



Ecosystems (Continuity and change) revision notes

How populations and ecosystems change over time. Natural selection changes the heritable traits of populations, ecosystems stay stable only while certain requirements are met, and human activity, including climate change, can push them past tipping points.

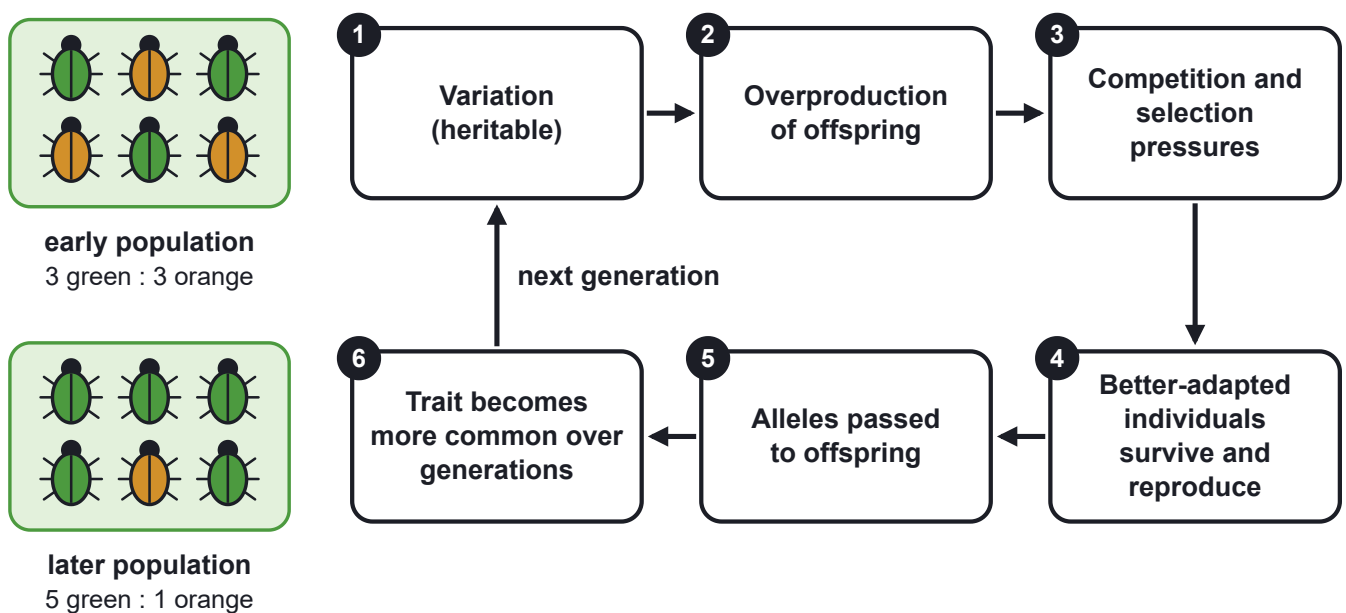
For IB Diploma Biology, Standard Level and Higher Level (first assessment 2025). **HL only** is additional higher level content, for HL students only.

1 Natural selection Spec D4.1

Natural selection as the mechanism of evolution Spec D4.1.1, D4.1.6

Natural selection is the mechanism driving evolutionary change. Evolution is a change in the heritable characteristics of a population over many generations. Natural selection operates continuously in every population, and it has done so for billions of years. Its accumulated effects have produced the biodiversity of life on Earth.

1. Individuals in a population vary, and much of this variation is heritable.
2. More offspring are produced than the environment can support.
3. Individuals compete for limited resources and face other selection pressures.
4. Individuals with traits better suited to the environment are more likely to survive and reproduce.
5. They pass the alleles for these traits to their offspring.
6. Over many generations, the frequency of these traits in the population rises.



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Natural selection: **heritable variation** plus overproduction and competition make better-adapted traits commoner over generations.

A paradigm shift

In Darwin's time it was widely understood that species evolved, but the mechanism was not clear. The leading idea was **Lamarckism**: organisms change during their lives through use and disuse, and pass these acquired changes on. Darwin's theory of natural selection gave a convincing mechanism and replaced Lamarckism. This is an example of a **paradigm shift**.

Paradigm shift	A fundamental change in the accepted theory and way of thinking in a field of science, when an old framework is replaced by a new one that explains the evidence better.
Lamarckism	The discarded idea that characteristics acquired during an organism's life, through use or disuse, are passed on to its offspring.

Traits must be heritable

Evolutionary change only happens if traits are **heritable**: coded in the base sequence of genes and passed on in gametes. Characteristics acquired during an individual's life due to environmental factors are not encoded in the base sequence of genes, so they are not heritable.

- Larger muscles built by training are not passed to offspring.
- A plant that grows tall in fertile soil does not produce taller offspring for that reason.
- A scar or a learned skill is not inherited.

Common mistake: Never write that organisms change 'because they need to'. Individuals do not evolve; populations do, as allele frequencies change over generations.

Mutation and sexual reproduction as sources of variation Spec D4.1.2

Natural selection can only act if individuals differ. Two processes generate the heritable variation it acts on.

Two sources of heritable variation		
Process	What it does	How
Mutation	Generates new alleles	A random change in the base sequence of DNA. Only mutations in cells that give rise to gametes are passed to offspring. Most are neutral or harmful; a few are beneficial.
Sexual reproduction	Generates new combinations of alleles	Crossing over in prophase I and random orientation of bivalents in metaphase I of meiosis give genetically different gametes. Random fertilisation of one gamete by another adds further combinations.

Mutation is the only source of genuinely new alleles. Sexual reproduction does not create alleles, but it shuffles existing ones into combinations that may never have existed before, so every offspring is genetically unique (apart from identical twins).

In asexual reproduction, offspring are genetically identical to the parent except where a mutation occurs, so variation is much more limited.

Exam tip: Keep the guide's distinction exact: mutation = new alleles; sexual reproduction = new combinations of alleles. Swapping them loses the mark.

Overproduction, competition and selection pressures Spec D4.1.3, D4.1.4, D4.1.5

Overproduction and competition

Most species produce far more offspring than can survive. The **carrying capacity** of an environment is the maximum population size it can support sustainably. Above it, there are not enough resources, so individuals of the same species compete: **intraspecific competition**.

- Animals: food (for example seeds for seed-eating birds), water, nesting or breeding sites, territory and shelter.
- Plants: light, water, mineral ions such as nitrate and phosphate, and space for roots.

Abiotic factors as selection pressures

A selection pressure is any factor that affects the chance of survival or reproduction differently depending on an individual's traits. Abiotic factors such as very high or very low temperatures, drought or flooding are **density-independent**: they affect survival whatever the population size. In a severe frost, for example, individuals with better insulation or more cold-tolerant tissues are more likely to survive.

Differences in adaptation, survival and reproduction

Individuals differ in how well adapted they are. Better-adapted individuals win more resources, survive longer and leave more offspring. This difference between individuals is the basis of natural selection.

Carrying capacity	The maximum population size of a species that an environment can support sustainably.
Density-independent factor	A factor, usually abiotic, that limits a population regardless of its density, such as a heatwave or a hard frost.
Fitness	The survival value and reproductive potential of a genotype: how many offspring it contributes to the next generation compared with other genotypes.

Exam tip: Survival alone earns no mark. Write 'survive and reproduce, passing on their alleles'.

Exam tip: Linking question: how do intraspecific interactions differ from interspecific interactions? Intraspecific competition is usually most intense because individuals of one species have identical resource needs.

Sexual selection and Endler's guppies Spec D4.1.7, D4.1.8

Sexual selection

Sexual selection is selection for traits that increase success in attracting a mate. Usually females choose between males, or males compete with each other. Differences in physical and behavioural traits can act as signs of overall fitness: only a healthy male in good condition can grow and display an elaborate ornament.

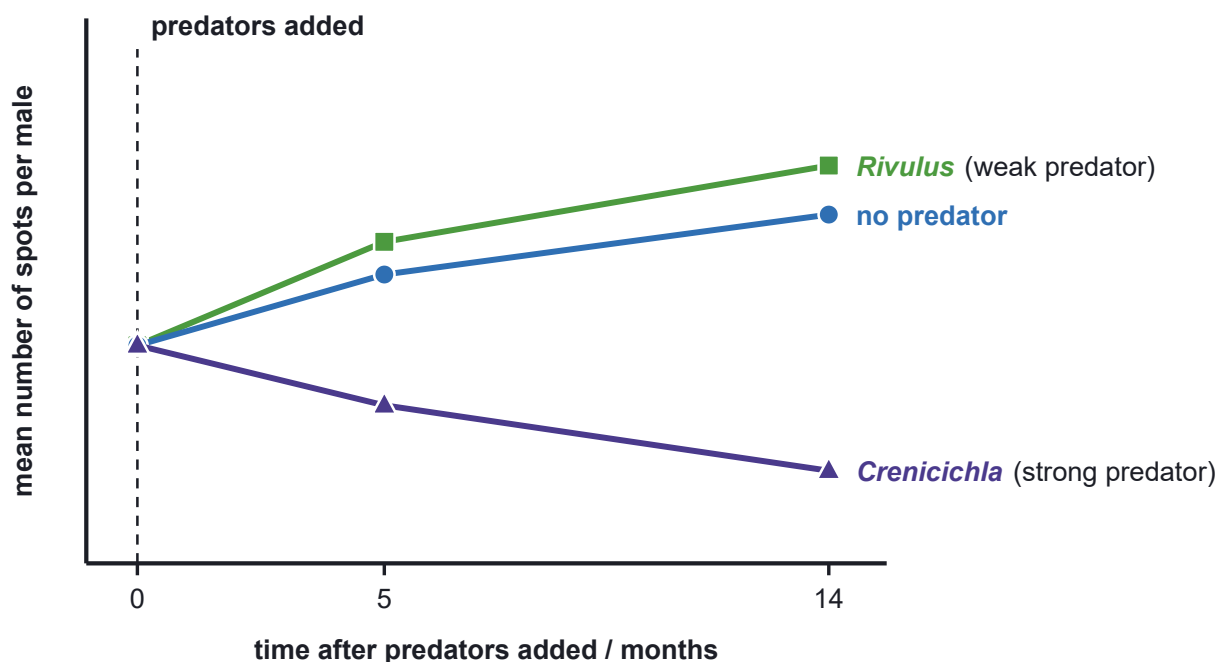
Male **birds of paradise** have brightly coloured plumage, long ornamental feathers and complex courtship displays, while females are dull brown. Females choose the males with the most impressive displays. Those males father more offspring, so alleles for elaborate plumage have increased in frequency, even though the plumage costs energy and makes the males more visible to predators.

