

Transfers of energy and matter

Revision notes • IB Biology C4.2: energy flow, autotrophs and heterotrophs, trophic levels, energy pyramids, production, the carbon cycle, the Keeling Curve and recycling.

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

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.

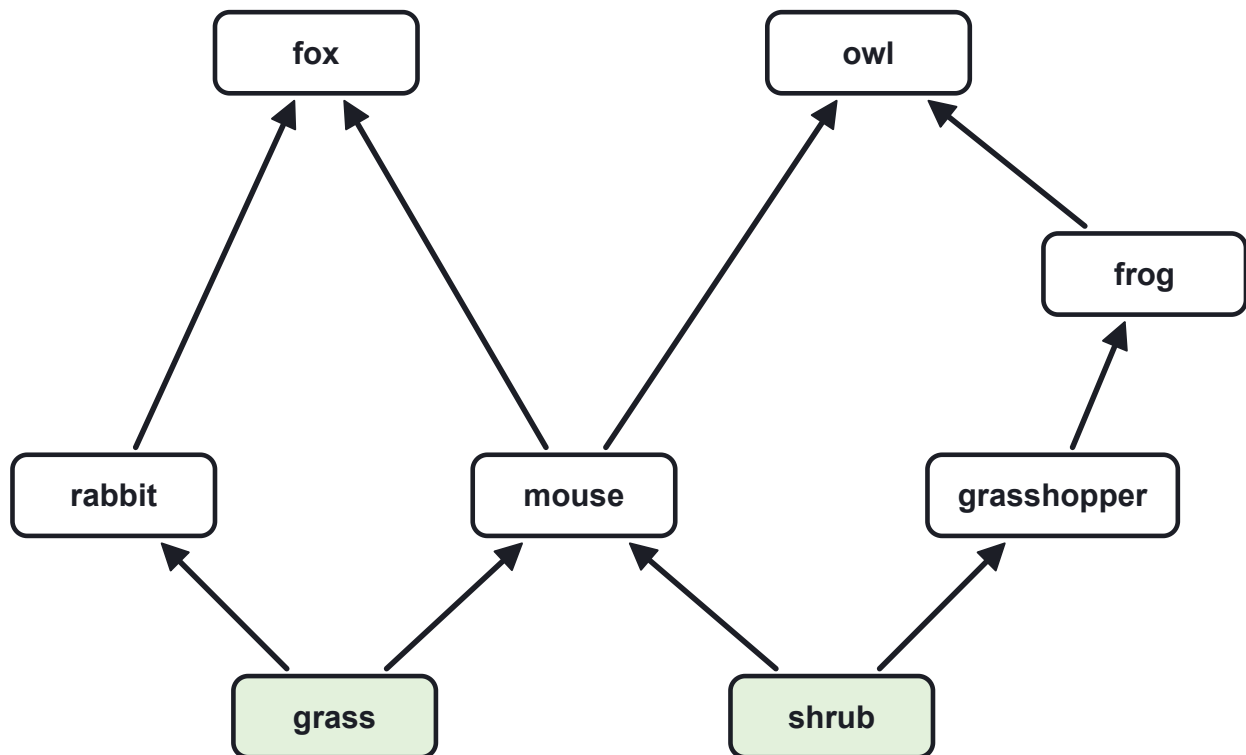
Food chains, food webs and decomposers **Spec C4.2.3, C4.2.4, C4.2.5**

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.

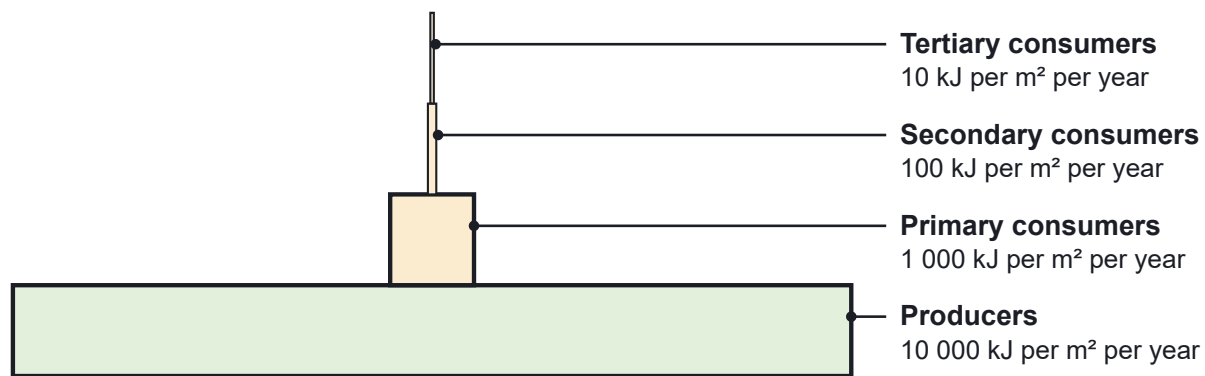
Trophic levels and energy pyramids Spec C4.2.10, C4.2.11

