

Ecosystems (Interaction and interdependence)

revision notes

This group looks at how organisms in an ecosystem depend on each other. C4.1 covers how populations are measured, how they grow and what limits them, and the relationships between species in a community. C4.2 follows energy as it flows through food chains and is lost as heat, and carbon and other elements as they are recycled.

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

1 Populations and communities **Spec C4.1**

Populations and random sampling **Spec C4.1.1, C4.1.2, C4.1.3**

Population	An interacting group of organisms of the same species living in an area.
Sampling error	The difference between the estimate of population size from a sample and the true size of the whole population.
Sessile	Fixed in one place, not moving about: for example plants, barnacles and mussels.

Members of a population normally **breed** with each other. Two populations of the same species are distinguished by **reproductive isolation**: individuals in one population rarely or never breed with individuals in the other, for example because a mountain range, a stretch of sea or a different breeding season separates them.

Why estimate rather than count?

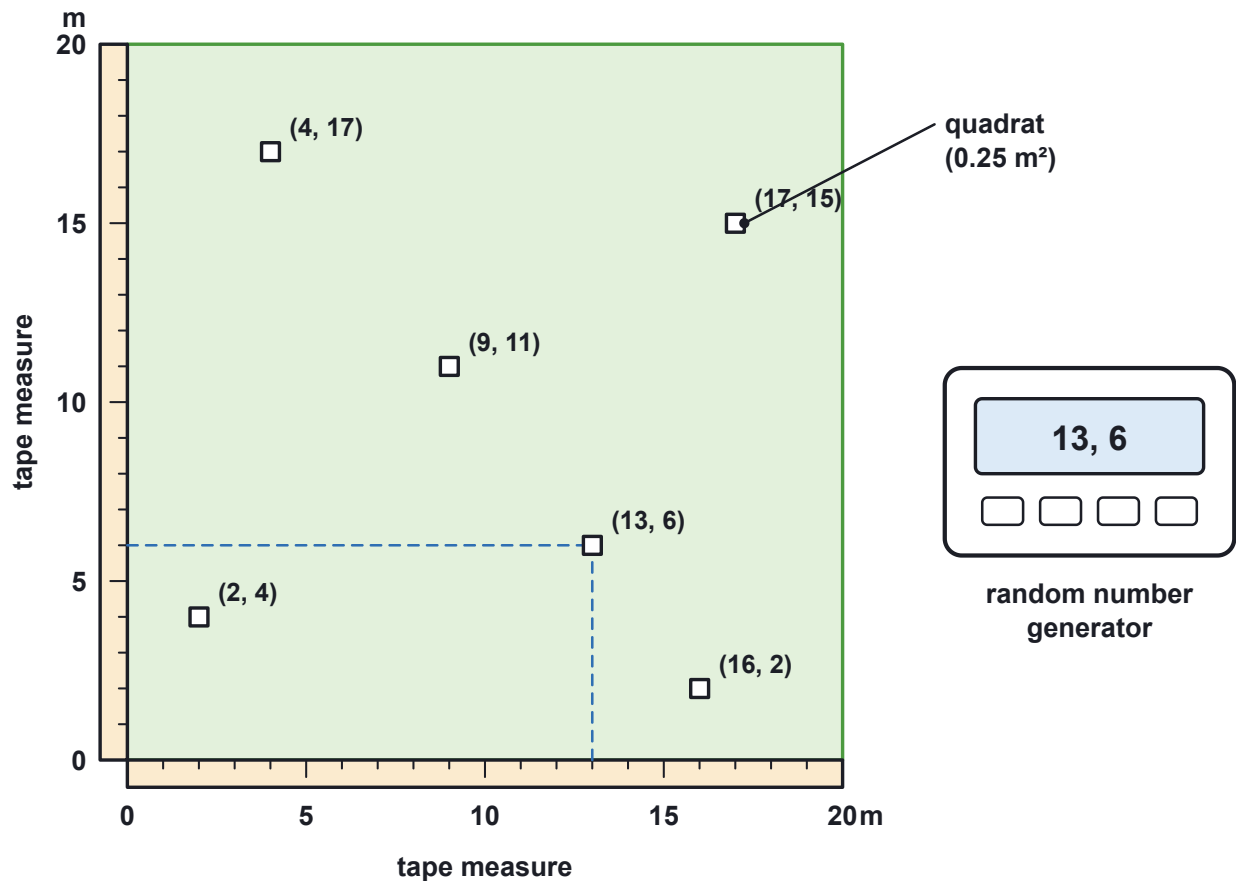
Counting every individual is usually impossible or impractical: the area is too large, the organisms are too numerous, too small or hidden, and counting would take too long or disturb the habitat. Ecologists therefore count a sample and scale up. Samples must be **random**, so that every individual or every part of the area has an equal chance of being included. A sampler who chooses where to look introduces bias (for example, towards dense patches).

Because only a sample is measured, the estimate will almost always differ from the true value. This sampling error is unavoidable, but it is reduced by taking more samples and by randomising them properly.

Random quadrat sampling

1. Mark out the sampling area with two tape measures at right angles to form a grid.
2. Use a random number generator to pick coordinates and place a quadrat of known area (for example 1 m²) at each one.
3. Count the individuals of the species inside each quadrat (use a rule for those on the edge, such as counting only those touching two sides).
4. Repeat for many quadrats and calculate the mean number per quadrat.

5. Population size estimate = mean number per m² × total area in m².



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Random quadrat sampling: coordinates from a random number generator decide where each quadrat goes.

This method suits **sessile** organisms, plants or animals, where the individuals in a quadrat can be counted. It does not work for animals that move in and out of the quadrat.

Practical skill: The standard deviation of the mean number per quadrat measures the spread of the counts. A small SD means the population is spread fairly evenly; a large SD means it is clumped. You do not need to memorise the formula: calculate it on a calculator or spreadsheet.

Estimating a population from quadrats

Ten random 1 m² quadrats in a 500 m² meadow contain 3, 5, 0, 2, 6, 4, 1, 3, 5 and 1 plantain plants. Estimate the population size.

1. Total = 3 + 5 + 0 + 2 + 6 + 4 + 1 + 3 + 5 + 1 = 30 plants.
2. Mean = 30 ÷ 10 = 3.0 plants per m².
3. Estimate = 3.0 × 500 = 1500 plants.

Answer: About 1500 plantain plants (an estimate, subject to sampling error).

Capture-mark-release-recapture and the Lincoln index Spec C4.1.4

Animals that move about (**motile** organisms) cannot be counted in quadrats. Instead, the proportion of marked animals in a second sample is used to estimate the whole population.

1. Capture as many individuals as possible in a set time with a suitable method (pitfall traps for beetles, sweep nets for insects, small mammal traps).

2. Mark each one in a way that does not harm it or make it more visible to predators (a dot of non-toxic paint, a fur clip, a ring). Count them: this is M.
3. Release them where they were caught and allow time for them to mix back into the population.
4. Capture a second sample with the same method and effort. Count the total caught (N) and the number already marked (R).

$$\text{Population size estimate} = (M \times N) \div R$$

M = number caught and marked initially; N = total number recaptured in the second sample; R = number of marked individuals recaptured.

Using the Lincoln index

In a woodland, 45 ground beetles are caught in pitfall traps, marked and released. Two days later 60 beetles are caught, of which 15 are marked. Estimate the population.