Modelling selection: Endler's guppies

Guppies (*Poecilia reticulata*) live in streams in Trinidad. Males have coloured spots; females prefer more colourful males. In pools with a dangerous predator, the pike cichlid (*Crenicichla*), males are dull with

fewer spots. In pools with only a weak predator, *Rivulus*, which rarely eats adults, males are bright with many spots. Endler hypothesised that colour is a balance between sexual selection and predation.

1. Ten large ponds were set up in a greenhouse, five with coarse gravel and five with fine gravel, and stocked with guppies from many different streams.
2. The guppies bred freely for six months with no predators.
3. Predators were then added: two ponds had no predator, four had *Rivulus* and four had *Crenicichla*. The selection pressure was experimentally controlled.
4. The number and size of spots on males were recorded at the start, 5 months and 14 months after predators were added (about 10 generations).
5. Spot numbers rose in ponds with no predator or with *Rivulus*, and fell in ponds with *Crenicichla*, where the spots also became smaller.
6. In a field experiment, guppies moved from a high-predation site to a stream with only *Rivulus* had more colourful males within about two years (about 15 generations).



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Endler's ponds: spots increased without strong predation and decreased with *Crenicichla* (pattern only; values illustrative).

Practical skill: With Endler-style data, name the independent variable (predation pressure), the dependent variable (spot number or size), controlled variables (pond size, gravel, food) and the replicate ponds.

Gene pools and allele frequencies

Spec D4.1.9, D4.1.10, D4.1.11

HL only

Gene pool

All the genes and their different alleles present in a population.

Allele frequency

The proportion of all copies of a gene in a population that are a particular allele, given as a value from 0 to 1.

Geographically isolated populations

When populations are geographically isolated, alleles do not flow between them. Different mutations arise, selection pressures differ, and chance events change allele frequencies, so the gene pools

diverge.

- **Lactase persistence** (digesting lactose as an adult): over 90% of people in Sweden and Denmark have it, and it is common in some pastoralist groups in East Africa, but rare (5% or less) in most East Asian populations. Different lactase-persistence alleles (different mutations near the lactase gene) are responsible in Europe and in East Africa.
- **ABO blood groups**: the I^B allele is most frequent in Central and South Asia, while many Indigenous populations of South America have almost only the i allele (blood group O).

Practical skill: Use an allele frequency database (for example the Allele Frequency Net Database or gnomAD) to compare one human allele across populations, and record the population, sample size and frequency.

Natural selection changes allele frequencies

Individuals differ in their heritable traits. Those with traits giving higher fitness leave more offspring, so the alleles for those traits make up a larger share of the next generation's gene pool. Evolution can therefore be described as a **change in allele frequency** in a gene pool over time.

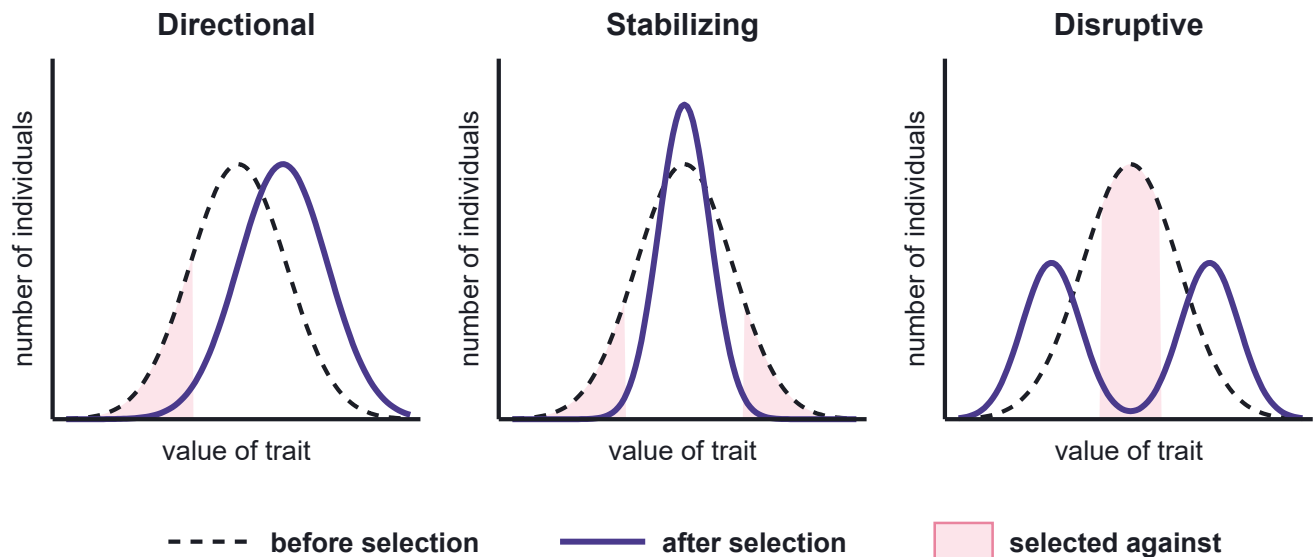
Darwin developed the theory of evolution by natural selection without knowing about genes. Biologists later integrated genetics with natural selection in what is now known as **neo-Darwinism**.

Directional, disruptive and stabilizing selection; artificial selection Spec D4.1.12, D4.1.15

HL only

Three patterns of natural selection on a continuously varying trait			
Type	Phenotypes favoured	Effect on the distribution	Example
Directional	One extreme	Mean shifts towards that extreme	Medium ground finches on the Galápagos after a drought: birds with deeper beaks could crack the large, hard seeds left, so mean beak depth increased.
Stabilizing	Intermediate values	Mean stays the same; variation decreases	Human birth mass: very light and very heavy babies historically had lower survival.
Disruptive	Both extremes	Variation increases; can split into two peaks	Black-bellied seedcrackers: small-billed birds feed well on soft seeds and large-billed birds on hard seeds; intermediates do neither well.

All three types result in a **change in allele frequency**, because individuals with some alleles leave more offspring than others.



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Directional, stabilizing and disruptive selection all change allele frequency.

Artificial selection

Artificial selection is carried out in crop plants and domesticated animals by choosing individuals with desirable traits for breeding, generation after generation.

- Wild cabbage (*Brassica oleracea*) has been bred into cabbage, kale, broccoli, cauliflower and Brussels sprouts by selecting for leaves, flower heads or buds.
- Dairy cattle have been selected for high milk yield.

Common mistake: Antibiotic resistance in bacteria is an unintended consequence of human action. Nobody chose which bacteria would breed, so it is natural selection, not artificial selection.

The Hardy-Weinberg equation and its conditions Spec D4.1.13, D4.1.14 HL only

For a gene with two alleles, **p** and **q** denote the two allele frequencies. Where one allele is dominant, **p** is usually the dominant allele and **q** the recessive allele. Every allele copy is one or the other, so $p + q = 1$, and with random combination of gametes the genotype frequencies are p^2 , $2pq$ and q^2 .

$$p + q = 1$$

$$p^2 + 2pq + q^2 = 1$$

What each term means

Term	Genotype frequency
p^2	Homozygous dominant (AA)
$2pq$	Heterozygous (Aa)
q^2	Homozygous recessive (aa)

Allele and carrier frequencies

In a population, 1 in 2500 people has a recessive genetic condition. Calculate the frequency of carriers (practice figures).

1. $q^2 = 1 \div 2500 = 0.0004$
2. $q = \sqrt{0.0004} = 0.02$
3. $p = 1 - q = 0.98$
4. $2pq = 2 \times 0.98 \times 0.02 = 0.0392$

Answer: Carrier frequency = 0.0392, about 3.9% or 1 in 26 people.

Maths skill: Start from q^2 , the homozygous recessive frequency, because it is the only genotype you can identify from the phenotype. Never take the square root of the dominant phenotype frequency.

Conditions for genetic equilibrium

- A very large population, so chance changes (genetic drift) are negligible.
- Random mating.
- No mutation.
- No migration into or out of the population (no gene flow).
- No natural selection: all genotypes survive and reproduce equally.

If observed genotype frequencies do not fit the Hardy-Weinberg equation, one or more conditions is not being met, for example **mating is non-random** or **survival rates vary between genotypes**.

Quick check

1. What generates new alleles?
2. Why are acquired characteristics not inherited?
3. What is fitness?
4. **HL only** What does $2pq$ represent in the Hardy-Weinberg equation?
5. **HL only** Is antibiotic resistance an example of artificial selection?

