart physically and genetically to form the different ethnic groups we see today.

11.3.3 How new species arise

Speciation

Speciation is the formation of new **species** from an existing population. Once a species has evolved to become well adapted to conditions in a stable environment, natural selection tends to keep things much the same. But if the environment changes or part of the population becomes separated from another, populations can gradually diverge into separate species by natural selection. Members of the same species and, therefore, the same gene pool can fail to reproduce as a result of a barrier that separates them. New species appear as a result of the population of a single species splitting into two or more new ones, each with its own gene pool.

KEY POINTS

population a group of organisms of the same species that live in the same area at the same time.

speciation the evolution of a new species.

Speciation can only occur if there is a barrier dividing the population (Figure 11.3.6). The barrier may take different forms, such as:

- geographical separation, such as a river, mountain range or a road
- temporal differences (meaning differences in time), when two groups mate at different times so that two populations never meet to mate and exchange genetic material

- behavioural differences, such as mating rituals or songs becoming different and incompatible so that two groups are no longer able or interested in reproducing.

When one part of the divided population is isolated from the other, mutation and selection can occur independently in the two populations so that each has the potential to become a new species.

Speciation is said to be sympatric or allopatric.

- **Allopatric speciation** occurs in different geographical areas.

- **Sympatric speciation** occurs in the same geographical area.

The differences between the two are summarised in Table 11.3.1.

Geographical separation, reproductive isolation and speciation

Bonobos (*Pan paniscus*) and chimpanzees (*Pan troglodytes*) are two species of ape which diverged from a common ancestor between 1 and 2 million years ago The apes are different in their behaviour, body shape and even their emotions and understanding.

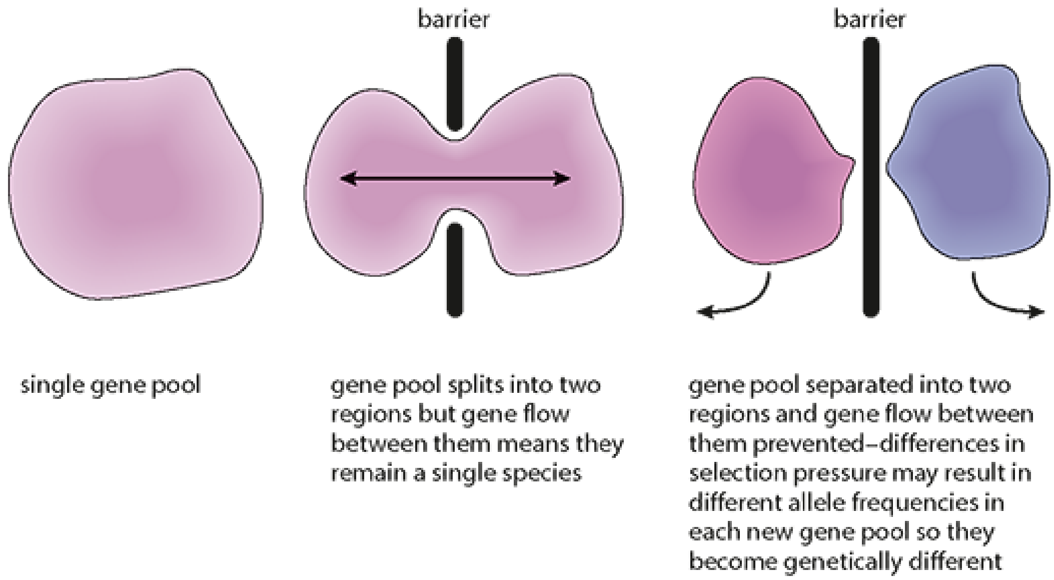

Figure 11.3.6: If a population is separated into two groups by a barrier the two groups may gradually diverge into separate species.

Sympatric speciation	Allopatric speciation
a new species arises from an existing species that is living in the same area	a new species arises because a geographic barrier separates it from other members of an existing species
temporal or behavioural isolation can produce significant changes in the genetic make-up within a species so that a new species is formed	geographic barriers may include mountain ranges, valleys or bodies of water, or human-made features such as roads, canals or built-up areas

Table 11.3.1: Comparison of sympatric and allopatric speciation.

Chimpanzees are larger and have stocky, muscular bodies and can be aggressive and confrontational even with members of their own species. Bonobos have smaller, more slender bodies and tend to be gentler and more cooperative, they are also more likely to walk on two legs (Fig 11.3.7). The common ancestor of both species was separated into two groups after the formation of the Congo River which divided one population of apes into two. Neither of the species can swim so there was no interaction between the separated groups. Once separated, the two groups faced different environments. To the north the group had to compete with gorillas for food and as a result there was also competition between individuals for resources. To the south, there were no gorillas, food was more available and so there was less fighting for food and mates. The northern group eventually became chimpanzees who are more aggressive than the group to the south of the river who became bonobos. The two groups developed into the two species we recognise today.

Infertile hybrids

Reproductive isolation prevents alleles in separated populations, which have evolved differences, from mixing. But sometimes individuals from different species may meet and attempt to breed, forming a hybrid. Hybrids between different species are known as interspecific hybrids and are formed when two species mate, or are bred by humans. The offspring of these crosses are usually **sterile** and are not able to produce fertile offspring. Hybrid sterility shows us how speciation can occur. It prevents genes moving from one species to another so both species are kept separate even if geographic, temporal or even behavioural barriers are removed.

KEY POINT

hybrid an offspring produced by interbreeding of two organisms of different species, or of genetically distinct populations within a species. Such offspring often possess combinations of new characteristics.

Hybrid offspring are often sterile because their parents have different numbers of chromosomes. One example is the mating of a donkey and a horse, which produces a mule or a hinny. Mules (Figure 11.3.8), which are produced by mating a male donkey and a female horse, and hinnies, from mating a female donkey and a male horse, develop normally and reach sexual maturity, but they cannot reproduce. Horses have 64 chromosomes while donkeys have 62. A hybrid between the two species has 63 chromosomes and cannot produce viable gametes because the odd chromosome cannot form homologous pairs at meiosis. Other examples of infertile hybrids include ligers, a cross between a lion and a tiger, and zonkeys which are hybrids between a zebra and a donkey.

Most organisms are diploid and have cells with two sets of chromosomes ($2n$), one from each parent, but **polyploid** organisms have cells that contain more than two sets.

Figure 11.3.8: A mule is produced by mating a male donkey and a female horse. Mules have a short, thick head, long ears, small hooves, and short mane.

Those containing three sets of chromosomes are said to be triploid (3*n*), those with four sets tetraploid (4*n*), five sets (5*n*) pentaploid, six sets (6*n*) hexaploid, and so on.

Polyploidy is widespread in plants but rare in animals. It happens when sets of chromosomes are not completely separated into individual nuclei during cell division so that one cell ends up with additional chromosomes. It is estimated that more than 50% of flowering plants have undergone polyploidy at some time during their evolution.

In many cases extra sets of chromosomes can produce plants that have improved 'vigour', such as a greater resistance to disease or larger fruits (Figure 11.3.9). Polyploidy happens naturally but can be induced by treatment with chemicals and is used in agriculture to produce higher yields. Bread wheat is a hexaploid plant and many members of the Brassica family (cabbages and mustard plants) are tetraploids.

Figure 11.3.9: Diploid ($2n$) and tetraploid ($4n$) grapes.

A tetraploid plant will have chromosomes that each have a matching pair and will be able to undergo meiosis to form fertile gametes. A tetraploid can cross with another tetraploid to form fertile offspring in just the same way as normal plants. But a cross between a tetraploid and a diploid plant would produce triploid plants that would be sterile and unable to form gametes. In this case polyploidy acts as a barrier between the diploid and tetraploid species. The two populations may become so different that they develop into new species.

Polyploidy in plants, which increases the number of sets of chromosomes in plant species, can result in the formation of new plant species without isolation from the parent plants. This ‘instant speciation’ occurs because the new polyploid plants cannot interbred with the diploid parent plants.

One example of possible ‘instant speciation’ can be seen in Japanese knotweed (*Fallopia japonica*). It was introduced into North America about 100 years ago and is now known as one of the world’s top 10 invasive species. In England, Japanese knotweed is sterile and is genetically a single, large female clone. It spreads by fragmentation (small pieces breaking off and starting new plants). But in other parts of Europe and North America, where there are no male plants, female Japanese knotweed plants are reproducing with male plants of other species. Female plants are being fertilized by pollen from giant knotweed (*Fallopia sachalinensis*), and other Fallopia species. A fertile hybrid Bohemian knotweed (*Fallopia bohemica*) is produced and is a special case of polyploidy called allopolyploidy which occurs when two different species interbreed and produce fertile hybrid offspring. Japanese knotweed is octoploid (88 chromosomes); giant knotweed is tetraploid (44 chromosomes); and many hybrid plants have varying numbers of chromosomes, the most common is sexaploidy (66 chromosomes). So the hybrid *F. bohemica* seems to be a new species, developed without geographic isolation from the parent species. This is an example of sympatric speciation and we may see more speciation within genus Fallopia as hybrids interbreed in future.