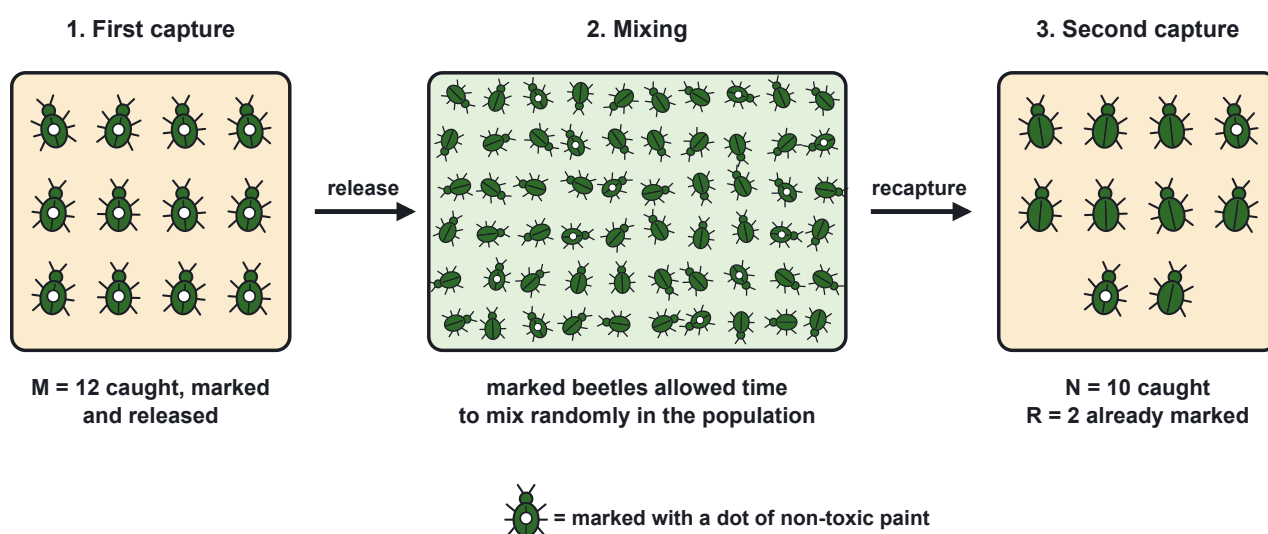
1. $M = 45, N = 60, R = 15$.
2. Estimate = $(45 \times 60) \div 15 = 2700 \div 15$.
3. = 180.

Answer: About 180 ground beetles.

Assumptions

- Marking does not harm the animals or change their behaviour or chance of being eaten.
- Marks are not lost (worn off or moulted) between the two samples.
- Marked individuals mix randomly back into the whole population before the second sample.
- Marked and unmarked animals have an equal chance of being caught (no trap-shyness or trap-happiness).
- No significant births, deaths, immigration or emigration between the two samples.

Maths skill: Check your answer is at least as big as $M + N - R$, the number of different animals actually seen. If R is very small, the estimate is very unreliable.



$$\text{estimate} = (M \times N) \div R = (12 \times 10) \div 2 = 60$$

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The Lincoln index: **population estimate** = $(M \times N) \div R$. Here $(12 \times 10) \div 2 = 60$ beetles.

Carrying capacity and density-dependent factors Spec C4.1.5, C4.1.6

Carrying capacity	The maximum population size of a species that an environment can support.
Density-dependent factor	A factor whose effect on the population increases as population density increases, such as competition, predation or disease.
Density-independent factor	A factor that affects a population regardless of its density, such as a flood, fire, drought or very cold winter.

Every environment has a **carrying capacity** for each species because resources are limited. When a population reaches it, individuals **compete** for the resources in shortest supply. Examples of limiting resources: food for animals; light, water and mineral ions such as nitrate for plants; space for sessile animals on a rocky shore; nesting sites for birds; oxygen in water for fish.

Negative feedback control

Density-dependent factors act as **negative feedback**: they reduce the birth rate or raise the death rate more strongly when the population is dense, and relax when it is sparse. This tends to push the population back towards the carrying capacity.

Density-dependent factors and how they act	
Factor	Effect in a dense population
Competition for limited resources	Less food, water or space per individual: lower survival and fewer offspring
Predation	Prey are easier to find and catch, and predator numbers rise, so more prey are killed
Pathogens and pests	Close contact transfers infections and parasites between individuals more easily, so disease spreads faster

1. Population rises above the carrying capacity.
2. Competition, predation and disease increase.
3. Death rate rises and/or birth rate falls.
4. Population falls back towards the carrying capacity; the factors then weaken.

Density-independent factors can make numbers **fluctuate**, for example a storm killing many seabirds at once, but they do not regulate the population around a set level.

Exam tip: Linking question: what factors can limit capacity in biological systems? Compare carrying capacity with limiting factors in photosynthesis or enzyme saturation.

Population growth curves Spec C4.1.7, C4.1.8

Exponential growth

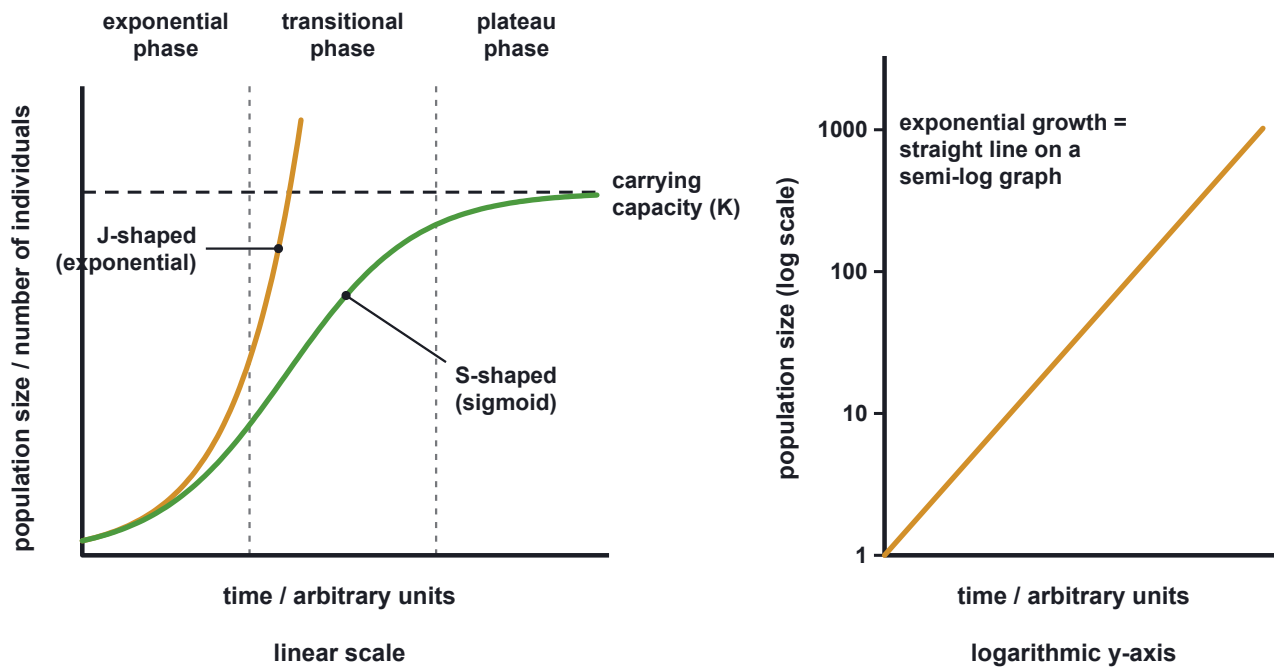
In the first phase, when a few individuals colonise a new area, numbers increase **exponentially**: the population doubles at regular intervals. Reasons: resources are abundant, so there is little competition; predators, pathogens and parasites are scarce or absent; so the birth rate greatly exceeds the death rate, and every new individual soon adds offspring of its own.

Case study: in 1937, eight ring-necked pheasants (two males and six females) were released on Protection Island, Washington, USA, which had plenty of food and few predators. The population grew roughly exponentially, to more than 1300 birds after five years, before growth slowed. A second case: 29

reindeer released on St Matthew Island, Alaska, in 1944 grew to about 6000 by 1963. Having overgrazed their lichen food supply, almost all of them starved in the severe winter of 1963–64, and only 42 were alive in 1966, showing that exponential growth cannot continue.

Sigmoid growth

- Exponential phase: rapid increase, birth rate far greater than death rate.
- Transitional phase: density-dependent factors begin to act; the rate of increase slows but numbers still rise.
- Plateau phase: births plus immigration balance deaths plus emigration; the population fluctuates around the **carrying capacity**.



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Exponential (J-shaped) and sigmoid (S-shaped) growth. On a semi-log graph, exponential growth gives a **straight line**. Idealised models, not real data.