2 Stability and change Spec D4.2

Stability of natural ecosystems Spec D4.2.1, D4.2.2

A stable ecosystem keeps a similar community and similar processes over time, and recovers after disturbance. **Stability** is a property of natural ecosystems. There is evidence, from fossils and from pollen preserved in sediments, that some ecosystems have persisted for millions of years.

- **Tropical rainforest** in the Daintree region of north-east Australia descends from forests that covered much of Gondwana. Fossil pollen shows rainforest in Australia for tens of millions of years, and it survived here while drier climates shrank it elsewhere. (Popular figures of 135–180 million years are not firmly supported.)
- The **Namib Desert** in south-west Africa has been arid or semi-arid for at least 55 million years, and extremely dry for the last few million. Many desert species there, such as fog-basking beetles, are found nowhere else.

Requirements for stability in ecosystems	
Requirement	Why it matters
Supply of energy	Sunlight captured by producers supports every trophic level; energy is not recycled, so the supply must be continuous.
Recycling of nutrients	Decomposers return carbon, nitrogen and phosphorus to the soil and air, so producers never run out.
Genetic diversity	Populations with many alleles are more likely to include individuals that survive a new disease or a change in conditions.
Climatic variables within tolerance levels	Temperature and rainfall must stay within the range the species can tolerate.

Exam tip: Linking question: over what timescales do things change in different biological systems? Ecosystems can be stable for millions of years yet collapse within decades once a requirement fails.

Amazon deforestation as a possible tipping point Spec D4.2.3

A **tipping point** is a critical threshold beyond which a small further change causes a large, often irreversible, shift to a different state.

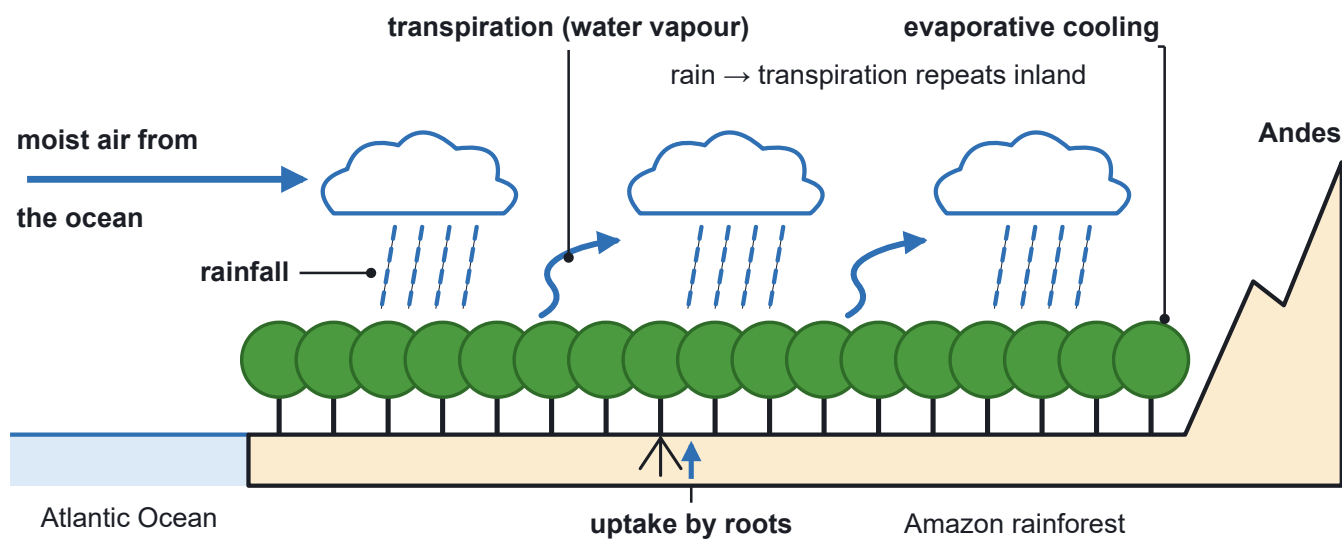
How the rainforest makes its own rain

1. Trees take up water from the soil and release huge amounts of water vapour by **transpiration**.
2. Evaporation of this water absorbs heat, which cools the land surface.
3. Rising moist air and the condensation of vapour drive air flows that draw in more moist air from the Atlantic Ocean.
4. The water vapour condenses and falls as rain further inland, where it is transpired again. Water is recycled several times across the basin.

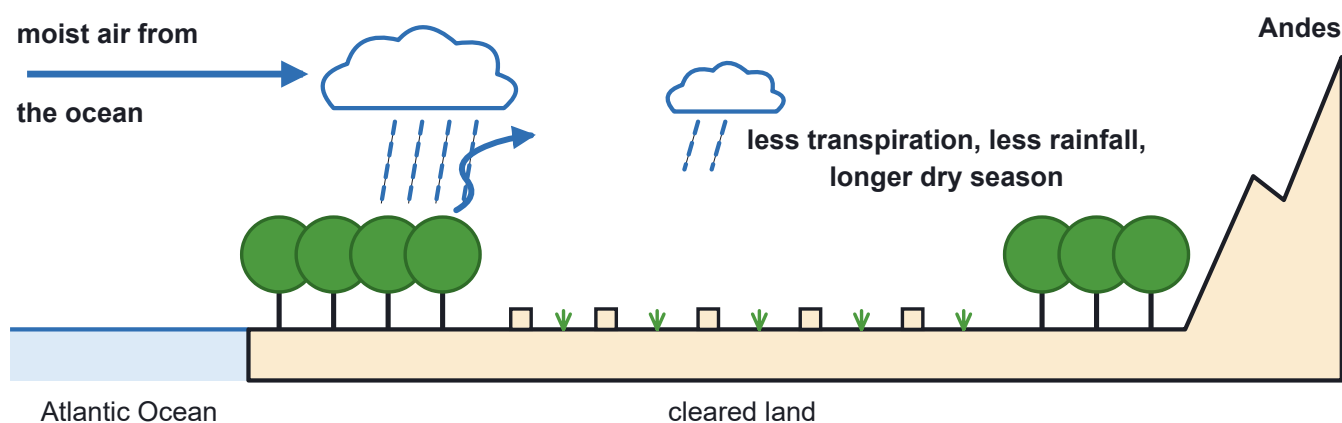
Deforestation reduces transpiration, so less rain falls and the dry season lengthens. Remaining trees become drought-stressed and fires spread more easily, killing more trees: a **positive feedback**. Beyond a tipping point, large parts of the forest could change to savannah.

A **large area** of rainforest is needed to keep these processes going, but there is uncertainty over the minimum area that is sufficient. Estimates differ between models, and climate change and fire make the threshold harder to predict.

intact rainforest



after deforestation



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The Amazon recycles its own rain by **transpiration**; clearing forest weakens the cycle.

Maths skill: The extent of deforestation can be assessed by calculating the percentage change from the original area of forest.

$$\text{percentage change} = (\text{final value} - \text{original value}) \div \text{original value} \times 100$$

Percentage change in forest area

A region originally had 4 200 000 km² of rainforest. It now has 3 486 000 km². Calculate the percentage change (practice figures).

1. Change = 3 486 000 – 4 200 000 = –714 000 km²
2. –714 000 ÷ 4 200 000 = –0.17
3. –0.17 × 100 = –17%

Answer: –17%: the forest area has decreased by 17% of the original.

Mesocosms and keystone species Spec D4.2.4, D4.2.5

Using a model: mesocosms

A **mesocosm** is a small, enclosed experimental ecosystem that models a natural one, so that one variable can be changed while others are controlled. Mesocosms can be set up in open tanks, but **sealed glass vessels** are preferable: entry and exit of matter is prevented, but energy transfer is still possible, as light enters and heat leaves. Aquatic or microbial ecosystems are likely to be more successful than terrestrial ones.

1. Set up several identical sealed glass jars with pond water, sediment, aquatic plants and algae.
2. Change one variable between jars, for example light intensity, temperature or added nitrate, with at least three replicates of each.
3. Keep other variables the same and leave the jars for several weeks.
4. Monitor stability, for example dissolved oxygen, pH, water clarity and the number of organisms of each type.

Practical skill: Care and maintenance of mesocosms should follow IB experimental guidelines: avoid causing harm or distress to animals, and use plants and microorganisms where you can.

Keystone species

A **keystone species** has a disproportionate impact on community structure compared with its abundance. If it is removed, the community changes greatly and the ecosystem may collapse.

- **Sea otters** in Pacific kelp forests eat sea urchins. Where otters were hunted out, urchins multiplied and grazed the kelp away, leaving 'urchin barrens' with far fewer species.
- **Ochre starfish** (*Pisaster*) on rocky shores eat mussels. When they were removed in experiments, mussels covered the rocks and the number of species fell sharply.

Sustainable harvesting and agriculture Spec D4.2.6, D4.2.7

Wild plants and fish are **renewable resources**. Sustainability depends on the **rate of harvesting being lower than the rate of replacement** by growth and reproduction.

Assessing the sustainability of harvesting	
Example	How sustainability is assessed
Brazil nut tree (<i>Bertholletia excelsa</i>), harvested from wild Amazon forest	Surveys of the size and age structure of tree populations, repeated over years. A study of 23 populations (2003) found that stands with a long history of heavy nut collection lacked young trees, so recruitment may be too low to replace old trees. Later long-term studies at some sites found stable populations despite heavy collection, so sustainability must be assessed site by site.
Atlantic cod (<i>Gadus morhua</i>), marine fish	Stock assessments estimate the mass of breeding adults from catches and research surveys; a catch dominated by young fish is a sign of overfishing. Quotas and net mesh sizes are then set. The northern cod stock off Newfoundland collapsed and a moratorium on commercial fishing began in 1992. Canada reopened a commercial fishery in 2024, which is controversial because the stock is still well below its former size.