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

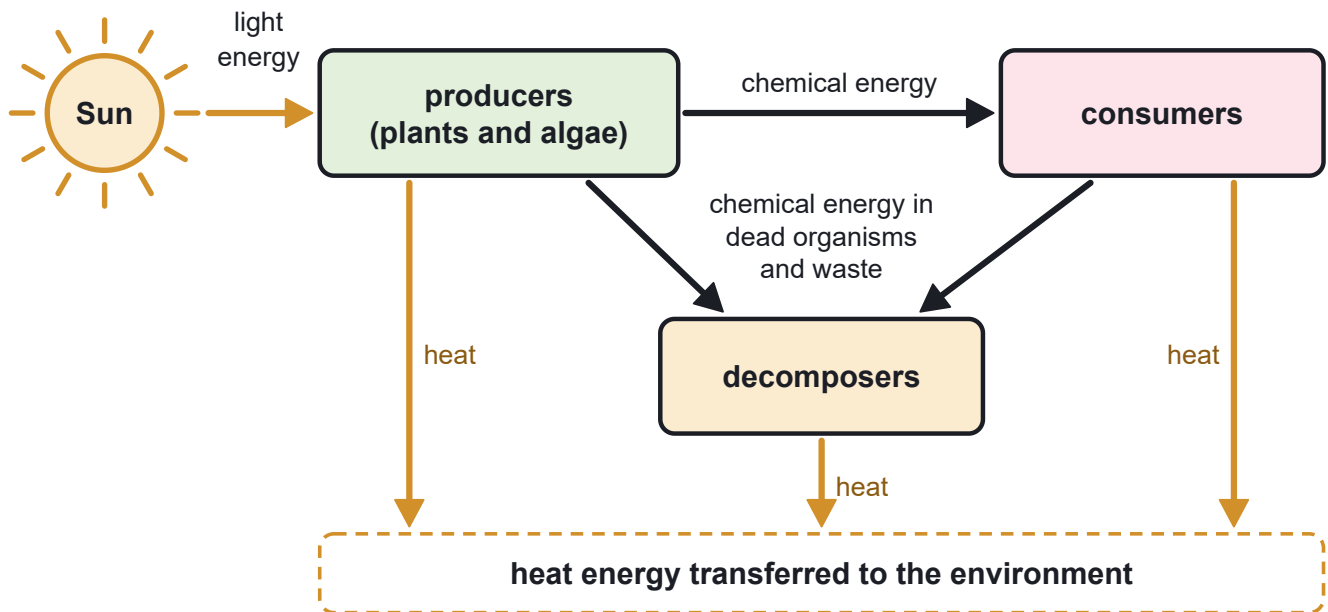
Causes of energy loss

- 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.