Maths skill: To test whether growth is exponential, plot population size on a logarithmic vertical axis against time on a normal horizontal axis. Exponential growth gives a straight line; the line bends and flattens as growth slows towards the carrying capacity.

The sigmoid curve is an idealised **model**. Real populations overshoot, oscillate or crash, and their carrying capacity changes from year to year. Models are simplifications of complex systems, useful for making predictions and for comparison with real data.

Practical skill: Model sigmoid growth with duckweed (*Lemna*): count fronds in a beaker of pond water every 2–3 days. Or use yeast in sugar solution: count cells in a haemocytometer, or measure cloudiness with a colorimeter, at regular intervals. Keep temperature and light constant.

Common mistake: The IB sigmoid curve starts with exponential growth: a lag phase is not expected. Do not add a death phase either; that belongs to a closed culture running out of resources.

Intraspecific and interspecific relationships Spec C4.1.9, C4.1.10, C4.1.11

Within a species

Members of the same species have the same needs, so **intraspecific competition** happens whenever a resource is in short supply. Reasons include limited food, water, space or territory, light (plants), nest sites and mates.

Examples of intraspecific competition and cooperation	
Relationship	Example
Competition for mates	Red deer stags roar and fight in the rut; winners mate with groups of hinds
Competition for light	Dense tree seedlings shade each other; only the tallest survive to form the canopy
Competition for territory	Robins defend feeding territories against other robins
Cooperation in hunting	Grey wolves hunt in packs, bringing down prey such as elk that one wolf could not kill
Cooperation in defence and care	Meerkats take turns as sentinels; worker honeybees rear the queen's offspring and defend the hive
Cooperation in keeping warm	Emperor penguins huddle in groups through the Antarctic winter, reducing heat loss

Communities

A **community** is all of the interacting organisms in an ecosystem: every population in the area, including plants, animals, fungi and bacteria. An ecosystem is the community together with its abiotic environment.

Between species

Categories of interspecific relationship		
Relationship	What happens	Example
Herbivory	A primary consumer feeds on a plant or alga	Dromedary camels browsing acacia shoots
Predation	A consumer kills and eats another animal	Canada lynx hunting snowshoe hares
Interspecific competition	Two species use the same limited resource, and both are harmed	Red and grey squirrels competing for seeds in British woodland
Mutualism	Both species benefit	<i>Rhizobium</i> bacteria in root nodules of legumes
Parasitism	A parasite lives on or in a host and takes nutrients from it, harming but not usually killing it	Ticks feeding on the blood of cattle
Pathogenicity	A pathogen causes disease in its host	<i>Mycobacterium tuberculosis</i> causing tuberculosis in humans

Exam tip: Intra- means within (one species); inter- means between (different species). Mixing these up costs easy marks.

Mutualism Spec C4.1.12

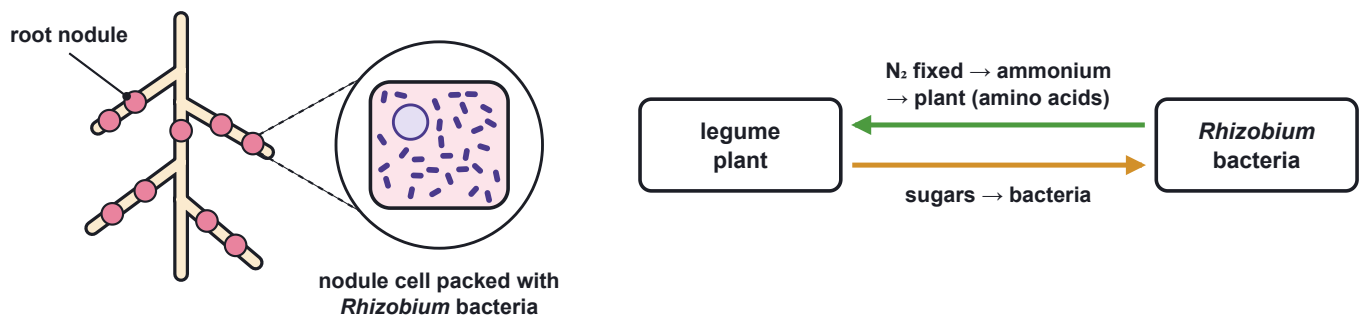
In **mutualism** both species gain. Each partner provides something the other cannot easily obtain alone.

Three examples of mutualism and the benefit to each partner

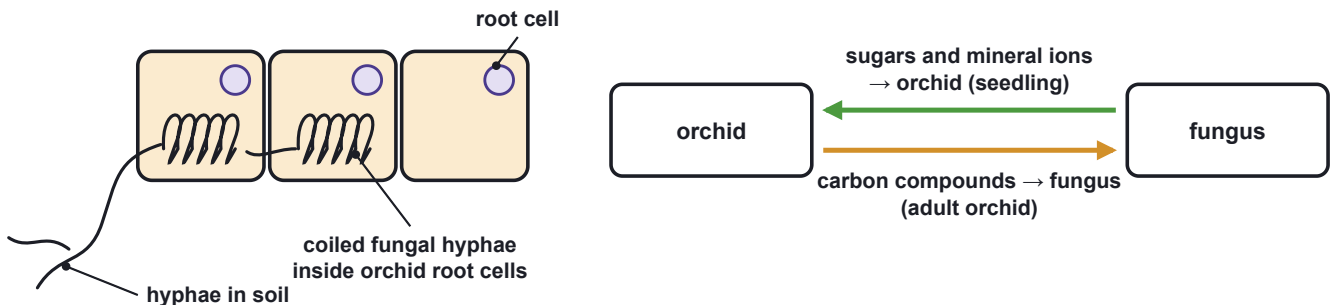
Example	Benefit to the first partner	Benefit to the second partner
Root nodules in Fabaceae (legumes such as peas, beans, clover)	Plant: <i>Rhizobium</i> bacteria fix nitrogen gas (N ₂) into ammonium, which the plant uses to make amino acids, so it grows in nitrogen-poor soil	<i>Rhizobium</i> : receives sugars and other carbon compounds from the plant's photosynthesis, and a protected, low-oxygen site inside the nodule
Mycorrhizae in Orchidaceae (orchids)	Orchid: fungal hyphae inside root cells supply sugars and mineral ions; orchid seeds are tiny with almost no food store, so seedlings depend on the fungus to germinate and grow	Fungus: receives carbon compounds such as sugars from the orchid once it has green leaves and photosynthesises (shown by isotope tracing in creeping lady's-tresses, <i>Goodyera repens</i>); a seedling gives nothing back, so the relationship becomes mutualistic only in the adult
Zooxanthellae in hard corals	Coral: the photosynthetic algae inside its cells pass sugars, other organic compounds and oxygen to the coral, supplying most of its energy	Zooxanthellae: receive carbon dioxide and nitrogen compounds (ammonia) from the coral's metabolism, and a protected, well-lit position near the surface

Zooxanthellae are dinoflagellates. If seawater gets too warm, corals expel them and **bleach**; without their partner they starve unless the algae return.

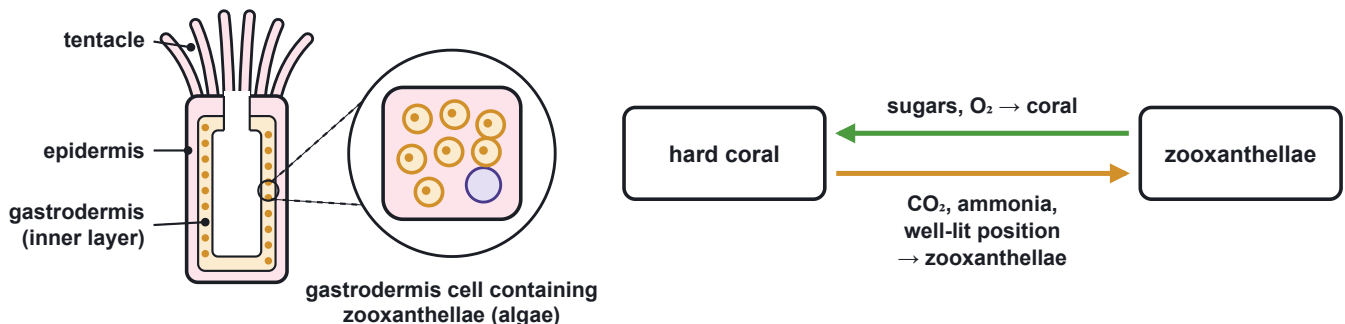
Root nodules: legumes (Fabaceae) and *Rhizobium*



Mycorrhizae: orchids (Orchidaceae) and fungi



Hard corals and zooxanthellae



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Three mutualisms. Each arrow is a benefit, so **both partners gain**.