Factors affecting the sustainability of agriculture

Factor	Problem	More sustainable practice
Soil erosion	Bare, ploughed soil is washed or blown away	Cover crops, contour ploughing, hedgerows
Leaching of nutrients	Nitrate and phosphate dissolve and drain out of the soil	Apply fertilizer in smaller amounts when crops need it
Supply of fertilizers and other inputs	Phosphate is mined from finite rock deposits; nitrogen fertilizer manufacture uses large amounts of fossil fuel	Crop rotation with nitrogen-fixing legumes, use of manure
Pollution due to agrochemicals	Pesticides and herbicides harm non-target species and water	Integrated pest management, targeted spraying
Carbon footprint	CO ₂ from machinery, transport and fertilizer manufacture; methane from livestock	Lower energy inputs, local supply chains

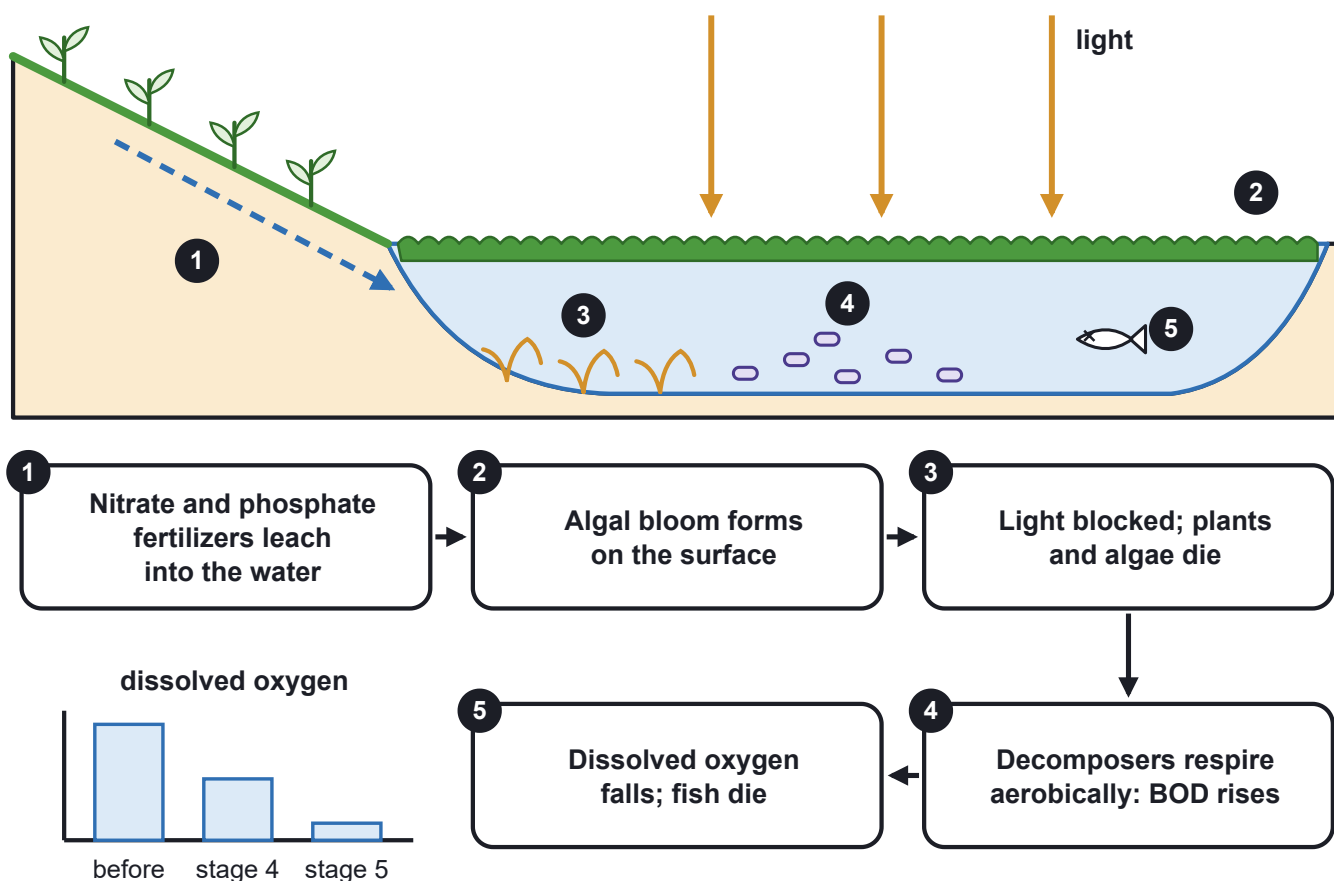
Eutrophication Spec D4.2.8

Eutrophication is the enrichment of water with nutrients. Nitrogen and phosphate fertilizers **leach** out of farmland and run into rivers, lakes and coastal seas.

1. Nitrate and phosphate leach from fields into the water.
2. Algae and other producers grow rapidly, forming an **algal bloom** at the surface.
3. The bloom blocks light, so plants below cannot photosynthesise and die; the short-lived algae die too.
4. Bacteria decompose the dead organic matter, using oxygen in aerobic respiration.
5. **Biochemical oxygen demand** rises and dissolved oxygen falls.
6. Fish and other animals that need oxygen die, forming a low-oxygen 'dead zone'.

Biochemical oxygen demand (BOD)

The amount of dissolved oxygen used by microorganisms in a water sample over a set time while breaking down organic matter. A high BOD shows heavy organic pollution.



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Eutrophication: decomposers raise **biochemical oxygen demand**, so dissolved oxygen falls and fish die.

Common mistake: Fish die from lack of oxygen used up by decomposers, not because algae 'use up the oxygen' by photosynthesis. Algae produce oxygen while alive.

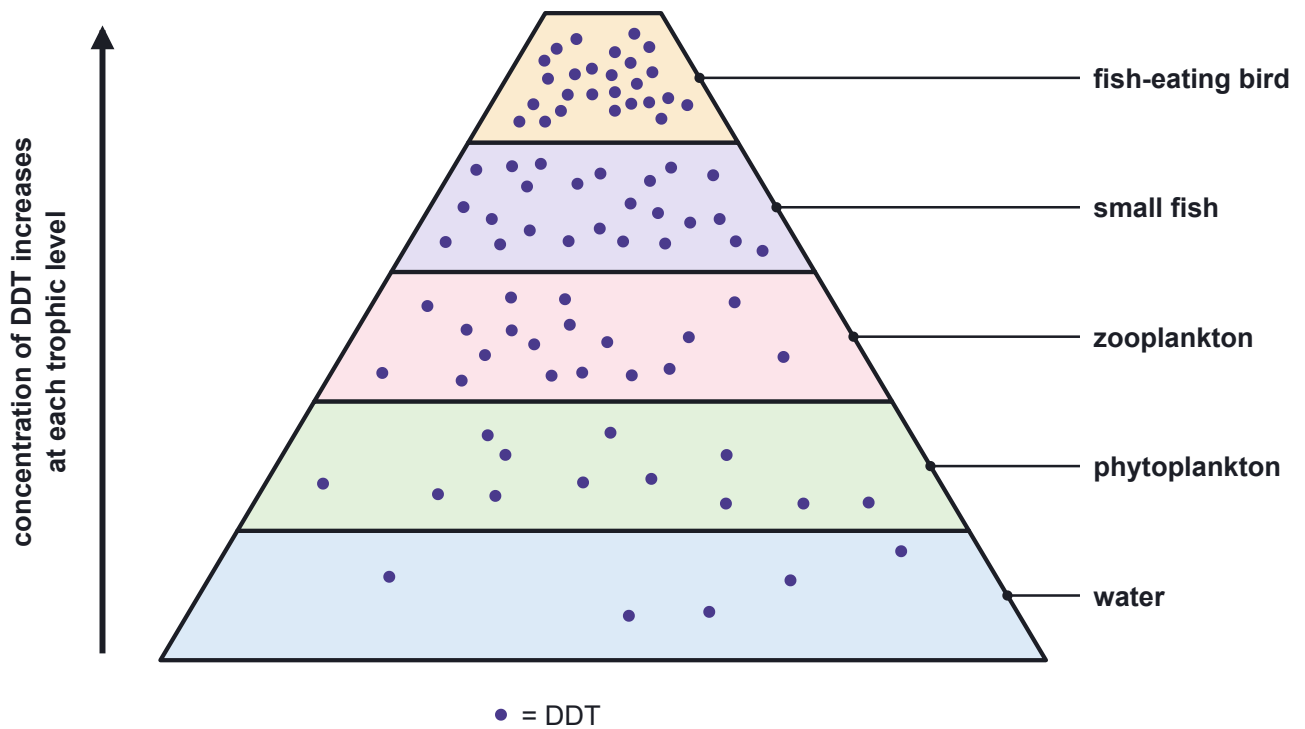
Biomagnification of pollutants Spec D4.2.9

Some pollutants are **persistent** (not broken down) and fat-soluble, so organisms store them in their tissues instead of excreting them. Their concentration builds up inside each individual over its life (bioaccumulation).