SCIENCE IN CONTEXT

Hybridisation is used commercially to develop new plants with desirable qualities such as disease resistance or the size of plants, flowers or fruits. Many plants that gardeners and horticulturalists buy are hybrids. A hybrid plant is produced by cross-pollinating two different plant species or varieties by hand and growing the seeds that the cross produces. Producing hybrid plants can take many years. Seeds from the first crosses are grown the following year and the plants they produce are evaluated. If they have the right features, the cross will be repeated and the seeds sold. If they are not what the grower wants, the hybridisation process must be repeated again.

Seeds for popular hybrids, such as varieties of tomatoes called Sungold (Figure 11.3.10), have to be crossed, harvested and saved every year. These plants are called F_1 (or first generation) hybrids because they are the direct product of a cross. The plant breeder who creates a hybrid owns the rights to it, which is why they are more expensive than non-hybrid plants.

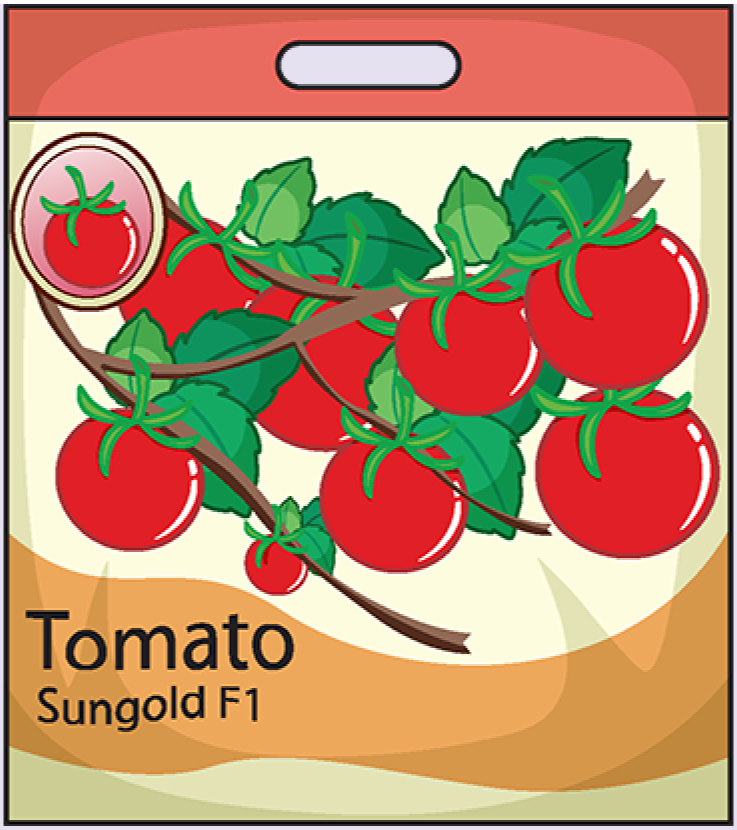

Figure 11.3.10: F_1 hybrid plants tend to be more expensive.

TEST YOUR UNDERSTANDING

15 Define a species.

16 List three sources of evidence that evolution has taken place.

17 Why is isolation of part of a population essential for speciation to take place?

18 Why are many hybrids infertile?

11.3.4 Effects of isolation on the gene pool

The gene pool is all the genetic information in a population that is reproducing at a given time. Allele frequency gives us an indication of the proportion of a specific gene variant in a population. Gene pools do not change greatly over time but new alleles can be introduced as a result of mutations, and other alleles may disappear from a population if the last individual that has it leaves or dies. Genetic drift can change the allele frequency in a gene pool due to chance events. It can cause gene pools of two isolated populations to become dissimilar, as some alleles are lost and others become fixed. Genetic drift can also occur when a small number of individuals separate from a larger group and establish a new population.

KEY POINTS

gene pool is when all the genes and their alleles are present in an interbreeding population.

genetic drift is a change in allele frequency in a gene pool due to chance events.

Alleles which are not favourable will be passed on to fewer offspring and so their frequency will tend to decrease. In Section 11.2 you can read about how over a period of time, selection will lead to an increase the frequency of a favoured allele in the gene pool. The initial increase in frequency of an advantageous, dominant allele that is rare at first is more rapid than that of a rare, but advantageous, recessive allele. A recessive allele cannot become fixed until it is frequent enough to occur in homozygous organisms, but a new dominant allele has an immediate effect on heterozygous individuals. If new individuals enter the population due to immigration there will be a change in allele frequencies as a result. Similarly if individuals emigrate the gene pool will be changed. If we can see that gene pools and allele frequencies have changed, we can deduce that some evolution of the population has happened.

Reproductive isolation

Reproductive isolation keeps two species separate so that there is no gene flow between populations. Three types of isolating mechanism operate in newly separated populations.

1 Geographical isolation describes isolation of a gene pool by a physical barrier such as a river, ocean, mountain range or desert. For example, many Galápagos Island species such as iguanas and finches are now separate from the South American mainland species that they arose from. The island populations have evolved to be different from their mainland ancestors (Section 11.2).

2 Temporal isolation occurs when individuals from different species do not breed because they are active at different seasons or times of the day. Flowers such as orchids in different species of the genus *Dendrobium* open at different times and can only be pollinated by pollen from their own species. Other members of the same genus living nearby cannot pollinate them because their pollen is not produced at the correct time.

3 Behavioural isolation occurs when different populations or species develop different courtship behaviours. Members of the same species are only attracted by the specific calls, songs or displays of their own kind and ignore or reject displays of other species. For example, the blue-footed booby (*Sula nebouxii*) lives in the same habitat as other species of the genus *Sula*. Even though they are similar, the blue-footed booby never mates with them. The female blue-footed booby selects a partner after watching a courtship ritual that is unique to its own species.

SCIENCE IN CONTEXT

Lactase persistence (LP) and allele frequency around the world

Lactase is an enzyme needed for the digestion of lactose in milk. Without the enzyme, drinking milk can cause the symptoms of lactose intolerance: bloating, flatulence, pain and nausea. Production of lactase in adult life, known as lactase persistence (LP), is a genetically determined characteristic and is common in people of European origin and some African, Middle Eastern and Southern Asian populations, but rare in other places.

Lactase persistence is an example of natural selection taking place in humans. About 65% of people stop or reduce the production of the enzyme lactase after they stop drinking milk as infants (at weaning). But five different variants of the lactase gene are found at different frequencies in different parts of the world. The persistence of lactase production is thought to be an example of the co-evolution of genes and culture. Analysis of ancient DNA has shown that in Spain, Germany and Sweden the alleles were present between 4000 and 5000 years ago. One of these alleles is fixed in some parts of Europe, while others are found at variable frequencies in the Middle East and Africa. Present-day frequencies of the alleles tell us that there is positive selection for lactase persistence. Nucleotide analysis shows that lactase persistence seems to have evolved independently in at least four parts of the world and several different mutations have been found. Lactase persistence can provide an evolutionary advantage. The ability to digest lactose in adulthood means that milk can be consumed to provide increased nutritional benefits as well as being a source of water. So natural selection works to retain the LP genes and alleles at high frequencies.

To consider:

1 Milk can be treated with lactase so that lactose-intolerant people can drink it. What happens to the lactose?

2 Why is this treatment important to people who do not have lactase persistence?

NATURE OF SCIENCE

Paradigm shift

A paradigm shift is a change in the core beliefs or assumptions of an accepted scientific theory. It occurs when scientists are faced with anomalies that cannot be explained by the accepted paradigm. In modern science, a number of paradigm shifts have taken place in recent times. These include the acceptance of plate tectonics to explain large-scale changes in the continents and the replacement of Newtonian mechanics with quantum mechanics. In biology, ‘pangenesis’ (Darwin’s provisional theory that a reproductive cell contained ‘gemmules’ from every part of an organism in order to produce a new individual) was replaced with an acceptance of Mendelian genetics.

Two competing theories – gradualism and punctuated equilibrium – attempt to explain the appearance of new species and the absence of intermediate forms in the fossil record. The first view assumes that species gradually change over long periods of time, while the theory of punctuated equilibrium proposes short periods of rapid evolution interspersed with long periods of equilibrium.

Some scientists reject punctuated equilibrium, but as it can be explained in terms of natural selection it is possible that both processes may have occurred. On the other hand, new evidence and analysis of gene sequences has given support to the gradualism viewpoint. For a long time scientists thought that the **mass extinction** of the dinosaurs 65 million years ago led to the rise of the mammals. This view seemed to be supported by the fossil evidence. But recent genetic analysis using the GenBank database has indicated that early mammals were present at least 100 million years ago, 35 million years before the extinction of the dinosaurs. Furthermore, their evolution followed a gradualism path, not a pattern of punctuated equilibrium.

To consider:

1. How does a paradigm shift take place in science?
2. What factors are involved in the acceptance of a paradigm shift?

TEST YOUR UNDERSTANDING

19. Give an example of a feature that can cause geographic isolation.

20 Outline the differences between gradual and punctuated evolution.

21 Define a gene pool.

REFLECTION

Reflect on how our understanding of genetics has increased our understanding of evolution and changes in populations. Could you explain our knowledge of DNA, genes and evolution to a scientist from 150 years ago?