Exam tip: For every example, give a benefit to each partner. Answers that give a benefit to only one partner lose marks. Common or scientific names are both accepted.

Invasive species and testing for competition Spec C4.1.13, C4.1.14, C4.1.15

Endemic and invasive species

An **endemic** species is native to an area. An introduced species becomes **invasive** when it has a competitive advantage in resource acquisition over endemic species and spreads at their expense. Often its natural predators, pathogens and competitors were left behind.

Local example (UAE): mesquite, *Prosopis juliflora*, is native to the Americas and was planted in the UAE from the 1970s to combat desertification. It grows fast, sets abundant seed that livestock spread, and can switch between shallow lateral roots and a deep taproot, so it takes up groundwater more effectively than native plants. It forms dense thickets, and the native ghaf tree, *Prosopis cineraria*, is the native plant most affected where they grow together. Another well-studied example: the grey squirrel, introduced to Britain from North America, outcompetes the endemic red squirrel for seeds such as acorns, which it digests more efficiently.

Testing for interspecific competition

- **Laboratory experiments:** grow each species alone and then together under controlled conditions. In Gause's experiments, *Paramecium aurelia* and *P. caudatum* both thrived alone, but together *P. aurelia* outcompeted *P. caudatum*.
- **Field observations by random sampling:** record where each species is found. If they rarely occur together, competition may be keeping them apart.
- **Field manipulation by removal:** remove one species from plots and compare with control plots. On rocky shores, when the barnacle *Semibalanus* (*Balanus*) was removed, the barnacle *Chthamalus* survived lower down the shore than before.

If one species is more successful in the absence of the other, competition is indicated but not proven, because other factors could explain the result. Hypotheses can be tested by both experiments (the investigator manipulates a variable and controls others) and observations (natural patterns are recorded without intervention); experiments give stronger evidence of cause.

Chi-squared test for association

Record the presence or absence of two species in many random quadrats and arrange the counts in a 2×2 contingency table. The null hypothesis (H_0) is that there is no association: the two species are distributed independently.

1. Expected frequency for each cell = (row total $\times$ column total) $\div$ grand total.
2. For each cell calculate $(O - E)^2 \div E$, where O is observed and E expected.
3. Add them: $\chi^2 = \sum (O - E)^2 \div E$.
4. Degrees of freedom = (rows - 1) $\times$ (columns - 1) = 1 for a 2×2 table. Critical value at $p = 0.05$ is 3.84.
5. If χ^2 is greater than 3.84, reject H_0 : there is a significant association. Compare O and E to see whether it is positive (found together more than expected) or negative (less than expected).

Chi-squared test for two plant species

In 40 random quadrats: both species present 4; species A only 16; species B only 16; neither 4. Species A is present in 20 quadrats and B in 20. Is there an association?

1. Expected (both) = $20 \times 20 \div 40 = 10$. By the same method every cell has $E = 10$.
2. $(O - E)^2 \div E$: both $(4 - 10)^2 \div 10 = 3.6$; A only $(16 - 10)^2 \div 10 = 3.6$; B only 3.6; neither 3.6.
3. $\chi^2 = 3.6 \times 4 = 14.4$. Degrees of freedom = 1; critical value = 3.84.
4. $14.4 > 3.84$, so reject H_0 . The species occur together less often than expected (4 observed, 10 expected).

Answer: $\chi^2 = 14.4$: a significant negative association, which is evidence consistent with interspecific competition (but does not prove it).

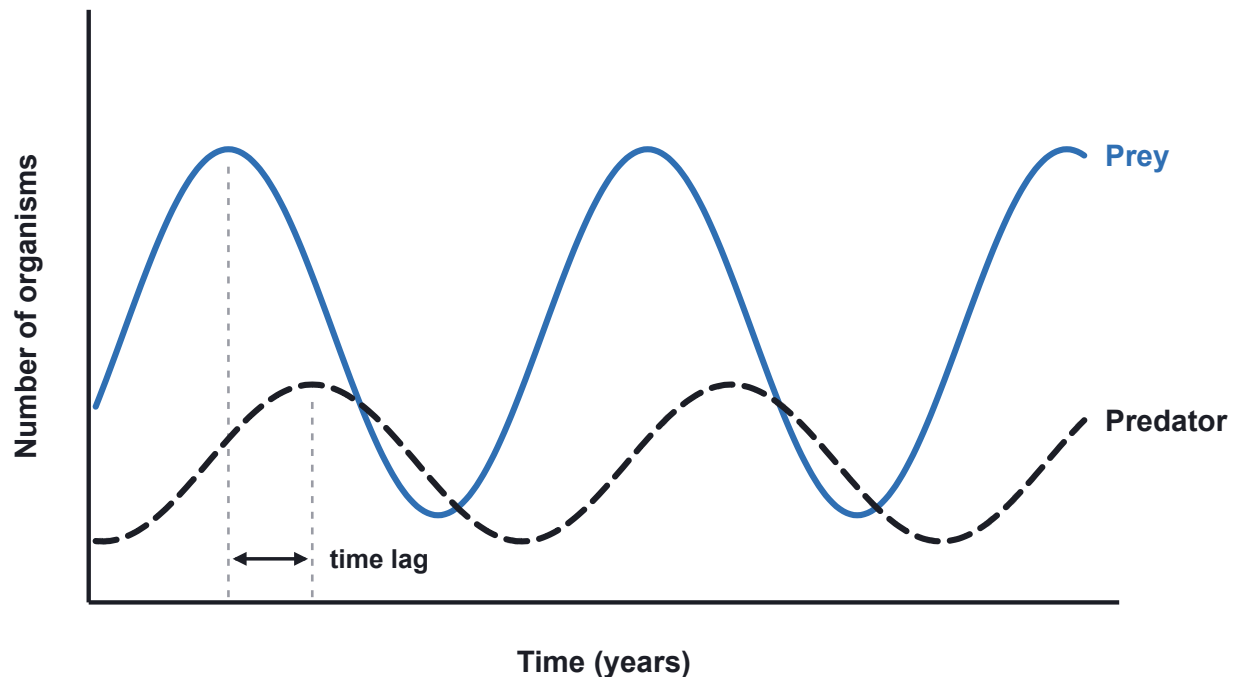
Maths skill: The critical value of 3.84 is given in exams. Always state H_0 , the degrees of freedom and whether you accept or reject H_0 , then interpret it in biological terms.

Predator-prey relationships and control of populations Spec C4.1.16, C4.1.17

Predation is a density-dependent factor: the denser the prey, the more successful the predators. The result is often linked cycles in predator and prey numbers, with predator peaks lagging behind prey peaks.

1. Prey numbers increase when food is plentiful and predators are few.
2. With more food, more predators survive and breed, so predator numbers rise after a delay.

- 3 . Heavier predation (and food shortage) reduces the prey population.
- 4 . Predators now starve or breed less, so their numbers fall.
- 5 . Predation pressure eases and the prey population recovers; the cycle repeats.



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Predator numbers follow prey numbers after a time lag.

Case study: fur-trapping records kept by the Hudson's Bay Company in Canada for about a century show the numbers of **Canada lynx** and **snowshoe hares** rising and falling in cycles of roughly 10 years, with lynx peaks a year or two after hare peaks. Field experiments show hare numbers are controlled by both predation and their winter food supply.