Each consumer eats many prey, taking in all the toxin they stored. So the concentration rises at each trophic level: **biomagnification**. Consumers in the highest trophic levels have the highest concentrations.

Two examples

Pollutant	Source	Effect at high trophic levels
DDT	Insecticide sprayed on crops and to control malaria mosquitoes	Birds of prey such as ospreys and peregrine falcons laid eggs with thin shells that broke, and populations crashed. Populations recovered after DDT was banned for farm use in many countries.
Mercury	Burning coal and gold mining; bacteria in sediments convert it to methylmercury	High levels in large predatory fish such as tuna and swordfish. It damages the nervous system of fish-eating mammals and birds, and of humans.



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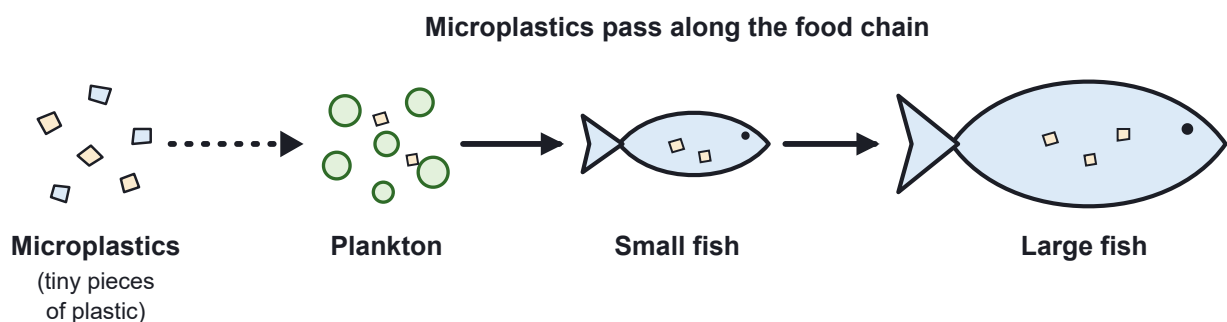
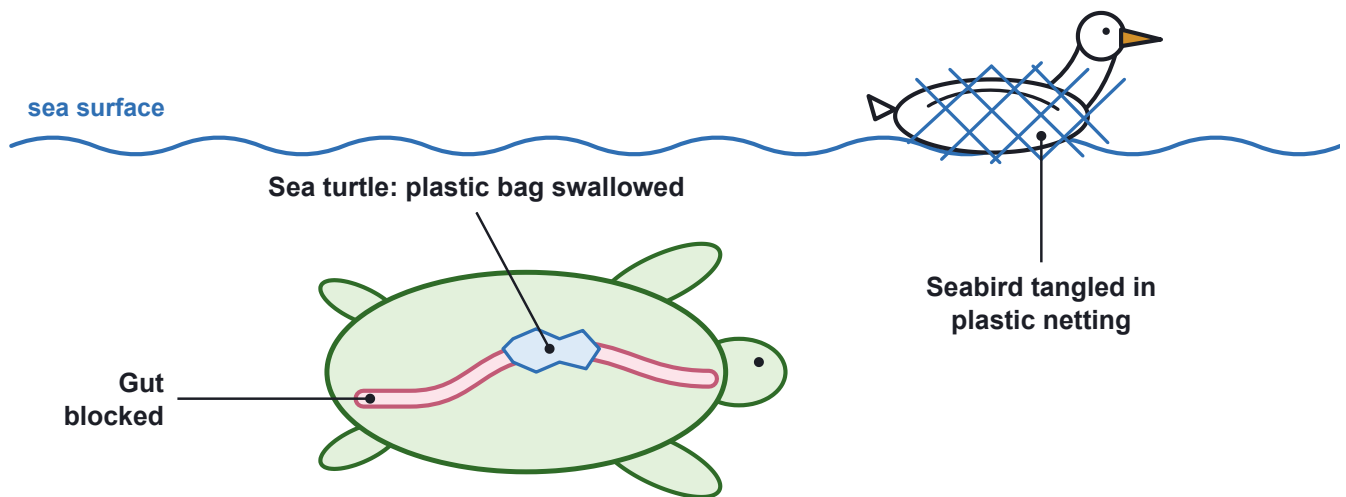
Biomagnification: DDT concentration rises at each higher trophic level.

Exam tip: Explain biomagnification with three ideas: persistent, stored in fatty tissue (not excreted), and each consumer eats many organisms from the level below.

Microplastic and macroplastic pollution of the oceans Spec D4.2.10

Most plastics are **non-biodegradable**: decomposers do not have enzymes to break them down. So plastics are **persistent** in the natural environment for decades or longer. Sunlight and waves break large pieces into smaller ones.

Type	Examples	Effects on marine life
Macroplastic (larger pieces)	Bags, bottles, packaging, lost fishing nets	Entanglement of seals, turtles and seabirds, causing drowning or injury; sea turtles swallow bags mistaken for jellyfish; albatross chicks are fed plastic, which fills their stomachs and causes starvation.
Microplastic (pieces under 5 mm)	Fragments of larger plastic, fibres from clothing	Eaten by zooplankton, filter feeders such as mussels, and fish; passed along food chains; can carry toxic chemicals that stick to their surfaces.



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Macroplastic entangles and blocks guts; **microplastics** pass along marine food chains.

Exam tip: Nature of science: scientists can influence citizens by giving clear information. Popular media coverage of plastic harming marine life changed public perception globally and drove measures such as bans on single-use bags and microbeads.

Rewilding Spec D4.2.11

Rewilding aims to restore natural processes so that an ecosystem can sustain itself with as little human management as possible.

- **Reintroduction of apex predators and other keystone species:** grey wolves were returned to Yellowstone National Park, USA, in 1995. Studies reported less browsing by elk and regrowth of willow and aspen in some areas, although the size of the effect is still debated.
- **Re-establishment of connectivity of habitats over large areas:** wildlife corridors link fragments so populations can move, find mates and exchange alleles.
- **Minimisation of human impact, including by ecological management:** removing livestock, controlling invasive species, then stepping back.

Hinewai Reserve, New Zealand

Hinewai Reserve on Banks Peninsula, South Island, is former sheep farmland that had become covered by gorse, an introduced shrub. Since 1987 it has been managed with minimal interference. Grazing animals were kept out, and the gorse was not burned or sprayed. Gorse acts as a nursery: native tree seedlings grow up through it, then overtop and shade it out. Native forest is now regenerating over more than 1 000 hectares.

Exam tip: Linking question: what is the distinction between artificial and natural processes? Rewilding uses a human decision to let natural processes take over again.

Ecological succession and primary succession Spec D4.2.12, D4.2.13 HL only

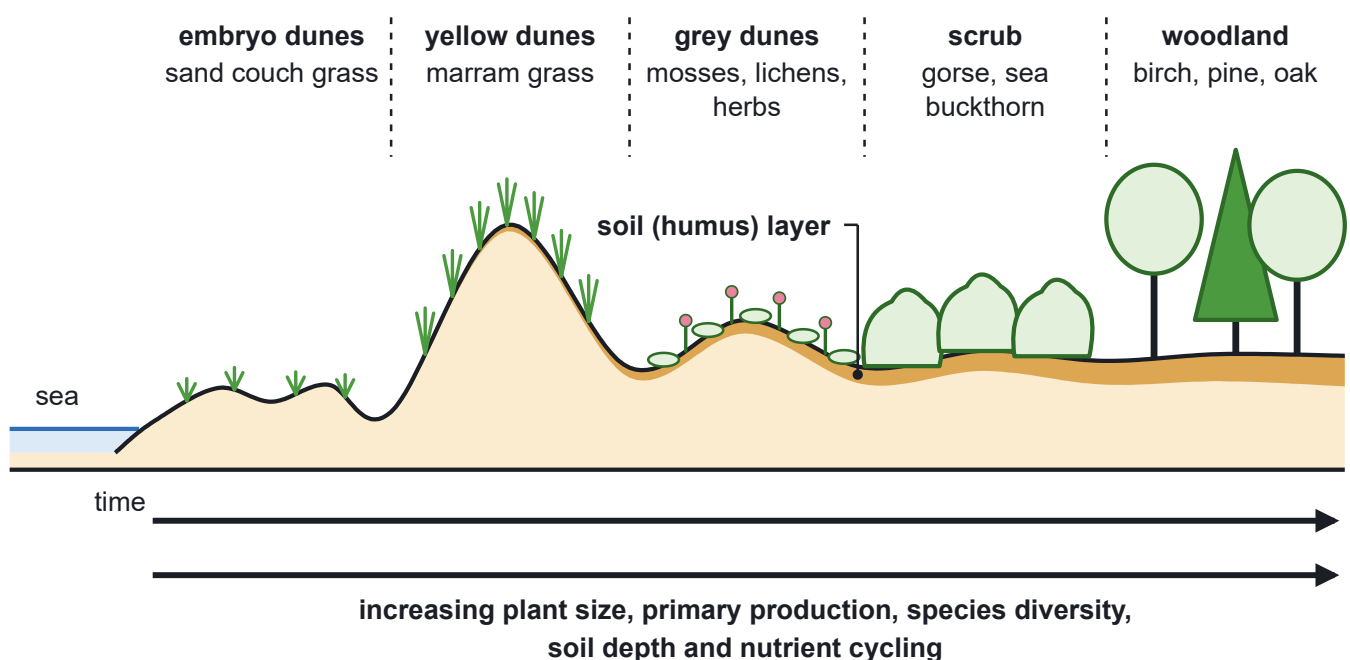
Ecological succession is a sequence of changes in the community of an area over time. It can be triggered by changes in the **abiotic environment**, for example new land exposed by a retreating glacier or deposited as sand dunes, and by **biotic factors**, for example organisms forming soil, casting shade or adding nitrogen, so that conditions suit different species.