Links

- What aspects of inheritance help us to explain evolution? (Chapter 4)

11.4 Ecological niches, adaptations and evolution

LEARNING OBJECTIVES

In this section you will:

- learn that environments contain a variety of different niches
- discover that every organism has a specific niche, defined by habitat, tolerance limits and an organism's function in the habitat
- learn that niches can vary in size and diversity
- understand the difference between fundamental and realised niches
- distinguish between convergent and divergent evolution
- understand the evolution of homologous structures by adaptive radiation to explain similarities in structure when there are differences in function
- recognise that homologous structures have evolved from a common ancestor
- understand that adaptive radiation increases the biodiversity of a community and use the Simpson's reciprocal index of diversity to analyse community
- distinguish between homologous and analogous structures

- Understand that two species cannot occupy the same niche in a habitat

GUIDING QUESTIONS

- What factors determine where a species is likely to be found?
- How are vacant niches filled in ecosystems?
- How do species evolve to occupy a niche?

11.4.1 Niches and community structure

Habitats and niches

In all communities, each species has a unique role. This role is determined by the species' place in the habitat and the interactions that it has with other species. A **habitat** is an area offering living space to a number of different types of organism, and includes all the physical and **abiotic** (non-living) factors such as climate or soil type in the environment. An example might be a woodland habitat, whose community includes a huge variety of species, from burrowing invertebrates at ground level to nesting birds in the tree canopy. Every organism occupies its own space in an ecosystem, which is known as its spatial habitat. The surroundings are changed by the presence of the organisms; for example, woodpeckers live in woods and forests and make their nests within hollows in trees, adapting them to provide shelter for eggs and chicks, while a rabbit burrowing underground affects the soil and plant species growing there.

A **niche** is the particular environment and 'lifestyle' that is adopted by a species. It includes the place where the organism lives and breeds – its spatial habitat – as well as its food and feeding method, and its interactions with other species. As an organism feeds within its niche, it affects the other organisms that are present. For example, an owl feeding on mice in woodland helps to keep the population of mice at a stable level, and rock limpets grazing on small algae on a rocky shore control the degree of algal cover. A habitat comprises a number of niches, each of which is unique to its particular species because it offers the exact conditions that the species needs or has become adapted to.

KEY POINTS

abiotic refers to non-living features of an environment such as climate, soil type or temperature.

habitat is the features that describe the environment where a species normally lives.

niche is a concept that describes where an organism lives (its spatial habitat), what and how it eats, and its interactions with other species.

11.4.2 Adaptations to environment

Tolerance limits

The organisms present in a community depend on the other organisms living there, as well as on the non-living, abiotic aspects, such as soil or climate. These abiotic aspects define a species' tolerance limits, those factors that affect a species' survival and distribution. Some of these abiotic factors that influence the distribution of plants and animals in communities are outlined here.

KEY POINTS

tolerance limits the abiotic factors in an environment that limit the survival and distribution of a species.

spatial habitat is the space within an ecosystem where an organism lives.

Plants

- Temperature – No plant can survive extremely cold conditions for very long, because to grow and reproduce plants must carry out chemical reactions in their cells. These reactions require enzymes. In cold climates plant growth is very slow, but it increases when the temperature rises.

- Water – All plants require water. It is the universal solvent in their cells, the substrate for photosynthesis and their transport medium. However, plants have evolved a variety of mechanisms to survive periods of drought. Some species remain dormant, some (such as cacti and succulent plants) store water and others complete their life cycle in a brief rainy season.

- Light – Plants need light for photosynthesis. Many plants use the changing day lengths of the different seasons to trigger flowering.

- pH, salinity and nutrients – Most plants prefer a pH of 6.5–7.0 because nutrients are easily available in this range. Saline (salty) soils present a particular problem to plants because salt makes it difficult for plants to take up water and minerals. A few plants, such as marram grass and lyme grass, can survive in saline conditions. Soils that are rich in minerals can support a diverse community of plant species, including trees and shrubs. Plants that survive in mineral-poor soils often have special adaptations to supplement their needs.

Animals

The distribution of animals is also affected by the abiotic factors in their environment. If any factor required by an animal is in short supply or is unsuitable for survival, the distribution of the species will be limited by that factor.

- Temperature – Animal enzymes are influenced by temperature in much the same way as those of plants. However, animals have the advantage that they can move to avoid the harshest of conditions and some use homeostasis to maintain their body temperature. Animals can also hibernate during cold months, or hide when temperatures are extreme (Section 8.5).

- Water – Most animals need to drink water to survive: very few have evolved to be independent of liquid water. Lack of water in certain seasons may change the distribution of animals. Herds of wildebeest and zebra in Africa undertake huge migrations to find new supplies of water and vegetation (Section 8.5).

- Breeding sites – Animals need to find appropriate sites to find a mate and perform their mating behaviours and then rear young. These sites may be chosen for safety away from predators, or because they provide rich feeding grounds so that the young may benefit.

- Food supply – All animals need a source of food and this will depend on the abiotic factors in the environment. Herbivores need plants and carnivores need other animals to feed on. The availability of food will determine the distribution of different types of animal.

- Territory – Territories provide sources of food and breeding sites. Herbivores, such as wildebeest, graze on large areas of grassland and, when the dry season arrives, migrate to find fresh grass. Some birds, such as the European robin, defend their territories vigorously because they contain food and a nesting area. Carnivores that live in packs, such as wolves, require a large area in which to hunt and they mark their territories with scent and defend it from other packs.

Coral reefs – a marine ecosystem

Corals are animals in the same taxonomic group as sea anemones, but unlike anemones coral secretes an exoskeleton of calcium carbonate over its body. Coral polyps do not photosynthesise but have a symbiotic relationship with microscopic algae called zooxanthellae (see section 12.3). These organisms live inside the polyps and provide organic nutrients such as glucose and amino acids A coral reef is a sensitive underwater ecosystem which is formed of colonies of coral polyps held together by calcium carbonate Most coral reefs occur in shallow water near shore and are very sensitive to water conditions As a result, they are particularly vulnerable to the effects of human activities either on nearby land or in the wider world.

A coral reef can only form and survive in the right abiotic conditions. They require:

- oxygen, and carbon dioxide
- water at the correct salinity, temperature, pH and clarity
- light: corals need a moderate amount of sunlight
- depth of water, corals grow at depths where sunlight can reach them.

Coral reefs have declined by about 50% in the last 70 years. Coral reefs are threatened by sediment which makes the water around them cloudy. Light cannot penetrate and the sediment can smother corals so they and the zooxanthellae cannot feed and grow. Pollution and toxins can also kill the coral. Ocean warming and acidification, caused by global warming, increase both levels of carbon dioxide and sea temperatures to a level which coral cannot tolerate.

Adaptations and tolerance limits of mangrove trees

Mangrove trees grow on tropical shores at the edge of the sea. Mangrove forests grow at tropical and subtropical latitudes near the equator where the sea surface temperatures never fall below 16°C. Mangrove trees line about two-thirds of the coastlines in tropical areas of the world. As a tropical species they survive at air temperatures above 19°C and cannot tolerate any change in temperature which is more than 10°C or below freezing for more than a short period of time.

Mangrove trees have two important adaptations that allow them to survive in the extreme conditions of shores and estuaries. They can survive in waterlogged and anoxic (no oxygen) soil, and they can tolerate salty water. Some mangroves remove salt from water using ultra-filtration in their roots, other species have glands on their leaves that actively secrete salt, so that salt crystals appear on the upper surface of the leaves. All mangrove trees have spreading roots and vertical anchor roots to hold them in place in the shallow soil as the tides come and go. In areas where their roots become flooded at high tides, mangrove trees grow aerial root called pneumatophores which absorb oxygen from the air to supply the roots. Mangrove trees can survive in water which is 100 times saltier than most plants can tolerate and withstand twice-daily flooding by the ocean tide that would kill other trees. The tides bring nutrients and carry waste products away from the mangroves. Tides also distribute tree seedlings which reduces interspecific competition for space. If the tides transport salt water into estuaries where it mixes with fresh water, mangrove trees can extend their range and grow further inland.

Figure 11.4.1: Buttress roots stabilise mangrove trees and help them resist tidal waters.

Obligate anaerobes, facultative anaerobes and aerobes

Plants and animals require oxygen for aerobic respiration to release energy from their food but several other groups of organisms do not. **Obligate anaerobes** are microbes that are killed by the concentrations of oxygen found in the air. Some bacteria and protozoa can only live in environments such as the intestines of animals, the deepest ocean and waterlogged soils where there is no oxygen present. Examples include the bacteria that cause tetanus and methanogenic bacteria found in hot thermal vents. Archaea are obligate anaerobes, living in extreme environments.

Some anaerobic organisms can use oxygen if it is available, but can also respire anaerobically, these organisms are called **facultative anaerobes** and include yeast which respires aerobically if oxygen is present but will change to fermentation (anaerobic respiration) when it is not.

Distribution of species and abiotic variables

When ecologists want to understand the distribution of a species and relate it to an abiotic factor, or to compare the distribution of one species with another in a different location, it is usually impossible to do so by a direct counting method. There are a number of sampling methods used to collect data. Two commonly used methods are **quadrats** and **transects**. They can show not only which species are present, but also how many individuals of each species there are. They provide a method of systematic sampling.