Top-down and bottom-up control

	Top-down control	Bottom-up control
Meaning	Populations are limited by consumers at the trophic level above (predators or herbivores)	Populations are limited by the supply of resources from the level below (nutrients, producers)
Example	Sea otters eat sea urchins; where otters were hunted out, urchins multiplied and grazed away kelp forests	Phytoplankton in the open ocean are limited by nitrate, phosphate or iron; more nutrients (as in upwelling zones) support more zooplankton and fish

Both types of control are possible in any community, but **one or the other is likely to be dominant**.

Allelopathy and secretion of antibiotics Spec C4.1.18

Both processes are a form of **chemical competition**: an organism releases a substance into its surroundings that harms competitors, giving it more access to resources such as light, water, mineral ions or nutrients.

	Allelopathy	Secretion of antibiotics
Organisms	Plants	Microorganisms (fungi and bacteria)
Effect	Inhibits germination or growth of nearby plants	Kills or inhibits the growth of bacteria
Example	Black walnut trees (<i>Juglans nigra</i>) release juglone from roots, leaves and fallen husks, which inhibits the growth of many plants beneath them, such as tomatoes	The mould <i>Penicillium</i> secretes penicillin , which stops bacteria building cell walls, so they burst; soil <i>Streptomyces</i> bacteria secrete streptomycin

Local example (Arabian Gulf): extracts of leaves of the invasive mesquite, *Prosopis juliflora*, reduce the germination or root growth of several native plants in laboratory tests, including the ghaf tree, and fewer native annuals grow beneath mesquite in the UAE. In the field it is hard to separate this chemical effect from shading and competition for water, so black walnut is the clearer example to learn.

Exam tip: Make the link to competition explicit: the chemical reduces the growth of competitors, so the producer gains more of a limited resource.

Quick check

1. What is the Lincoln index formula?
2. Why must quadrats be placed randomly?
3. Give three density-dependent factors.
4. What benefit do zooxanthellae get from hard corals?
5. What is the critical value of χ^2 for a 2×2 table at $p = 0.05$?

2 Transfers of energy and matter Spec C4.2

Ecosystems as open systems and the source of energy Spec C4.2.1, C4.2.2

	Open system	Closed system
Energy	Can enter and exit	Can enter and exit
Matter	Can enter and exit	Cannot enter or exit
Example	A natural ecosystem: a lake gains leaves and nutrients in streams, loses water and fish	A sealed bottle garden: light enters and heat leaves, but no matter is exchanged

Natural ecosystems are **open systems**. Matter crosses their boundaries all the time: animals migrate, seeds and pollen blow in, nutrients wash out in rivers, gases are exchanged with the atmosphere.

Sunlight as the principal energy source

Most ecosystems are sustained by **sunlight**. Producers capture light energy in photosynthesis and convert it to chemical energy in carbon compounds, which then passes to every other organism.

Exceptions are ecosystems with no light. **Caves**: Movile Cave in Romania, sealed off for millions of years, supports a community based on chemoautotrophic bacteria that oxidise hydrogen sulfide. **Deep ocean** below the level of light penetration: around hydrothermal vents, chemoautotrophic bacteria oxidise hydrogen sulfide from the vents and support tube worms, clams and crabs. Other deep-sea communities depend on dead organic matter sinking from the sunlit surface, so they still rely on sunlight indirectly.

Exam tip: Nature of science: 'sunlight sustains most ecosystems' is a generalisation, like a scientific law. It describes a pattern and allows predictions but does not explain it, and a useful generalisation states its exceptions.

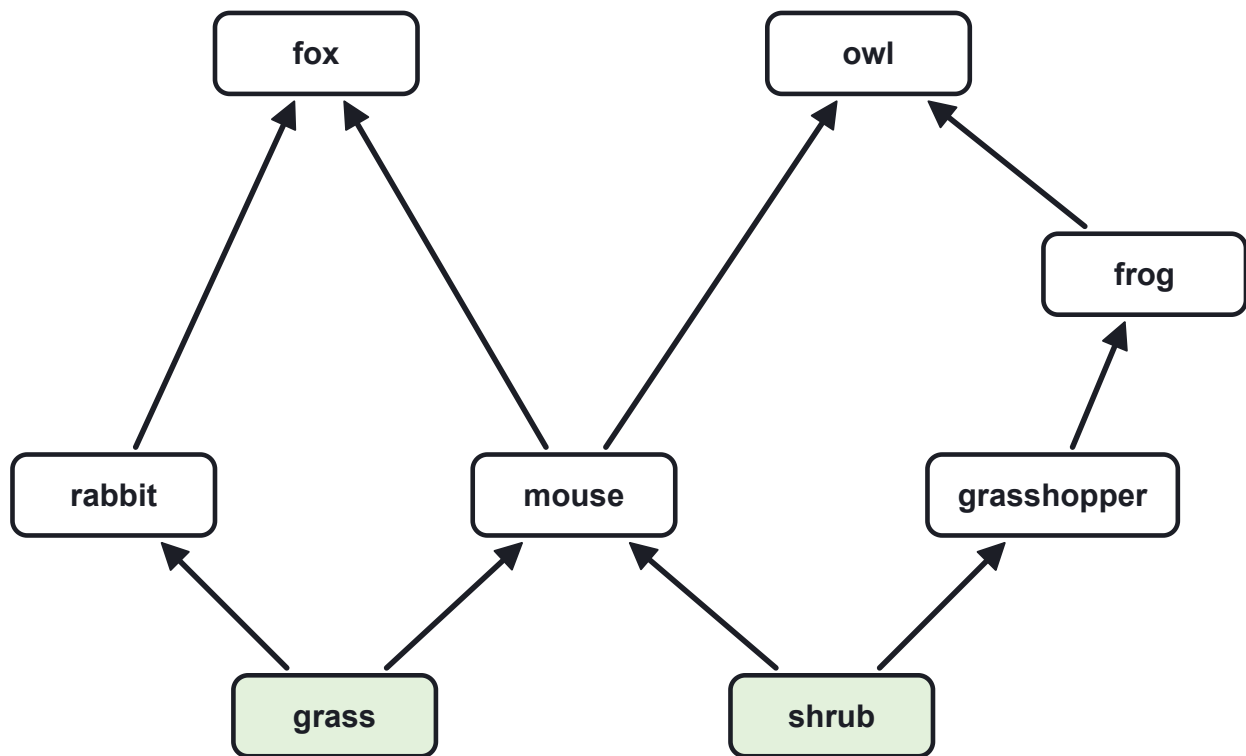
Food chains, food webs and decomposers Spec C4.2.3, C4.2.4, C4.2.5

Energy enters a food chain as light and is stored as **chemical energy** in carbon compounds made by producers. When a consumer eats an organism from the previous stage, it takes in those carbon compounds and the chemical energy in them.

Constructing food chains and webs

- Start with a producer on the left (or bottom).
- Arrows point from the organism eaten to the organism that eats it: they show the direction of transfer of **energy and biomass**, not 'is eaten by' in reverse.
- A food web links many food chains, because most consumers eat, and are eaten by, more than one species.

Example from an Arabian desert community: grasses and shrubs → Cape hare → Arabian red fox. The fox also eats jirds (desert rodents) and beetles, so several food chains link together into a food web.



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A food web. Arrows show the direction of transfer of energy and biomass, from the food to the feeder.

Decomposers

Not all organic matter is eaten. **Decomposers** (saprotrophic bacteria and fungi) obtain energy from carbon compounds in dead organic matter: **faeces**, dead parts of organisms (fallen leaves, shed skin, hair, feathers) and dead whole organisms. Detritivores such as earthworms feed on the same material. In doing so they release the last of the chemical energy as heat and return mineral ions to the soil.

Common mistake: Arrows that point from the predator to the prey reverse the direction of energy flow and lose the mark.

Autotrophs and heterotrophs Spec C4.2.6, C4.2.7, C4.2.8, C4.2.9

Autotroph	An organism that uses an external energy source to synthesise carbon compounds from simple inorganic substances.
Heterotroph	An organism that uses carbon compounds obtained from other organisms to synthesise the carbon compounds that it requires.

Autotrophs need energy for two jobs: **carbon fixation** (turning carbon dioxide into organic compounds) and the **anabolic reactions** that build macromolecules such as starch, cellulose, proteins and nucleic acids.