Primary succession starts on land with no soil. **Secondary succession** starts where soil remains after a disturbance, such as a fire.

Example: sand dune succession

1. Pioneer species such as sand couch grass tolerate salt spray and wind and colonise bare sand above the high-tide line.
2. Their roots trap sand; marram grass grows up through new sand and stabilises taller dunes.
3. Dead plant matter adds humus, so the soil holds more water and nutrients; mosses, lichens and many herbs colonise.
4. Shrubs such as gorse and sea buckthorn grow in the deeper soil and shade out low plants.
5. Woodland of trees such as birch, pine and oak develops.

General changes during primary succession	
Feature	Change
Size of plants	Increases, from low pioneers to shrubs and trees
Amount of primary production	Increases
Species diversity	Increases
Complexity of food webs	Increases, with more trophic links
Amount of nutrient cycling	Increases, as more organic matter is decomposed and soil deepens



Primary succession on sand dunes: moving inland means moving **forward in time**.

Cyclical succession, climax communities and arrested succession Spec D4.2.14, D4.2.15

HL only

Cyclical succession

In some ecosystems there is a **cycle of communities** rather than a single unchanging climax community. In heathland dominated by heather (*Calluna vulgaris*), patches go through a repeating cycle.

1. Pioneer phase: young heather plants establish in a gap.
2. Building phase: heather forms a dense canopy and dominates the patch; few other plants grow beneath it.
3. Mature phase: the plants lose vigour and the canopy starts to open in the centre.
4. Degenerate phase: old woody stems collapse outwards, leaving gaps colonised by lichens, mosses and other plants such as bearberry, then new heather seedlings, and the cycle restarts.

One full cycle takes roughly 30–40 years, so a heathland is a mosaic of patches at different phases while the heathland as a whole stays the same. This model was first described for heather in Scotland; it does not apply everywhere, for example not on wet bogs.

Climax communities and arrested succession

Given any specific environmental conditions, succession tends to lead to a particular type of **climax community**, a relatively stable community determined mainly by climate and soil, often forest where rainfall allows. Human influences can stop it from developing: **arrested succession**.

- **Grazing by farm livestock:** sheep and cattle eat tree seedlings, so grassland or moorland persists where woodland would grow.
- **Drainage of wetlands:** lowering the water table removes waterlogged conditions, so wetland and peat-forming communities are lost and the land is used for farming; the natural sequence cannot continue to its climax.

*Exam tip: A community kept by human activity at a stage short of the natural climax is called a **plagioclimax**.*

Quick check

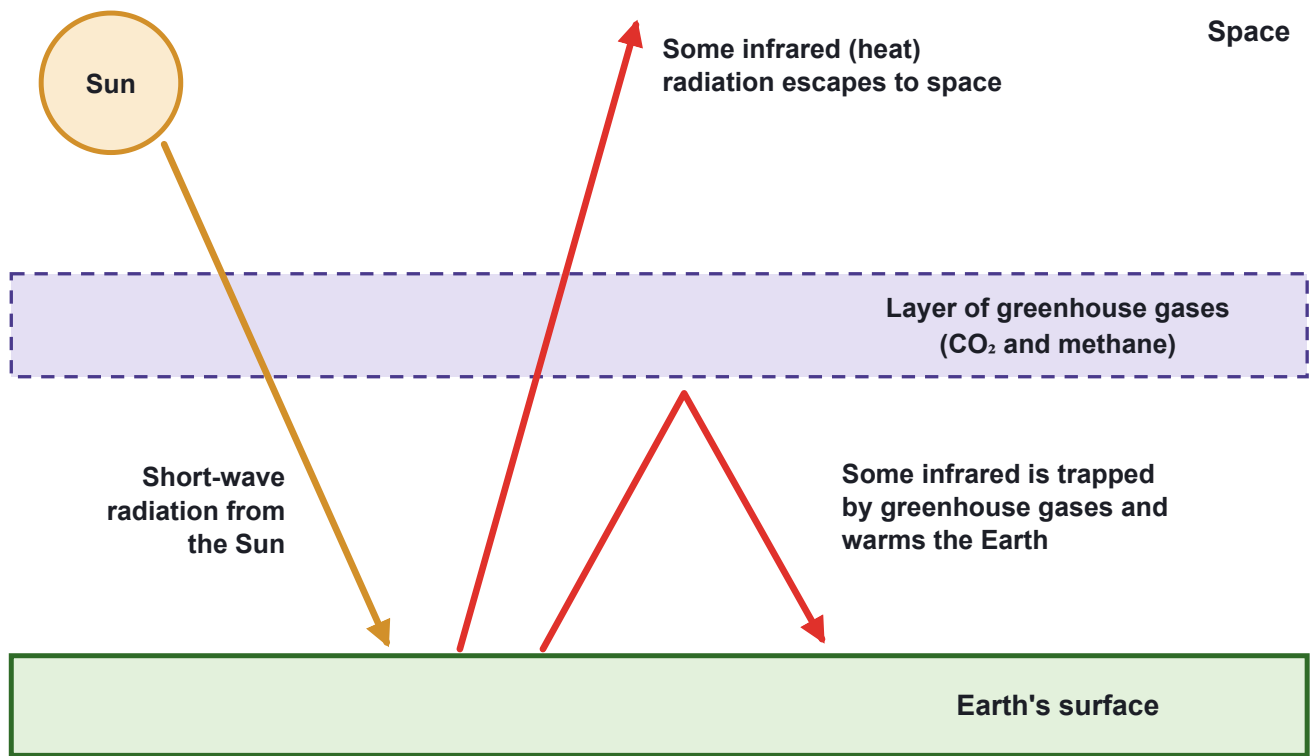
1. Name the four requirements for ecosystem stability.
2. When is harvesting sustainable?
3. What does BOD stand for?
4. Why are sealed glass vessels preferred for mesocosms?
5. **HL only** Give two human causes of arrested succession.

3 Climate change Spec D4.3

Anthropogenic causes and positive feedback Spec D4.3.1, D4.3.2

Carbon dioxide and methane are greenhouse gases: they absorb and re-emit longer-wave infrared radiation from the Earth's surface, warming the atmosphere. **Anthropogenic** (human-caused) increases in their concentrations enhance the greenhouse effect.

Gas	Main anthropogenic sources
Carbon dioxide	Combustion of coal, oil and natural gas; deforestation and burning of forests; cement production
Methane	Livestock such as cattle (fermentation in the gut); flooded rice fields; landfill; leaks from fossil fuel extraction



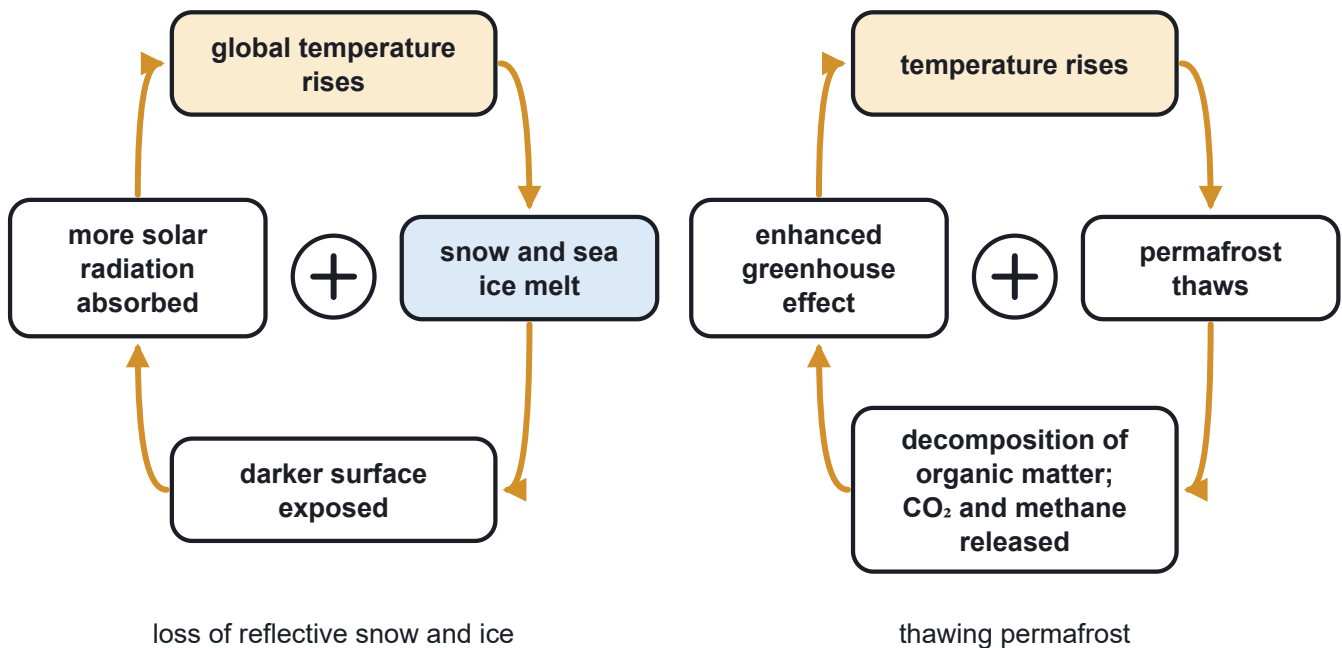
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Increased CO₂ and methane trap more **infrared radiation**, warming the Earth.