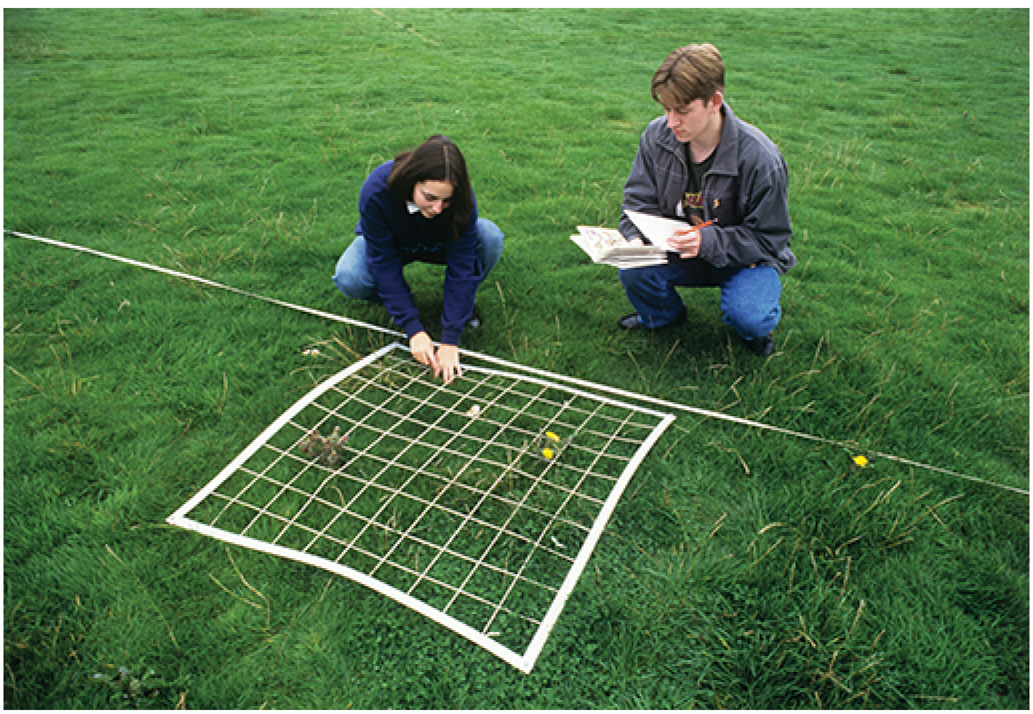

Figure 11.4.2a: These students are using a transect line to survey the plants in a grassy area. A quadrat is placed at measured intervals along the transect line and the plants at each location

are counted and recorded. In this way, the plant population can be estimated from a series of samples in a few areas.

A quadrat is a portable square with a fixed area. It is placed on the ground and the species inside the square are counted and recorded (See Figure 11.4.2a). A transect consists of a tape or rope stretched from a fixed point across an area of interest, where the abiotic factors may be changing and the distribution of organisms may be different. Transects can be used to sample the distributions of plants along a beach or through a field, or to study the vegetation as soil or moisture changes along a line of interest. Samples are taken by placing a quadrat down at intervals along the tape so that the organisms within it can be accurately counted (Fig 11.4.2b). Relevant abiotic factors such as temperature, light, salinity or soil pH can also be measured at each location. In this way a transect can reveal the distribution of a species in relation to a particular abiotic factor or it can give an idea of successions or changes in communities of organisms across a habitat (Figure 11.4.2c).

The type of transect that is used will depend on the terrain and on the organisms present. Sometimes organisms are recorded at specific sampling points at intervals along the tape. Or, a continuous ‘belt’ transect can be used, where all species in a 1 m zone along the transect are recorded. This can be helpful in providing a detailed picture of the area.

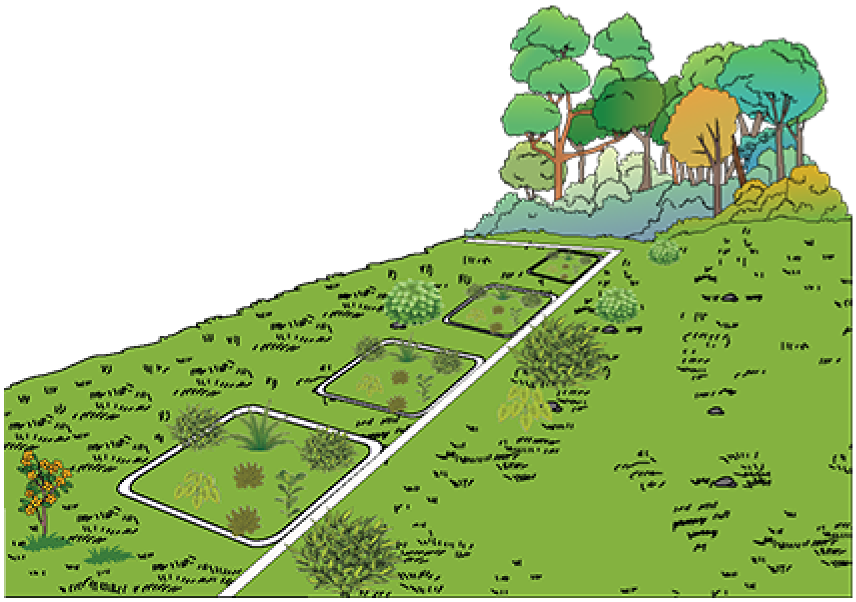

Figure 11.4.2b: Sampling along a transect like this one and measuring light intensity at each sample point enables us to relate distribution of plants to light intensity.

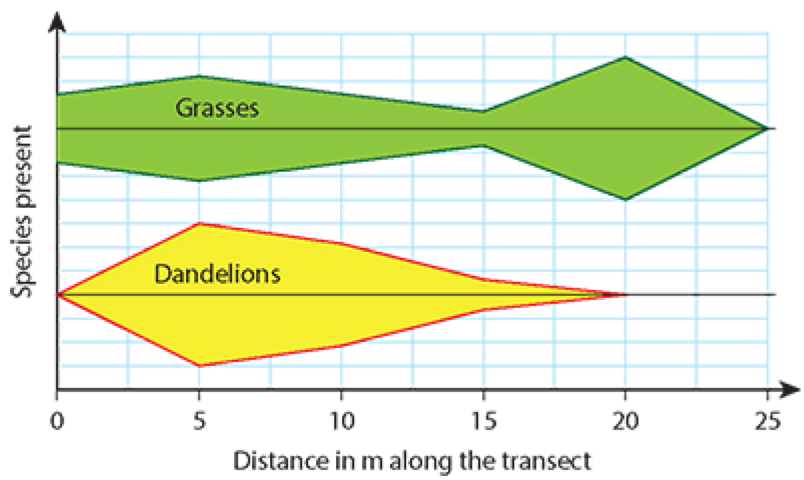

Figure 11.4.2c: This kite diagram of data from grassland shows how kite diagrams are used to present data. It shows that dandelions are more abundant near the starting point of the transect while grasses are present in greater numbers 20 metres along the transect.

NATURE OF SCIENCE

Using models to study the real world: limits of tolerance graphs

Ecologists often use models to predict events in the natural world. Graphs such as the one shown in Figure 11.4.3 can be drawn to indicate the likely ranges of different species in different situations. Information about the stresses, such as temperature, desiccation (drying out through lack of water) or availability of nutrients, that apply to different species can help ecologists to predict whether a species might be able to survive in a habitat or whether the species being studied could survive in a different location with different pressures.

Consider the graph and try to identify the environmental conditions that apply in the case of:

1 The common limpet, a mollusc which lives in an area of the rocky seashore between the high and low tide marks. This area is covered and uncovered twice a day by the tide. Limpets are adapted to being exposed to air and immersed in sea water but their range is limited by their tolerance of several of the conditions higher up on the seashore.

2 The bristlecone pine (*Pinus aristata*) is a conifer native to the USA. It grows in Colorado and other states at altitudes of between 2000 and 4000 metres. It is able to live on exposed, cold, dry rocky slopes and high mountain ridges but its limit of tolerance is 4000 metres, above which environmental conditions are too extreme for it to survive.

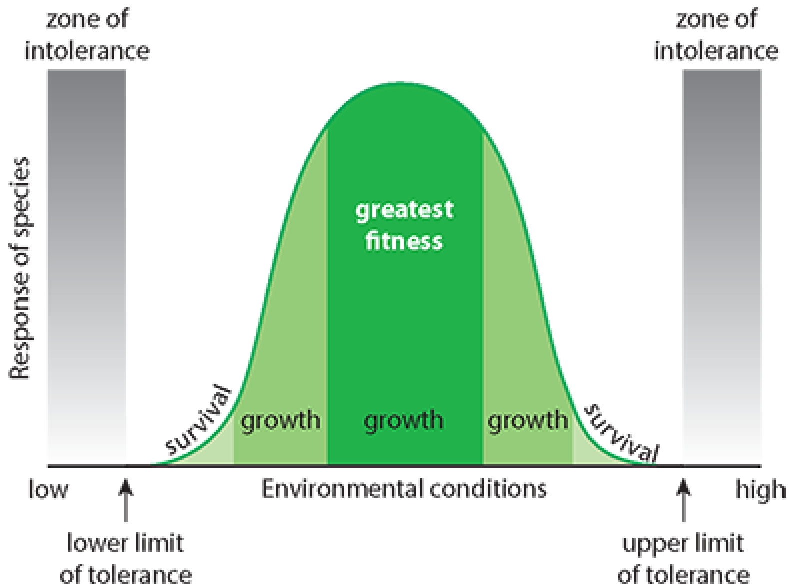

Figure 11.4.3: The graph shows how the range of a species is limited at the upper and lower environmental extremes by zones of intolerance in which the organism cannot survive.