Two types of autotroph		
	Photoautotrophs	Chemoautotrophs
External energy source	Light	Energy released by oxidation reactions of inorganic chemicals
Examples	Plants, algae, cyanobacteria	Iron-oxidising bacteria such as <i>Acidithiobacillus ferrooxidans</i> ; sulfur bacteria at hydrothermal vents

Oxidation reactions release energy, so they are useful to living organisms. **Iron-oxidising bacteria** oxidise dissolved iron(II) ions to iron(III) ions ($\text{Fe}^{2+} \rightarrow \text{Fe}^{3+}$) and use the energy released to fix carbon dioxide. They are found where iron-rich water meets air, for example in mine drainage, and leave orange iron oxide deposits.

Heterotrophs

Heterotrophs take in complex carbon compounds such as proteins, carbohydrates, lipids and nucleic acids. These are **digested** into smaller molecules, either internally (in the gut of animals) or externally (fungi and many bacteria secrete enzymes onto their food). The products are absorbed and **assimilated**: used to build the heterotroph's own carbon compounds, for example its own proteins from absorbed amino acids.

Releasing energy

Both autotrophs and heterotrophs release energy from carbon compounds by **oxidising** them in cell respiration, producing ATP. Plants respire all the time, in the dark and in the light.

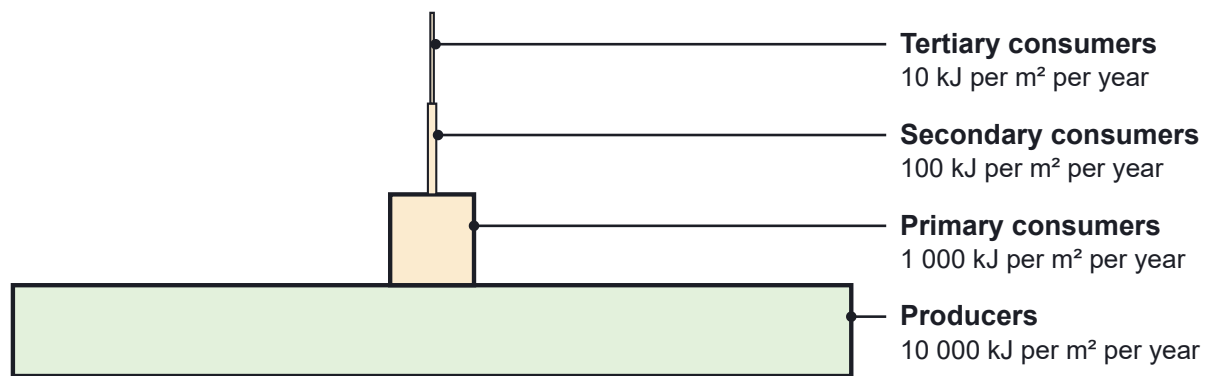
Trophic levels and energy pyramids Spec C4.2.10, C4.2.11

Trophic level	Name	Feeds on
1	Producer	Makes its own carbon compounds (autotroph)
2	Primary consumer	Producers
3	Secondary consumer	Primary consumers
4	Tertiary consumer	Secondary consumers

Many organisms have a **varied diet** and occupy **different trophic levels in different food chains**. A red fox eating berries is a primary consumer; eating a hare it is a secondary consumer; eating an insect-eating bird it is a tertiary consumer.

Energy pyramids

An **energy pyramid** is a bar chart turned on its side, with one horizontal bar per trophic level, producers at the bottom. The width of each bar is proportional to the energy flowing through that level, in $\text{kJ m}^{-2} \text{yr}^{-1}$. Energy pyramids are always pyramid-shaped, because energy is lost at every transfer.



Scale: this length = 1 000 kJ per m² per year

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An idealised energy pyramid with 10% transfer at each step. Data from real ecosystems give less regular bars.

Percentage energy transfer

In a grassland (practice data), producers fix 25 000 kJ m⁻² yr⁻¹ and primary consumers take in 2 250 kJ m⁻² yr⁻¹. Calculate the percentage transfer.

1. Percentage transfer = (energy at higher level ÷ energy at lower level) × 100.
2. = (2 250 ÷ 25 000) × 100.
3. = 9.0%.

Answer: 9.0% of the energy reaches the primary consumers.

Practical skill: When you construct an energy pyramid from research data, choose a scale so the smallest bar is still visible, label every level with its value and units, and centre the bars.

Energy losses between trophic levels Spec C4.2.12, C4.2.13, C4.2.14

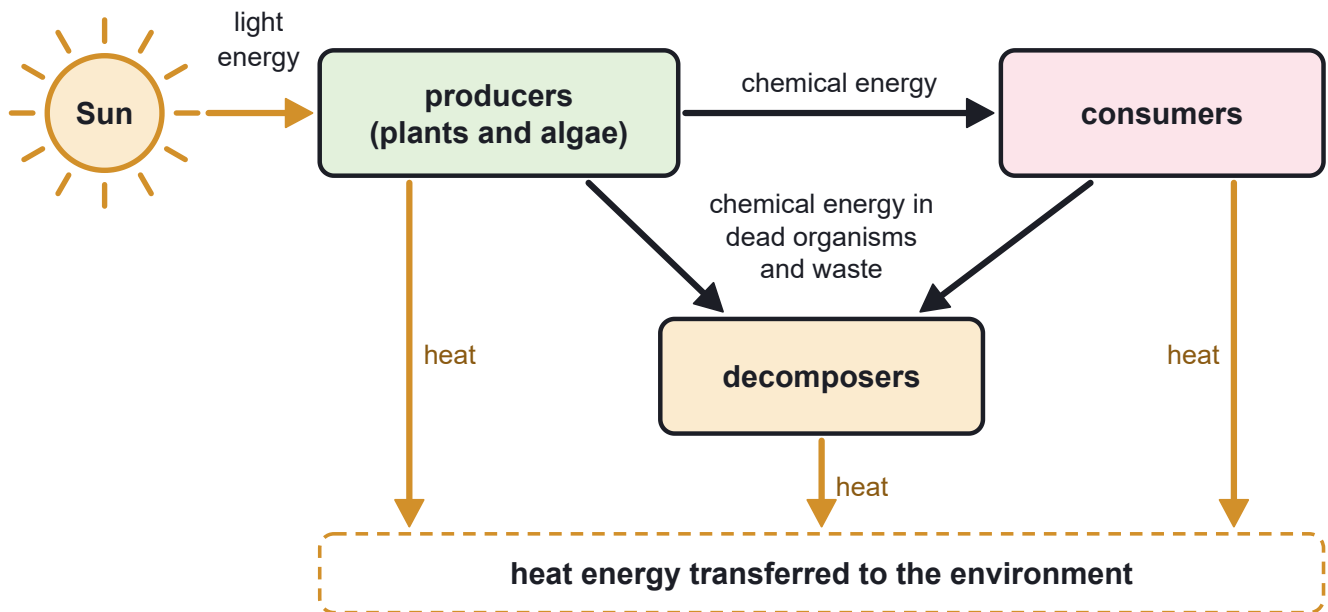
Causes of energy loss

- Not all of the organisms at one level are eaten: some die and parts such as roots, bones or shells are left uneaten.
- Not all of the food eaten is digested and absorbed: undigested material such as cellulose is egested as faeces.
- Much of the absorbed energy is used in **cell respiration** and is converted to heat.
- Some energy is lost in excretory waste such as urea.

Uneaten parts, dead organisms and faeces pass to **decomposers and detritus feeders**. These are not usually placed in food chains, but they transform the energy in this dead matter too, finally releasing it as heat.

Heat from cell respiration

Energy transfers in cells are never 100% efficient. Heat is produced both **when ATP is produced** in cell respiration (not all the energy in glucose is captured in ATP) and **when ATP is used** in cells, for example in muscle contraction or active transport. This applies to autotrophs and heterotrophs alike. Heat is lost to the environment and cannot be converted back to chemical energy by organisms, so **energy cannot be recycled**; it must be replaced continually by sunlight.



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Energy flows one way: it enters as light and leaves every trophic level as heat.