Positive feedback cycles

In **positive feedback**, warming causes changes that cause further warming.

- **Release of CO₂ from the deep ocean:** warmer water holds less dissolved CO₂, and changing circulation brings CO₂-rich deep water to the surface, where it is released.
- **Loss of reflective snow and ice:** dark land and sea absorb more solar radiation than white ice, so warming speeds up.
- **Decomposition of peat and permafrost:** thawing allows faster decomposition of peat and of previously undecomposed organic matter, releasing CO₂.
- **Methane from melting permafrost:** anaerobic decomposition in waterlogged thawed soil releases methane.
- **Droughts and forest fires:** fires release CO₂, and drought-stressed plants absorb less CO₂.



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Two **positive feedback** cycles: loss of reflective ice and thawing permafrost both speed up warming.

Boreal forest tipping point and polar habitat change Spec D4.3.3, D4.3.4

Boreal forests: from carbon sink to carbon source

Boreal forest (taiga) covers much of Canada, Scandinavia and Russia. It has stored huge amounts of carbon in trees and deep soil layers, accumulating more carbon each year than it loses. Climate change could switch it to **net carbon loss**, an example of a tipping point.

1. Warmer temperatures and decreased winter snowfall mean less meltwater in spring.
2. Drought becomes more frequent, so primary production in the taiga falls.
3. Stressed trees lose needles and die: **forest browning**.
4. Forest fires become more frequent and intense.
5. Fires burn **legacy carbon**: old organic matter in deep soil layers that survived earlier, less intense fires.
6. The forest releases more carbon than it absorbs.

Melting of landfast ice and sea ice

Landfast ice is sea ice attached to the coast. **Emperor penguins** (*Aptenodytes forsteri*) breed on it in the Antarctic winter, and chicks need stable ice until they grow waterproof feathers. Early breakout of the ice drowns or chills chicks, so breeding grounds can be lost. In 2022, several colonies in the Bellingshausen Sea region lost almost all their chicks this way.

Walruses in the Arctic use floating sea ice as a platform for resting and nursing calves between dives to feed on shellfish on the shallow sea bed. As sea ice retreats, walruses crowd onto beaches in very large groups, where calves can be crushed in stampedes, and must swim further to feed.

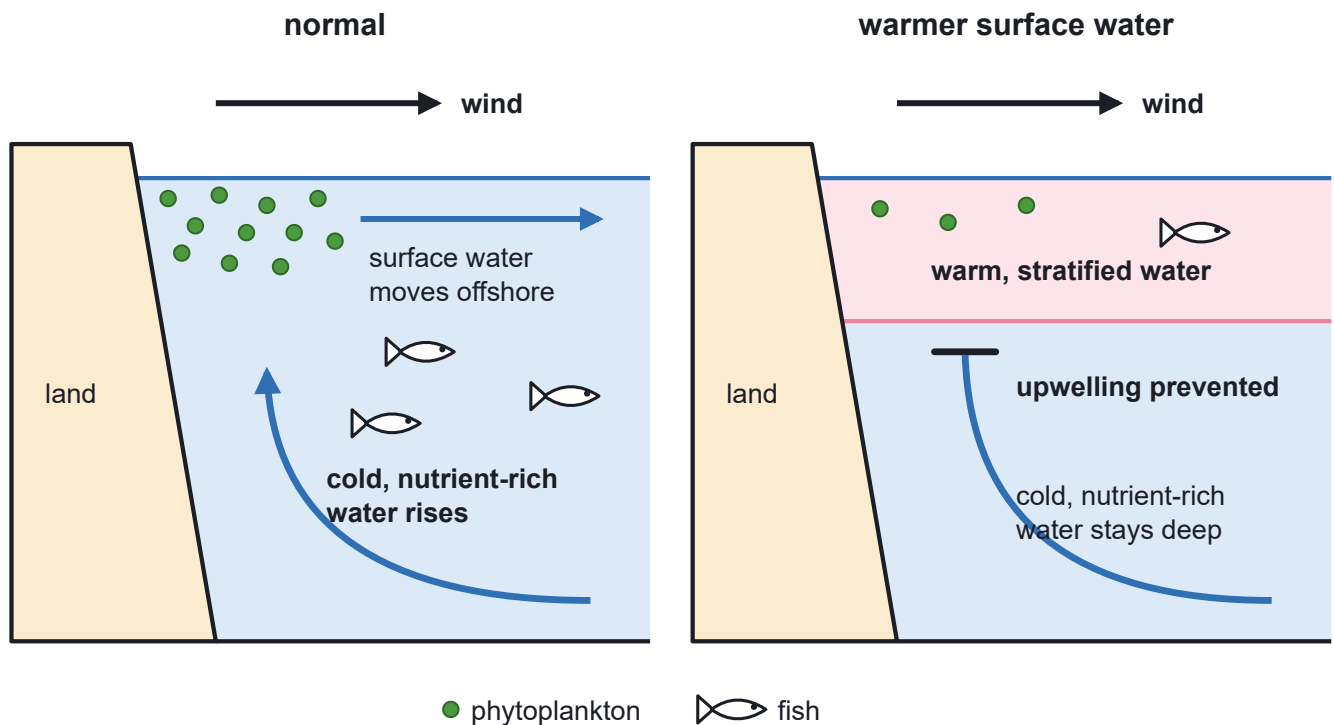
*Exam tip: In the exam you may use either the common name or the scientific name of an organism, for example emperor penguin or *Aptenodytes forsteri*.*

Nutrient upwelling and threats to coral reefs Spec D4.3.5, D4.3.7

Nutrient upwelling

In **upwelling** zones, currents bring cold, nutrient-rich water from the deep ocean to the sunlit surface, where phytoplankton use the nitrate and phosphate for growth. These zones support some of the most productive fisheries.

Warmer surface water is less dense and forms a stable layer that does not mix with the cold water below. This can **prevent nutrient upwelling** to the surface. Ocean primary production decreases, so less energy flows through marine food chains to fish, seabirds and marine mammals. Changes in currents also alter the timing of upwelling, so it may not match the breeding seasons of consumers.



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Warm, stratified surface water can **prevent nutrient upwelling**, lowering ocean primary production.

Threats to coral reefs

- **Ocean acidification:** increased CO₂ dissolves in seawater, forming carbonic acid. The pH falls and fewer carbonate ions are available, which suppresses **calcification**, so corals build calcium carbonate skeletons more slowly.
- **Coral bleaching:** increases in water temperature cause corals to expel their symbiotic algae (zooxanthellae). The corals turn white and lose their main source of food; if high temperatures last, they die.

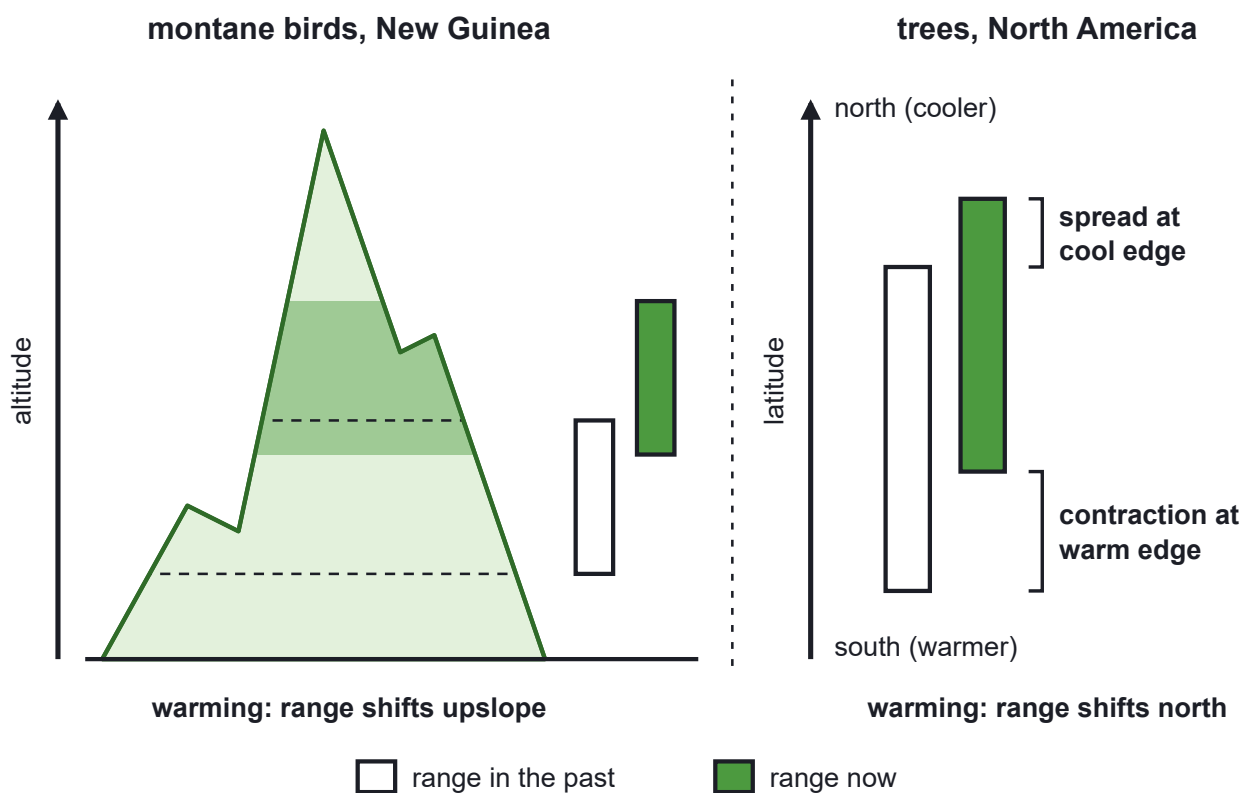
Corals build the reef structure that provides habitat and food for very many species. Loss of corals causes the **collapse of reef ecosystems**, so coral reefs are an example of potential ecosystem collapse.