3 For each species, try to describe what conditions might be like in the 'zone of intolerance' where the species are absent.

To consider:

Choose an organism that lives in your home area and try to identify limiting factors that affect its survival. What are the limits of tolerance for the species you have chosen?

11.4.3 Niches and the effects of competition

Organisms interact with other organisms living in the same community. The interactions include competition, different methods of feeding such as being herbivore, a carnivore or a parasite. Almost all organisms influence the lives of others and their interactions all have different effects.

Ecosystems have complex community structures involving interactions between all the species that live in them and are affected by the abiotic factors in the area. We can say that ecosystems show emergent properties. Ecosystems have properties that you would not find in any of the individual species on their own and make up the community structure we can observe.

Competition and competitive exclusion

Competition occurs when two organisms require the same limited resource. For example, if a pride of lions kills an antelope, they must protect this source of food from scavenging hyenas and vultures that will compete with them for the prey. In most cases, competition will lead to the exclusion of one species by another. As one species uses the resource, less is available to the other, so that the less successful species may have to adapt to use a different resource to enable it to survive.

Plants also compete for resources such as light and space. Fast-growing birch trees quickly become established in areas of cleared land, but they require high light levels. Slower-growing species such as oak begin to grow up around them and, for a while, they form a mixed woodland. Eventually the birch trees are over-shadowed and outcompeted by the more dominant oaks.

Loss of habitat, often caused by human activities such as farming or deforestation, severely limits vital resources such as food, water and breeding sites for the species that live there. When two different species require the same limited resources in the same area, they may find themselves in competition for the same niche. If they are prey species, they may become susceptible to the same predators as well. The principle of competitive exclusion states that no two species can occupy the same niche. The species cannot exist together because one will come to dominate and exclude the other. The oak and birch trees are examples of competitive exclusion. Both compete for soil resources and light but eventually the oak trees block the light from the birches and the birches die out.

KEY POINT

competitive exclusion no two species can occupy the same niche because one will come to dominate and exclude the other.

Fundamental and realised niches

We have described a niche as the special space and 'lifestyle' inhabited by a particular species. This is the **fundamental niche** for a species. It is the potential way of life of the species, given its adaptations. Often the environment will change through natural events, competition or human intervention. So a species may find that its niche becomes more restricted or begins to overlap with that of another species. This more restricted life pattern is known as the **realised niche**.

KEY POINTS

fundamental niche is the potential mode of existence of a species given its adaptations.

realised niche is the actual mode of existence of a species resulting from its adaptations and competition with other species.

The realised niche is the actual mode of existence of a species resulting from its adaptations as well as from competition with other species. A realised niche can only be the same size as or smaller than the fundamental niche.

Gause's study with *Paramecium* (described in the Nature of Science box) showed that the fundamental niche of both *P. aurelia* and *P. caudatum* was the tank in which they grew alone. However, in a tank together each occupied a more restricted, realised niche where *P. caudatum* was outcompeted and failed to thrive as it became limited by *P. aurelia*.

In natural and urban situations, we can observe animals occupying realised niches. For example, normally wild animals such raccoons and foxes have fundamental niches living in open countryside and hunting small mammals, amphibians and other small prey. As humans have encroached on forest and open countryside, turning areas into roads or farmland, the fundamental niche of the fox has reduced. Some prey items have disappeared and the animals find themselves in competition with other species. The new smaller niche is the realised niche. In some areas foxes compete with coyotes, and both racoons and foxes may occupy a realised niche in which they scavenge on the waste left by humans.

NATURE OF SCIENCE

Evidence for competition and niches

In 1934, a famous study on competition was conducted by G.F. Gause (1910–1986), a Russian ecologist. He experimented with two species of *Paramecium*, a large protozoan that is common in fresh water: *P. aurelia* and *P. caudatum*. If the two species were allowed to grow in separate cultures on a food source of bacteria, both species grew well. When the two species were cultured together with an identical food source, *P. aurelia* survived while *P. caudatum* died out (Figure 11.4.4). Both species had similar needs in the culture but *P. aurelia* had an advantage that enabled it to outgrow *P. caudatum*.

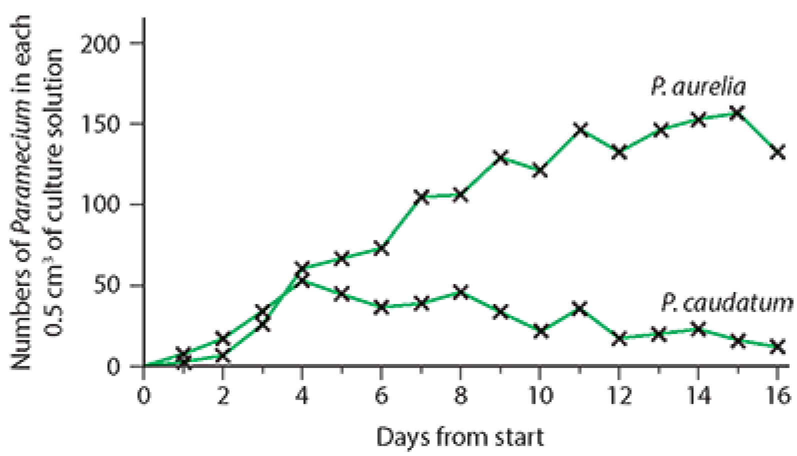

Figure 11.4.4: Over the 16-day culture period, the population of P. aurelia increased while P. caudatum declined. P. caudatum was competitively excluded by P. aurelia.

Another example is a sparrow population living in woodland where the birds feed on berries that grow on bushes. The fundamental niche of the sparrows is the area where there are berries, and includes the bushes as well as the forest floor where berries fall to the ground. But mice also live in the woodland, where they eat berries that fall to the ground. The presence of the mice causes competition between the two species and means that there are fewer berries on the woodland floor for birds to eat. The fundamental niche of the sparrows is partly occupied, so they fill a smaller, realised niche, which is just the area on the bushes.

11.4.4 Convergent and divergent evolution and changes in structure

Organisms have adapted to fill available niches. In some cases, they have done this through either convergent or divergent evolution. A population that moves to a new location may diverge from its ancestors and form new species. If two or more different species are formed from an original group in different habitats then a process known as divergent evolution takes place. If a large number of new species form from an original ancestor and occupy new niches the process is known as adaptive radiation. Convergent evolution takes place when different organisms that are not closely related ancestors independently evolve similar characteristics as they adapt to similar environments or niches. Table 11.4.1 compares the two types of evolution.

Divergent evolution	**Convergent evolution**
new species arise from a common ancestor	different ancestors
species diverge and produce homologous structures	species converge and have analogous structures
species appearance becomes more different over time	species appearance becomes more similar over time
species are closely related and have genes in common	species are genetically different and unrelated
examples include the pentadactyl limbs of vertebrates, and Galápagos	examples include wings in birds, bats and insects

finches	

Table 11.4.1: The two types of evolution.

Divergent evolution

One of the most famous examples of divergent evolution was observed by Charles Darwin on the Galápagos Islands (Figure 11.2.7). Darwin noticed that each of the islands had a population of finches that belonged to the same family but that individual bird populations on each island had beaks of different shapes and sizes. Darwin suggested that each species had originally belonged to a single common ancestor species, which had diverged and undergone modifications of its features based on the type of food available on each island. For example, the birds that fed on seeds evolved a short stubby beak, those that fed on nuts evolved a large crushing beak, while cactus eaters developed a longer beak, and insect eaters evolved a finer beak to pick insects out of holes in trees.

KEY POINTS

adaptive radiation divergence of organisms into a range of new forms from a common ancestor under the influence of selection pressure is adaptive radiation.

convergent evolution is when unrelated organisms evolving similar characteristics occupy similar niches.

divergent evolution is diversification of new species from a common ancestor to occupy available niches.

DNA analysis indicates that all 13 species now found on the islands probably evolved from a small flock of about 30 birds that became established there around 1 million years ago. When the ancestral form of finches colonised the islands, each group contained some individuals who were able to adapt to the conditions and the available food source more readily than others. As the population of birds grew and competition increased, the individuals with favourable characteristics survived and reproduced. Each species now occupies its own niche exploiting its own source of food on each island and this is an example of adaptive radiation (Figure 11.4.5).

Convergent evolution

When convergent evolution takes place, similar phenotypes evolve independently in unrelated species. For example, flight has evolved in both bats and insects; they both have wings, which are adaptations to flight, but the two groups evolved this ability independently and the wings of bats and insects have evolved from very different original structures. Another example of convergent evolution is shark and dolphin body shape. Sharks are fish and dolphins are mammals but over time both populations have been exposed to the same selection pressures. Changes in body shape to make swimming more efficient have been favoured in each group. Structures like wings and body shapes that develop as a result of convergent evolution are known as analogous structures.