Limits on food chain length

Typically only around 10% of the energy at one trophic level reaches the next (it varies widely). After four or five transfers there is too little energy left to support another population. At each successive stage there are fewer organisms or smaller organisms, so there is **less biomass**, but the **energy content per unit mass is not reduced**: a gram of fox tissue holds about as much energy as a gram of hare tissue.

Exam tip: Linking question: how does the transformation of energy from one form to another make biological processes possible? Light → chemical energy → ATP → work and heat is the chain to describe.

Primary and secondary production Spec C4.2.15, C4.2.16

Primary production	Accumulation of carbon compounds in biomass by autotrophs.
Secondary production	Accumulation of carbon compounds in biomass by heterotrophs.

Biomass accumulates when organisms **grow or reproduce**. Production is a rate, so its units are mass of carbon per unit area per unit time, usually **$\text{g m}^{-2} \text{yr}^{-1}$** .

Biomes vary in their capacity to accumulate biomass. Production is high in tropical rainforests, where it is warm, wet and light all year, and low in deserts and tundra, where water or temperature limits photosynthesis and the growing season is short.

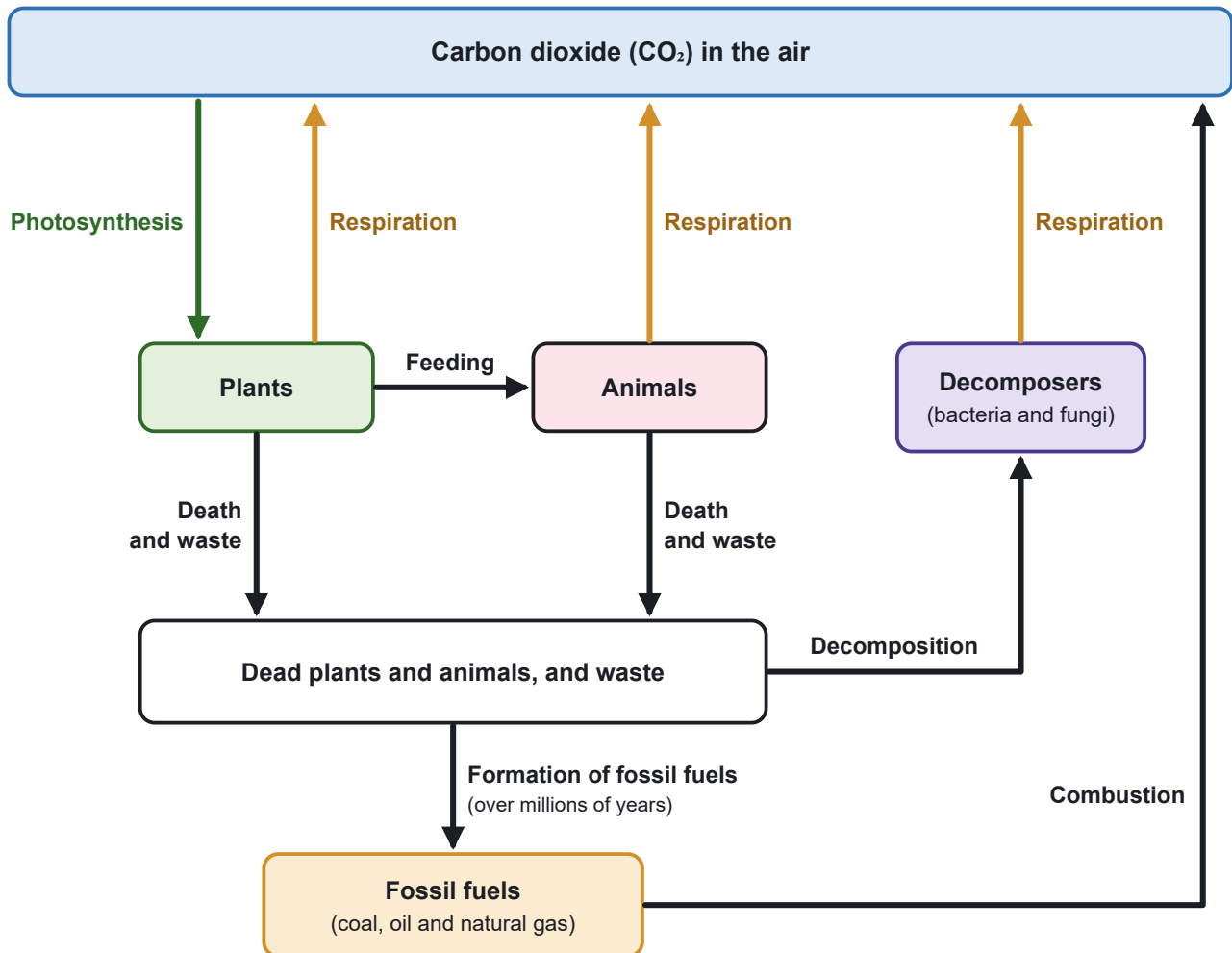
Secondary production is lower than primary production in an ecosystem. When carbon compounds are oxidised in cell respiration, they are converted to carbon dioxide and water and leave the organism, so that biomass is lost. Only the part of the food that is not respired, egested or excreted is built into new heterotroph biomass.

Common mistake: Production is not the same as biomass. Biomass is the mass present at one moment (g m^{-2}); production is how fast it accumulates ($\text{g m}^{-2} \text{yr}^{-1}$).

The carbon cycle, carbon sinks and combustion Spec C4.2.17, C4.2.18, C4.2.19

Carbon cycle diagrams

- **Photosynthesis**: autotrophs fix CO₂ from the air (or dissolved in water) into carbon compounds.
- **Feeding**: carbon compounds pass to consumers when they eat.
- **Death and egestion**: carbon compounds in dead organisms and faeces pass to decomposers.
- **Respiration**: producers, consumers and decomposers oxidise carbon compounds, releasing CO₂.
- **Combustion**: burning biomass and fossil fuels releases CO₂.



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The carbon cycle. Each arrow is a process; each box is a store of carbon. Biomass and peat can also burn, releasing CO₂.

Sinks and sources

If **photosynthesis exceeds respiration**, an ecosystem has a net uptake of CO₂ and is a **carbon sink** (a growing forest, an expanding peat bog). If **respiration exceeds photosynthesis**, there is a net release of CO₂ and it is a **carbon source** (a drained peatland where peat now decomposes).