Poleward and upslope range shifts Spec D4.3.6

Each species can only live within a range of temperatures. As the climate warms, the warm edge of a range becomes too hot and areas beyond the cool edge become suitable. So species ranges shift **towards the poles** and **upslope**, to higher altitudes.

Evidence-based examples	
Example	Evidence
Tropical-zone montane birds in New Guinea	Surveys repeated on the same mountain slopes decades apart found that many bird species now live higher up than before, with their upper and lower limits moved upslope .
North American tree species	Surveys of forest plots show some species with range contraction at their southern, warmer edge and northward spread at their cooler edge. Trees disperse slowly, so many ranges are shrinking faster than they spread.

Species on mountain tops and near the poles have nowhere further to move, so they are at particular risk of extinction.



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Warming shifts ranges **upslope** and **towards the poles** (schematic).

Afforestation, forest regeneration and peatland restoration Spec D4.3.8

Carbon sequestration is the capture of carbon dioxide from the atmosphere and its long-term storage, here as organic carbon in plants and soil.

Approach	What it involves
Afforestation	Planting trees on land that has not been forest for a long time
Forest regeneration	Allowing or helping forest to regrow on land where it has been cleared
Restoration of peat-forming wetlands	Blocking drains to rewet peatland, so waterlogged conditions return and peat forms again

Peat forms because waterlogged soil is anaerobic and acidic, so decomposers break down dead plant matter very slowly and carbon accumulates. Peat formation naturally occurs in waterlogged soils in temperate and boreal zones, and also very rapidly in some tropical ecosystems.

An active scientific debate		
Approach	For	Against
Plantations of non-native trees	Fast-growing species can absorb CO ₂ quickly	Often monocultures with low biodiversity; harvesting releases stored carbon
Rewilding with native species	Higher biodiversity; more resilient to pests and climate	May sequester carbon more slowly at first

Exam tip: When asked to evaluate, weigh both sides: speed of carbon uptake against biodiversity and long-term storage.

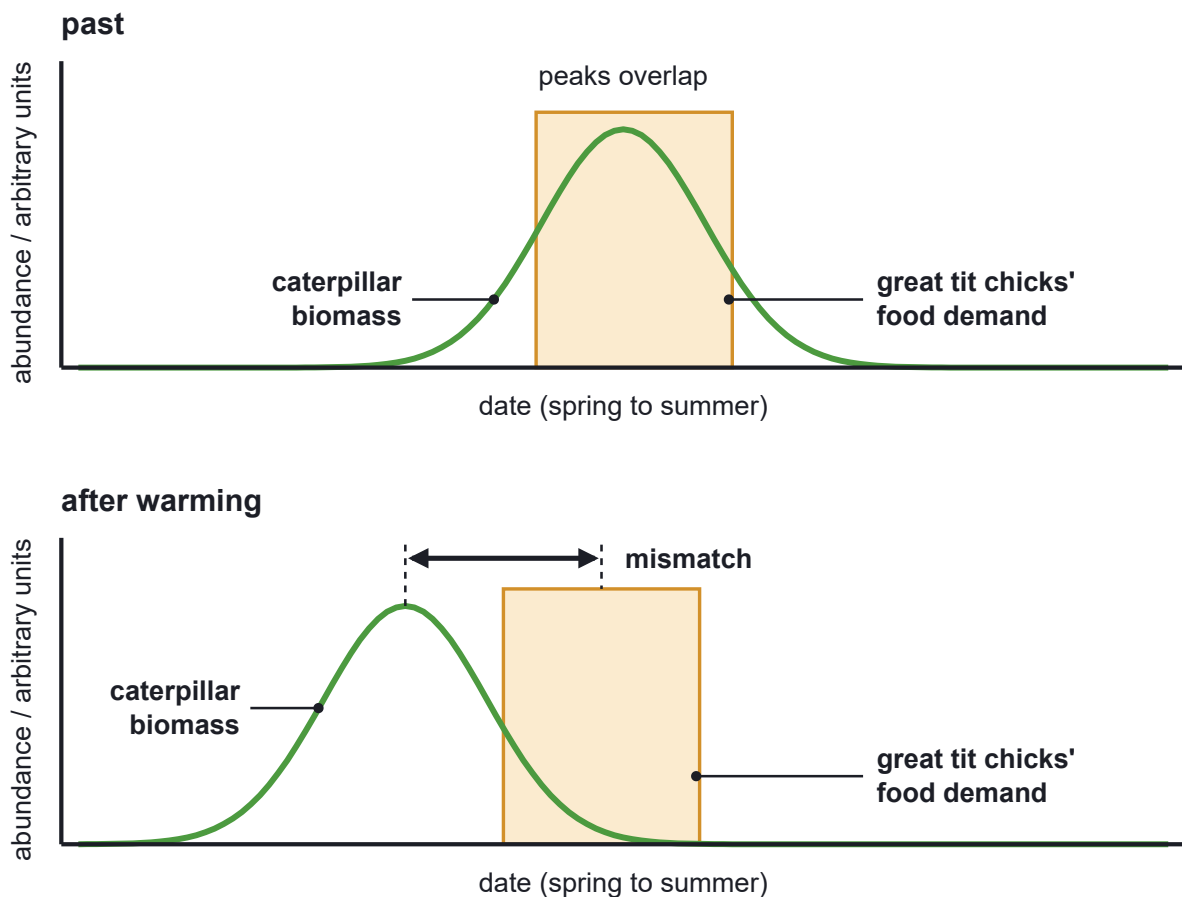
Phenology and disrupted synchrony Spec D4.3.9, D4.3.10 HL only

Phenology is research into the timing of biological events. Examples include flowering, budburst and bud set in deciduous trees, bird migration and nesting.

Two variables commonly act as cues: **photoperiod** (day length), which is not affected by climate change, and **temperature patterns**, which are. Within an ecosystem, temperature may act as the cue in one population and photoperiod in another.

Disruption to synchrony

Example	Cues	Effect of warming
Arctic mouse-ear chickweed (<i>Cerastium arcticum</i>) and migrating reindeer (<i>Rangifer tarandus</i>) in Greenland	Plant growth is cued by temperature; reindeer migration to calving grounds is cued by photoperiod	Plants grow earlier in warm springs, so peak food has passed when reindeer arrive and calve. Fewer calves survive.
Great tit (<i>Parus major</i>) and caterpillars in north European forests	Caterpillar emergence follows temperature and leaf budburst; great tit laying date changes less	Peak caterpillar biomass comes earlier, so chicks hatch after the peak and fewer survive.



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After warming, the caterpillar peak comes earlier but great tit chicks do not: a **mismatch** (illustrative).

Exam tip: Name the cue for each species. The mismatch only arises because the two populations respond to different cues.

Insect life cycles and evolution due to climate change Spec D4.3.11, D4.3.12 HL only

More insect life cycles per year

Insect development speeds up at higher temperatures, and warmer springs and autumns lengthen the breeding season. The **spruce bark beetle** (*Ips typographus*) used to complete one generation a year in much of northern Europe. In warmer years it can now complete two, or even three.

- Populations grow much faster, leading to outbreaks.
- Beetles bore into spruce bark and lay eggs; larvae feed beneath the bark, killing trees.
- Drought-stressed trees produce less resin to defend themselves, so damage increases further.

Evolution as a consequence of climate change

The **tawny owl** (*Strix aluco*) has two heritable colour variants, grey and brown. In cold, snowy winters, grey owls survive better than brown ones, probably because they are better camouflaged against snow and cope better with cold. As winters in Finland have had less snow cover, the survival disadvantage of brown owls has weakened, so their **fitness** has increased. The proportion of brown owls in the population has risen, a change in allele frequency.

Exam tip: Link back to natural selection: the colour is heritable, the selection pressure (snow cover) has changed, so the fitter variant leaves more offspring and allele frequencies change.

Quick check

1. Which two greenhouse gases does the guide limit anthropogenic causes to?
2. What is legacy carbon?
3. What causes coral bleaching?
4. **HL only** What is phenology?
5. **HL only** Why are spruce bark beetle outbreaks increasing?

Quick check answers

Natural selection

1. Mutation: a random change in the base sequence of a gene.
2. They are not encoded in the base sequence of genes.
3. The survival value and reproductive potential of a genotype.
4. The frequency of heterozygotes.
5. No, it is natural selection; nobody chose which bacteria would reproduce.

Stability and change

1. Supply of energy, recycling of nutrients, genetic diversity, climatic variables within tolerance levels.
2. When the rate of harvesting is lower than the rate of replacement.
3. Biochemical oxygen demand.
4. Matter cannot enter or leave, but energy transfer is still possible.
5. Grazing by farm livestock and drainage of wetlands.

Climate change

1. Carbon dioxide and methane.
2. Old organic carbon in deep soil layers of boreal forest that survived earlier fires.
3. Increases in water temperature cause corals to expel their symbiotic algae.
4. Research into the timing of biological events.
5. Warming lets them complete more life cycles each year.