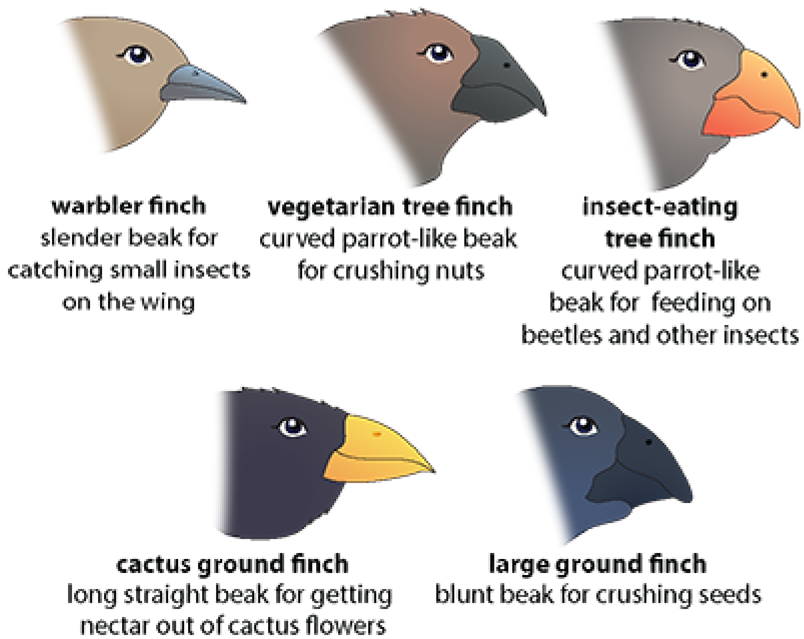

Figure 11.4.5: These diagrams show how the beaks of each of the finches have become adapted so that each bird now occupies its own niche, exploiting its own source of food on the different islands.

KEY POINT

analogous structures are structures that are similar because they have evolved to have the same function not because they are inherited from a common ancestor.

Homologous structures

Homologous structures are anatomical features showing similarities in shape, though not necessarily in function, in different organisms. The evolution of homologous structures by adaptive radiation explains similarities in structure and suggests that the species which have them are closely related and derived from a common ancestor. A good example is the vertebrate pentadactyl limb. This is found in a large range of animals including bats, whales and humans, as shown in Figure 11.4.6. In each group, limbs have the same general structure and arrangement of bones but each one is adapted for different uses in the different environments that the organisms inhabit. Bird wings and reptile limbs are also homologous structures. Even though a bird uses its wings for flying and reptiles use their limbs for walking, they share a common arrangement of bones.

In many plants, homologous structures are made by modifications of primary leaves, stems or roots to form structures for a range of functions. Leaves are modified to form the insect-trapping pitchers of pitcher plants, the insect traps of the Venus flytrap and the spines of cacti. Modified leaves also form tendrils to grip on to surrounding objects and enable plants to climb upward towards the light. Figure 11.4.7 shows some homologous structures found in plants.

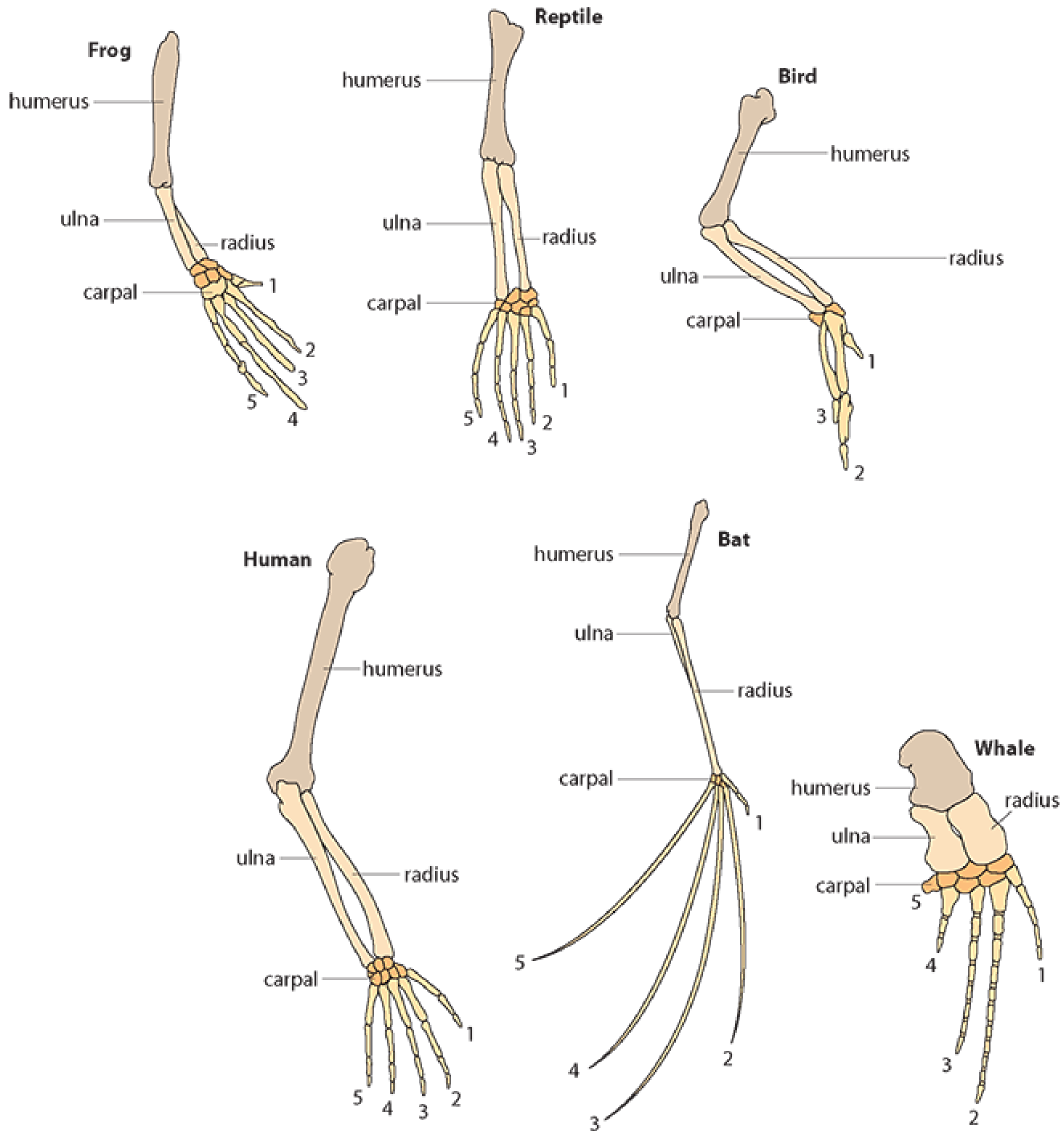

Figure 11.4.6: Homologous structures: the forelimbs of animals with pentadactyl limbs all have a clearly visible humerus, radius, ulna and carpal bones.

Adaptive radiation is a term used to explain how organisms diverge into a range of new forms from a single common ancestor. It can occur if the environment changes and new sources of food or new habitats become available. The pentadactyl limb demonstrates adaptive radiation in the vertebrates, and Darwin’s finches are an example of how one original species adapted to exploit new resources and fill available niches.

Analogous structures

Analogous structures evolve by convergent evolution to fulfil the same functions in very different species. The vertebrate eye is very similar in structure to the eye of the octopus but the octopus and vertebrates are not closely related.

Figure 11.4.7: Homologous structures derived from leaves occur in many plant species.

One key difference is that the octopus eye does not have a blind spot (fovea). Also, unlike the vertebrate eye, an octopus eye is focused by the lens moving backwards and forwards, in a similar way to focusing the lens of a camera. In contrast, a vertebrate eye focuses by changing the shape of the lens using ciliary muscles.

In vertebrate eyes, the nerve fibres to the optic nerve line the inside of the retina and create a blind spot where they pass through the retina. In octopus eyes, the nerve fibres run to the optic nerve from behind the retina, and so do not block light and cause a blind spot (Figure 11.4.8). These differences are all due to the very different ways in which the two types of eye are formed during development. Octopus and human eyes have evolved from different structures, the two organisms do not share a common ancestral structure.

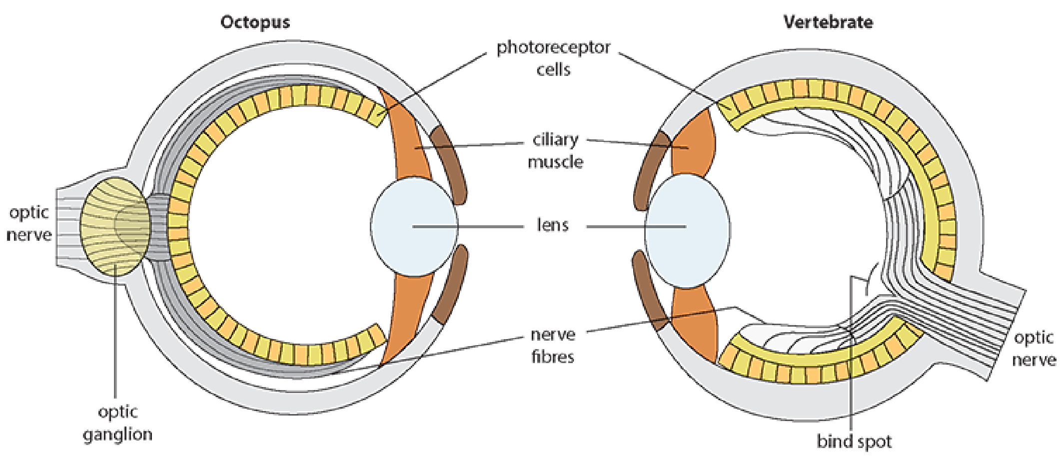

Figure 11.4.8: Analogous structures: the octopus and vertebrate eye have many similarities but have evolved in completely different ways.