Combustion

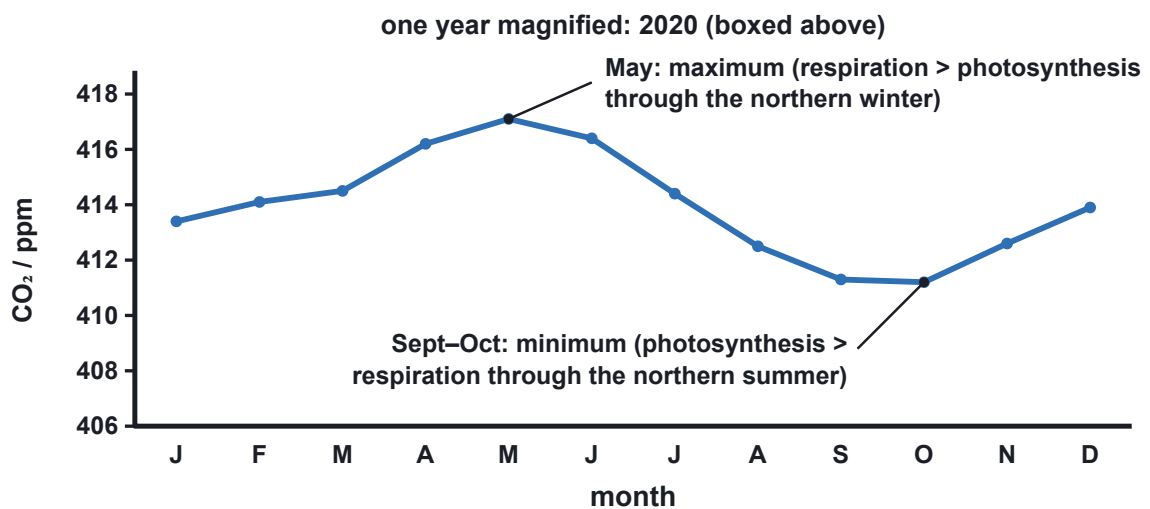
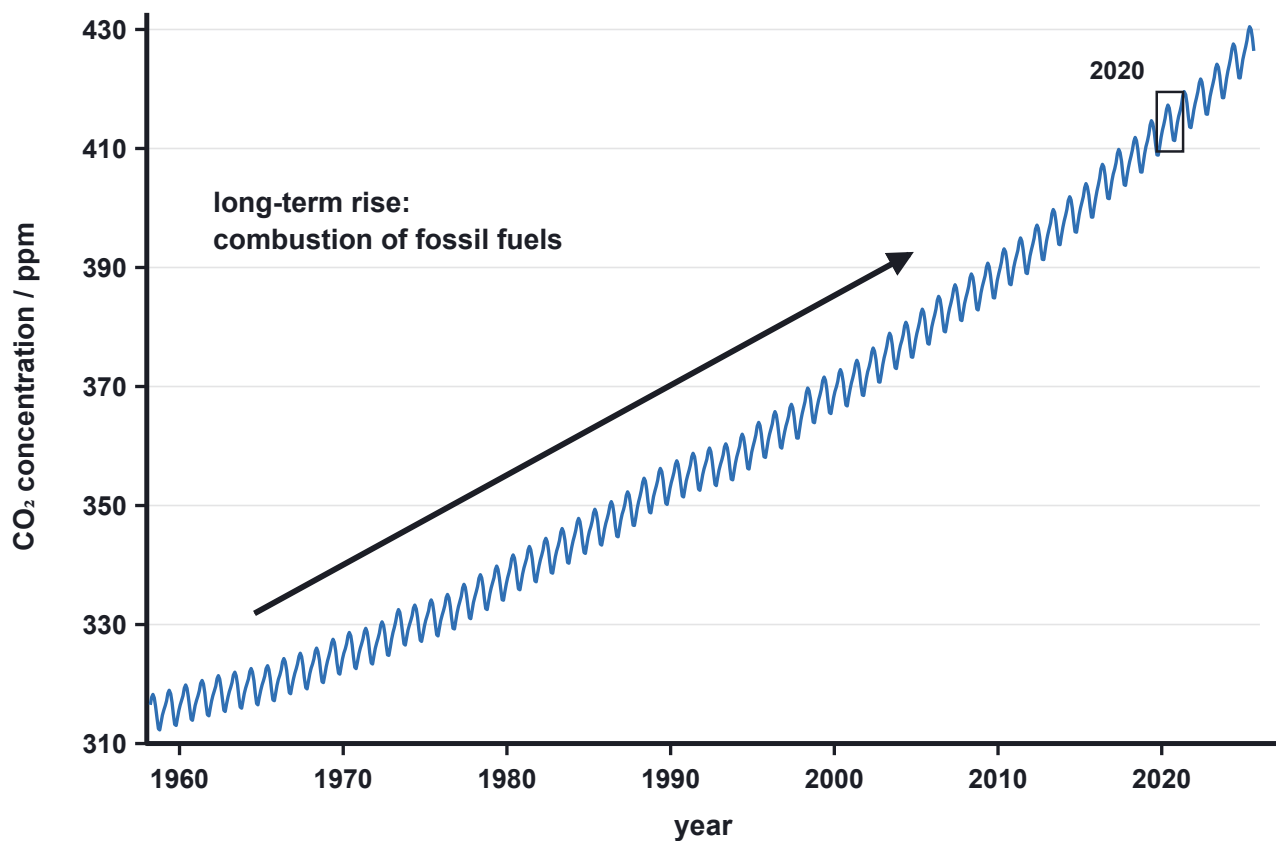
Carbon stores that release CO ₂ when burned	
Store	How and when it formed
Biomass (wood, crops)	Recent: from photosynthesis over years to centuries
Peat	Partly decomposed plant matter in waterlogged, acidic, anaerobic bogs, building up over thousands of years
Coal	Buried plant remains compressed over hundreds of millions of years, much of it from the Carboniferous period
Oil and natural gas	Remains of marine plankton buried in sediments and transformed by heat and pressure over millions of years

Combustion sometimes happens naturally, for example when **lightning strikes** start forest or peat fires, but **human activities have greatly increased combustion rates**, through burning fossil fuels and clearing forests by fire.

The Keeling Curve Spec C4.2.20

Measurements of CO₂ at the Mauna Loa Observatory, high on a volcano in Hawaii and far from local pollution, began in 1958. The graph shows two patterns.

Pattern	Description	Explanation
Annual fluctuation	A saw-tooth of about 6 ppm each year: highest around May, lowest around September-October	Most land and vegetation is in the northern hemisphere. In the northern spring and summer, photosynthesis exceeds respiration, so CO ₂ falls. In autumn and winter, leaves fall and photosynthesis slows while respiration (especially by decomposers) continues, so CO ₂ rises
Long-term trend	A steady rise, from about 315 ppm in 1958 to over 420 ppm in the 2020s, getting steeper over time	Combustion of fossil fuels (and deforestation) releases CO ₂ faster than photosynthesis and the oceans remove it



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The Keeling Curve: a **yearly cycle** of about 6 ppm on top of a **long-term rise**. Drawn from NOAA Mauna Loa annual means with the average seasonal cycle; 2020 monthly values are approximate.

Exam tip: When analysing the Keeling Curve, explain both patterns: the annual cycle in terms of photosynthesis and respiration, the long-term trend in terms of combustion. Quote values with units (ppm) and calculate a rate of increase where asked.

Exam tip: Linking question: what are the direct and indirect consequences of rising carbon dioxide levels in the atmosphere? Link to the enhanced greenhouse effect (D4.3) and ocean acidification.

Interdependence of autotrophs and heterotrophs and recycling of elements

Photosynthesis and aerobic respiration are linked through the atmosphere. Photosynthesis takes in CO_2 and releases O_2 ; aerobic respiration takes in O_2 and releases CO_2 . Aerobic respiration depends on oxygen produced by photosynthesis, and photosynthesis depends on carbon dioxide produced by respiration. The fluxes involved each year are huge, so this is a major interaction between autotrophs and heterotrophs.

Photosynthesis: $6\text{CO}_2 + 6\text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2$ **Aerobic respiration:** $\text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O}$

Recycling of all elements

Living organisms need many elements besides carbon: nitrogen, phosphorus, sulfur, potassium, calcium, magnesium, iron and others. The supply of each element on Earth is finite, so all of them are recycled. Producers absorb them as inorganic ions or molecules; they pass to consumers by feeding; and decomposers break down dead organic matter, releasing the elements again as inorganic forms that producers can reuse.

This is why matter can be recycled in ecosystems but energy cannot: atoms are conserved and reused, while energy ends up as heat that organisms cannot use.

Common mistake: Details of the nitrogen cycle and other nutrient cycles are not required for C4.2. Focus on the general principle and the role of decomposers.

Quick check

1. What can cross the boundary of a closed system?
2. What is the energy source of iron-oxidising bacteria?
3. What are the usual units of primary production?
4. Which way do arrows point in a food chain?
5. Why does atmospheric CO_2 fall each northern summer?

Quick check answers

Populations and communities

1. Population size estimate = $(M \times N) \div R$: M marked first, N caught second time, R marked in the second sample.
2. To avoid bias, so that every part of the area has an equal chance of being sampled.
3. Competition for limited resources, predation, and the transfer of pathogens or pests.
4. Carbon dioxide and nitrogen compounds from the coral, and a protected, well-lit position.
5. 3.84 (1 degree of freedom).

Transfers of energy and matter

1. Only energy; matter cannot enter or leave.
2. Energy released by oxidising iron(II) ions to iron(III) ions, an oxidation reaction.
3. Mass of carbon per unit area per unit time, usually $\text{g m}^{-2} \text{yr}^{-1}$.
4. From the organism eaten to the organism that eats it, showing the direction of transfer of energy and biomass.
5. Photosynthesis exceeds respiration on the large northern land masses, so there is a net uptake of CO_2 .