Analogous structures are also present in plants and we can see an example of this in the adaptations of the North American cacti and African euphorbias. Both these species have structures that enable them to survive in dry environments. Their features make the species appear similar but they have evolved from very different plant families. Both plants were typical of the species that lived many millions of years ago on the early Earth; both would have had slim stems and large, wide leaves. As the supercontinents, Pangaea and Gondwana, were separated by continental drift, from about 180 million years ago, plants became isolated on continents that we now know as Africa, America and Australia. Plants on these different continents began to evolve as the changing climate caused the development of arid, desert environments. Long ago the cactus and euphorbia families evolved and adapted to new conditions in order to survive. Despite the fact that they live on separate continents, they have converged to have similar forms and metabolisms because they were exposed to similar environments. Their present-day similarities include branching stems with ribs that run along their length, small leaves and short spines, a spreading shallow root system and succulent stems that can store water (Figure 11.4.9). Table 11.4.2 summarises the differences in the origins of the adaptations in the two plant types.

Cacti	**Euphorbia**
have condensed growth nodes called areoles that produce spines and flowers	no areoles present
spines are modified leaves produced by areoles	spines are modified shoots that grow in pairs from the stem
flowers grow from areoles and have visible petals and stamens. they are often colourful	tiny flowers occur inside a cuplike structure, known as a cyathium
most cacti contain watery sap	euphorbias contain thick,

	milky sap, known as latex

Table 11.4.2: Comparison of the origins of structures in cacti and euphorbias.

Figure 11.4.9: Cacti and euphorbias have evolved by convergent evolution to have similar appearances but are from different plant families.

Table 11.4.3 summarises the differences between homologous and analogous structures in vertebrate limbs.

Homologous structures **Similar structure, different function**		**Analogous structures** **Different structure, similar function**	
lizard forelimb	digging	whale flipper	swimming
bird wing	flying	turtle forelimb	swimming
whale flipper	swimming	fish fin	swimming

human arm	grasping	penguin flipper	swimming

Table 11.4.3: Comparison of homologous and analogous structures in vertebrate limbs.

11.4.5 Evolution and biodiversity

As organism diverge and evolve into new forms from common ancestors, the biodiversity in a community or ecosystem increases. ‘Biodiversity’ simply means the ‘variety of life on Earth’. Adaptive radiation increases the biodiversity in a community or ecosystem ‘biodiversity’ is a term that simply means ‘the variety of life on Earth’. One of the best ways to assess the health of an ecosystem is to measure its biodiversity: the variety of species living in communities there. This can be done using Simpson’s diversity index. This index allows us to quantify the biodiversity of a habitat by taking into account both the number of different species present (the species ‘richness’ of the habitat) and the abundance, or number, of each species.

Diversity can also be assessed on a much smaller scale at the level of genes present in a species. A high genetic variation indicates a large and stable population which has a large pool of genes and maintains the ability to respond to selection pressures if conditions change.

On a much larger scale, diversity can be assessed by looking at the types of ecosystems in an area of the biosphere. Ecosystem diversity considers both biodiversity and abiotic factors that are present. Examples of ecological diversity are variations in ecosystems, such as deserts, wetlands, oceans or forests. This type of diversity is important because it maintains the biological health of the planet. For example, diversity in ecosystems increases oxygen production and absorption of carbon dioxide by photosynthesis. Diversity in aquatic habitats maintains water quality. You can read more about biodiversity and the effects that humans have had on biodiversity in different areas of the world in Chapter 12.5.

KEY POINT

biodiversity a measure of variation at the genetic, species, and ecosystem level.

NATURE OF SCIENCE

Measurement of Biodiversity using Simpson's diversity index

Simpson's diversity index allows us to quantify the biodiversity of a habitat. It takes into account both the number of different species present and the abundance of each species. If a habitat has similar population sizes for each species present, the habitat is said to have 'evenness'.

Simpson's diversity index gives us a measure of both richness and evenness. It is calculated using the formula:

$$D = \frac{N(N-1)}{\Sigma n(n-1)}$$

where:

- D is the diversity index
- N is the total number of organisms in the habitat
- n is the number of individuals of each species
- Σ is a Greek letter that means total, or sum of.

Calculating Simpson's diversity index

The value of Simpson's diversity index is best illustrated by comparing two habitats. Two ponds might contain species of invertebrates in the numbers shown in Table 11.4.4.

Although there are fewer organisms in pond B, the individual populations are more even, so the community is not dominated by one or two species. We conclude that pond B is more biodiverse.

If we want to predict the effect of changes in an ecosystem, we can alter some of the figures we have collected. For example, by increasing the number of water spiders, we could get an idea of what effect an increase in this species might have on the value of *D* and the diversity in the pond.

An advantage of the index is that you do not need to know the name of every different species: it must simply be distinguished as a separate species.

Calculating Simpson's diversity index at intervals over time can give a good indication of the health of an ecosystem and whether conservation measures in some circumstances might be valuable.

	Species					**Total number of organisms**
	Water boatmen	Water measurers	Pond skaters	Whirligig beetles	Water spiders	
number of organisms in pond A	43	18	38	3	1	103
number of organisms in pond B	26	18	29	11	5	89

Table 11.4.4: The numbers of invertebrates in two ponds, A and B.

WORKED EXAMPLE 11.4.1

Using the formula, calculate the diversity index for pond A and pond B:

Answer

For pond A:

Simpson's diversity index D

$$= \frac{(103 \times 102)}{43(43-1)+18(18-1)+38(38-1)+3(3-1)+1(1-1)}$$
$$= \frac{10\,506}{3524}$$
$$= 2.98$$

For pond B:

Simpson's diversity index D

$$= \frac{(89 \times 88)}{26(26-1)+18(18-1)+29(29-1)+11(11-1)+5(5-1)}$$
$$= \frac{7832}{1898}$$
$$= 4.13$$

TEST YOUR UNDERSTANDING

22 Define the term niche.

23 Distinguish between a fundamental and a realised niche.

24 Distinguish between convergent and divergent evolution.

25 Give an example of homologous structures.

INTERNATIONAL MINDEDNESS

International cooperation and collaboration

Conserving biodiversity requires international cooperation between scientists, organisations and politicians. In the last 50 years, the importance of biodiversity has come to the forefront of science. Species are not evenly distributed on Earth. Biodiversity is far richer around the tropics and areas containing rainforest are among the most diverse on the planet. People have come to realise that there are many compelling reasons for conserving the biodiversity of habitats such as the rainforests, where as-yet-undiscovered species may provide valuable medicines and other resources for future generations. Conservation in one part of the world may depend on cooperation and collaboration in another. International organisations such as the World Wide Fund for Nature (WWF) and the United Nations Environment Programme (UNEP) coordinate such work in many countries.

The key objective of all conservation organisations is to preserve species and their habitats. Some work at a local level while others are global. Some organisations, such as UNEP, are funded by governments while others, such as WWF, are non-governmental organisations (or NGOs), which are funded by individuals or groups. Organisations

such as WWF work with businesses, governments and local communities to create solutions that take account of the needs of both people and nature. Conservation programmes must select which species are to be protected, but it is often difficult to decide which species most merit conservation efforts.

To consider:

1. On what basis should one species be chosen over another? For example, is a large mammal such as a tiger or panda more important than a small, seemingly insignificant mollusc? An endearing mammal may encourage people to support a conservation programme but smaller, less appealing species may be more important and play a pivotal role in an ecosystem.
2. Should endangered animals be given priority over other species whose numbers are not yet so low?
3. How can international cooperation help less wealthy countries conserve the biodiversity in their regions?

11.4.6 Competition in identical niches

The competitive exclusion principle explains that two species cannot have exactly the same niche and coexist because species with identical niches also have identical needs and compete for all the same resources. G.F. Gause's experiments with *Paramecium* show us that two species cannot survive indefinitely in the same habitat if their niches are exactly the same. There will be competition between them. Competition occurs when two organisms require the same limited resource. For example, if a pride of lions kills an antelope, they must protect this source of food from scavenging hyenas and vultures that will compete with them for the prey. In most cases, competition will lead to the exclusion of one species by another. As one uses the resource, less is available to the other, so that the less successful species may have to adapt to use some other resource if it is going to survive. Species such as lions and hyenas have adapted so that their niches only partly overlap. They may be able to coexist if food or other resources are plentiful. But over long periods of time, species may adapt to make use of more different, or less overlapping resources.

In the 1960s the American ecologist Joseph Connell (1923–2020) tested Gause's ideas on competition by studying barnacles (shelled marine organisms) that live on rocks along European coastlines and need similar resources. He found that two barnacle species, *Balanus* and *Chthamalus*, can coexist because of two important differences between them. Firstly they grow at different rates, and secondly they have a different tolerance to dry conditions. *Balanus* grows rapidly, which allows it to grow over and cover the slower-growing *Chthamalus* if both species are present. But *Balanus* dies in areas close to shore because it cannot tolerate the dry conditions that occur at low tide. *Chthamalus* tolerates these dry conditions well. Although *Balanus* is a better competitor for space, the two species of barnacle coexist in the same areas because *Chthamalus* can survive in dry conditions where *Balanus* cannot (Figure 11.4.10). This example supports the competitive exclusion principle. Species can only coexist if they have different niches.

When ecologist Joseph Connell did this he found that when *Chthamalus* was alone, the species occupied all the rocks between the high and low tide marks (its fundamental niche). When the two species were present together, both occupied their smaller, realised niches.

Loss of habitat, often caused by human activities such as farming or deforestation, may limit vital resources such as food, water and breeding sites for the species that live there. As we have seen, when two different species require the same limited resources in the same area, they may find themselves in direct competition for the same niche. If they are prey species, they may become susceptible to the same predators as well. Since the principle of competitive exclusion states that no two species can occupy the same niche, some species avoid competition and predators by adapting to extreme niches.

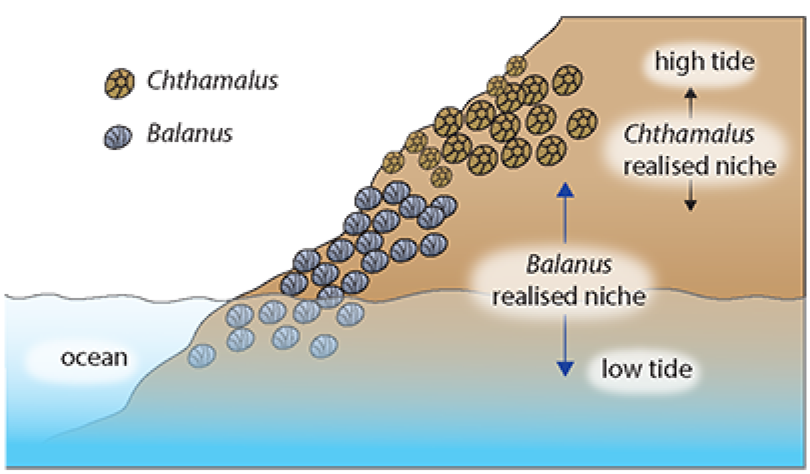

Figure 11.4.10: Connell experimented by removing Balanus barnacles from rocks.

11.4.7 Adaptations to different niches

All organisms are adapted to the conditions in their niche. Organisms that can adapt to extreme niches encounter less stress from competition and predation because few organisms live in these difficult environments. With fewer competitors the adapted species can thrive. You can learn more about the abiotic conditions in different biomes in Section 12.4.

Hot deserts

Organisms that can survive in hot deserts have adaptations that enable them to live where temperatures are very high and water is scarce.

Desert plants such as cacti and other succulent plants have adaptations that we can observe are:

- The plants appear swollen, spiny and have no leaves.
- They store water in fleshy stems or roots.
- They can absorb large quantities of water in the very short periods when desert rain falls.
- Most have extensive, shallow root systems to absorb water close to the surface.
- Waxy cuticles prevent water loss when stomata are closed.

Desert animals such as the camel also have a range of adaptations:

- Camels have few or no sweat glands.
- They produce tiny amounts of very concentrated urine.

- They store fat reserves in humps rather than as an insulating layer around their body.
- They can drink up to 100 litres of water when it is available.
- Broad lips allow them to feed on dry thorny vegetation.
- Large flat feet spread their weight on soft sand and protect them from the heat.
- Their nostrils can close and their eyelashes are long to prevent sand blowing into them.

Tropical rainforests

In tropical rainforests conditions are hot and humid but rainfall is very high. It is an environment which has many species but in which there is great competition for the natural resources. Soil in the forest is shallow and not very fertile as nutrients cycle rapidly and are quickly eroded in the heavy rain. Plants compete for light and nutrients.

Adaptations that allow plants such as the woody vine lianas to survive include:

- roots in the shallow rainforest soil
- long woody stems that climb up trees to reach sunlight for photosynthesis
- leaves and flowers only in the high canopy layers.

Epiphytes are plants which live high in the canopy. They have no contact with the ground and get all their nutrients from the air and water, not from the soil.

Trees are also adapted to the conditions. They have tall smooth trunks which grow rapidly to reach the light. Many have smooth trunks which allow heavy rain to run quickly down to the tree roots. Large buttress roots support tall trees and extend into the shallow soil. (Fig 11.4.11)

Although it covers extensive areas, the tropical rainforest contains very few large animals because its understory (the layer above the forest floor) is so dense that it makes it hard for them to move around. Animals avoid predators using camouflage and hiding from view. For example, the sloth has a colour that matches the tree trunks and branches, and it moves extremely slowly so that predators do not notice it. Much of the food that is in the forest grows high up in the branches so rainforest monkeys have long, strong limbs to move easily between the trees, while tree frogs have webbed hands and feet so that they can glide between trees. Birds can fly up into the trees, but the branches may be too weak to support their weight. Toucans have long strong beaks to reach and cut fruit from thin branches.

Figure 11.4.11: Buttresses support rainforest trees

Some species develop physiological, morphological or behavioural adaptations to extreme environments that other species cannot inhabit. Two examples of such species are emperor penguins (*Aptenodytes fosteri*), which live on the ice in the frozen waters of the Antarctic, and marram grass (*Ammophila arenaria*), which grows on coastal sand dunes where water is difficult to obtain.

Freezing conditions (*Emperor penguins*)

Emperor penguins are the largest of the Earth’s penguins and are 115 cm tall.

The birds have physiological adaptations and cooperative behaviour strategies to survive in an environment where the temperature can reach −60°C.

- They huddle together in groups to protect themselves from the wind and conserve heat. Individuals take turns moving to the centre of the huddle. When they have warmed their bodies they change places with other birds and move to the edge of the group.
- Emperor penguins breed on the open ice. A females lays one egg and then leaves it with the male bird while they go to hunt in the ocean for period of up to 2 months. They may need to travel 40 km across the ice to reach the ocean where they feed on fish and squid.
- The male bird remains on the ice and incubates the egg, standing upright and keeping the egg on his feet. A brood pouch made of feather-covered skin encloses the egg. A male does not feed at all for the 2 months that he incubates the egg and guards the chick (Figure 11.4.12).

Figure 11.4.12: The male emperor penguin cares for its chick for up to 2 months until the female returns to feed it.

- The female returns to feed their newly hatched chick and the male leaves to feed. Another adaptation is the penguins' ability to dive down to 500 metres, deeper than any other birds, and stay underwater for up to 20 minutes.

- In the Antarctic summer (December), when the ice begins to melt, the chicks are able to reach open water and swim and fish for themselves.

Dry conditions (*Marram grass*)

Marram grass grows on mobile, coastal sand dunes and is one of the few species that can survive there. The plant is known as a xerophyte and has physiological adaptations to survive shortages of water. The conditions on a sand dune are harsh, with strong winds which carry salt spray from the sea. Sand dunes drain quickly and bare sand has few nutrients. The terrain is composed of calcium carbonate from seashells and rotting seaweed on the sand adds a few nutrients. Few species can survive here but marram grass has adaptations to the harsh conditions.

- Marram has deep, matted roots which reach the water table and bind the sand together.
- Marram has reduced rates of transpiration compared to other plants. They have protected stomata situated deep inside the plant's waxy leaves. The leaves are rolled up to prevent evaporation from the surface, with tiny hairs that minimise air flow, trap water vapour and prevent water being carried away.

You can read more about the detailed structure and adaptations of marram grass in Section 6.3.

Figure 11.4.13: Marram grass is a species which stabilises the shifting sand of a dune.

SCIENCE IN CONTEXT

Marram grass was once harvested and used to weave mats for barn roofs, nets for fishing and even shoes. Long ago, a family that lived near the sea would have its own sand dune and the whole village would often be involved in collecting the grass. Today it is not harvested because of its the importance in stabilising fragile sand dune habitats.

TEST YOUR UNDERSTANDING

26 Why can two species with identical niches not survive indefinitely?

27 Outline the behavioural adaptations of the emperor penguin that enable it to survive in an extreme habitat.

28 Why do organisms in extreme niches have less stress from competition?

Links

- What are the mechanisms that allow species to adapt to their niches? (Section 11.3)
- What interspecific interactions limit a species to its realised niche? (Section 11.2)
- What are the roles of heterotrophs in recycling nutrients in an ecosystem (Section 12.3)

SELF-ASSESSMENT CHECKLIST

Think about the topics covered in this chapter. Which parts are you most confident with? Which topics require some extra practice?

I can...	**Subsection**	**Needs more work**	**Nearly there**	**Confident to move on**
list the hierarchy of taxa used for classification	11.1.1			
explain why scientists use a binomial name in the identification of species	11.1.1			
recall that organisms are classified into three domains based on rRNA evidence	11.1.2			
design a key to identify different organisms	11.1.2			
define a clade and understand	11.1.3			

diagrams of phylogeny to explain evolutionary relationships				
outline the reasons for using DNA or amino acid sequences to establish relationships	11.1.4			
draw and interpret cladograms	11.1.5			
outline reasons for a positive correlation between differences in two species and the time they diverged from a common ancestor	11.1.4, 11.1.5			
describe how natural selection can occur and how variation, adaptations, reproduction and sexual selection are important	11.2.1			
summarise how	11.2.2			

human impact provides evidence for evolution by exposing populations to pesticides, pollutants and antibiotics				
explain how selective breeding provides evidence for evolution	11.2.3			
define a gene pool	11.2.4			
outline directional, disruptive and stabilising selection	11.2.5			
use the Hardy–Weinberg theory to compare allele frequencies	11.2.6			
define a species and state that all species have originated from a common ancestor by evolution	11.3.1			
define evolution	11.3.1			
summarise how	11.3.2			