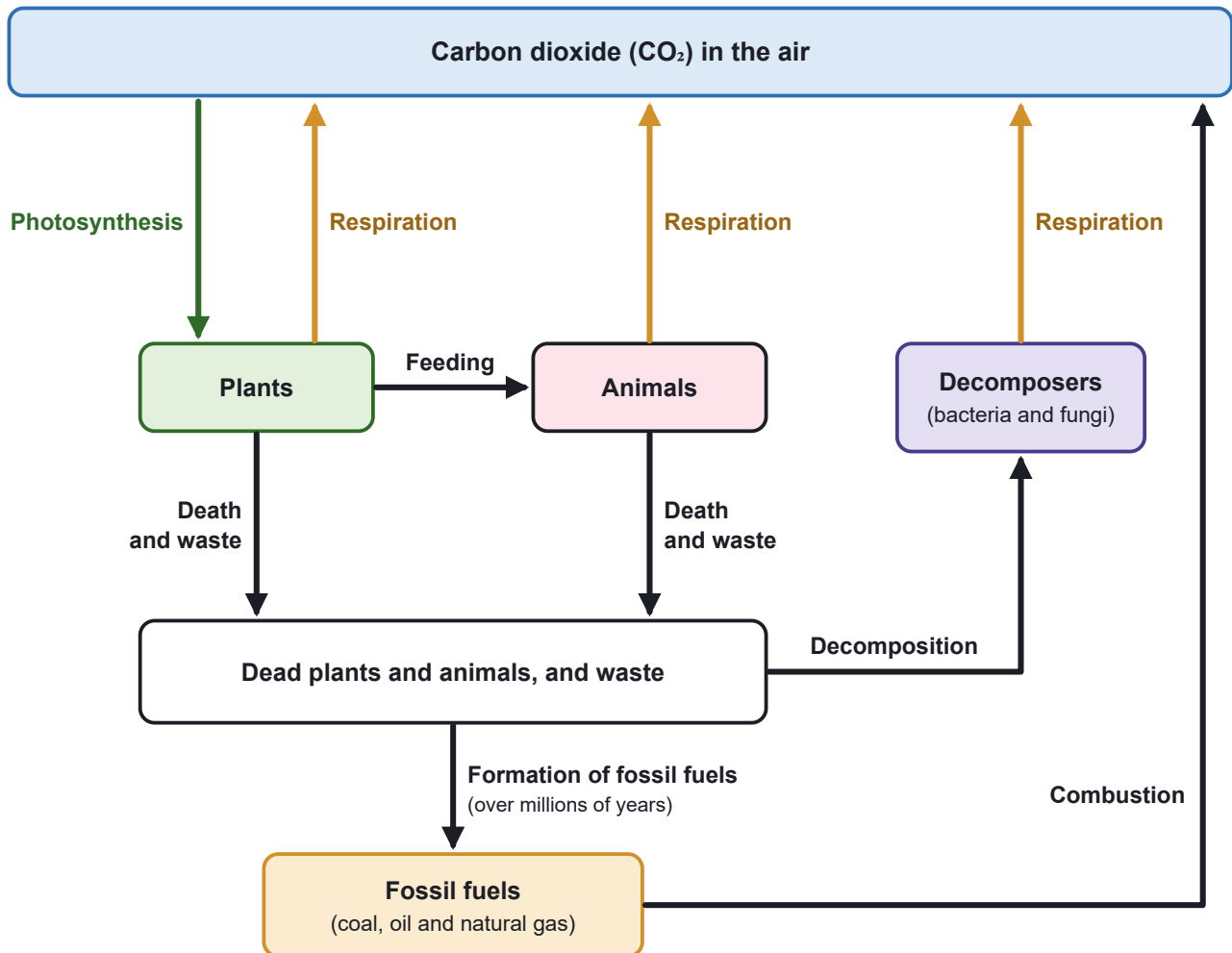
Secondary production is lower than primary production in an ecosystem. When carbon compounds are oxidised in cell respiration, they are converted to carbon dioxide and water and leave the organism, so that biomass is lost. Only the part of the food that is not respired, egested or excreted is built into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

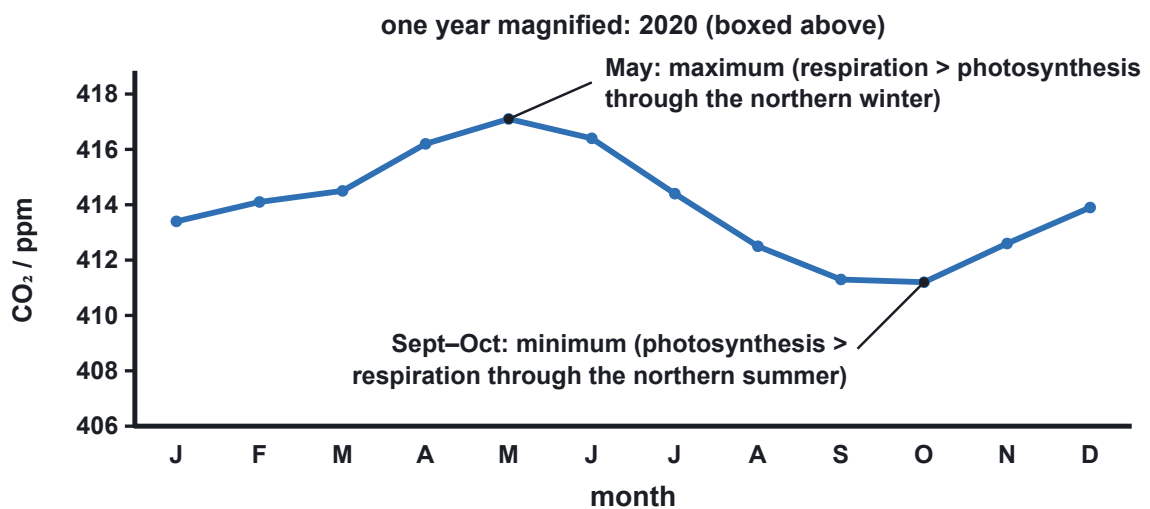
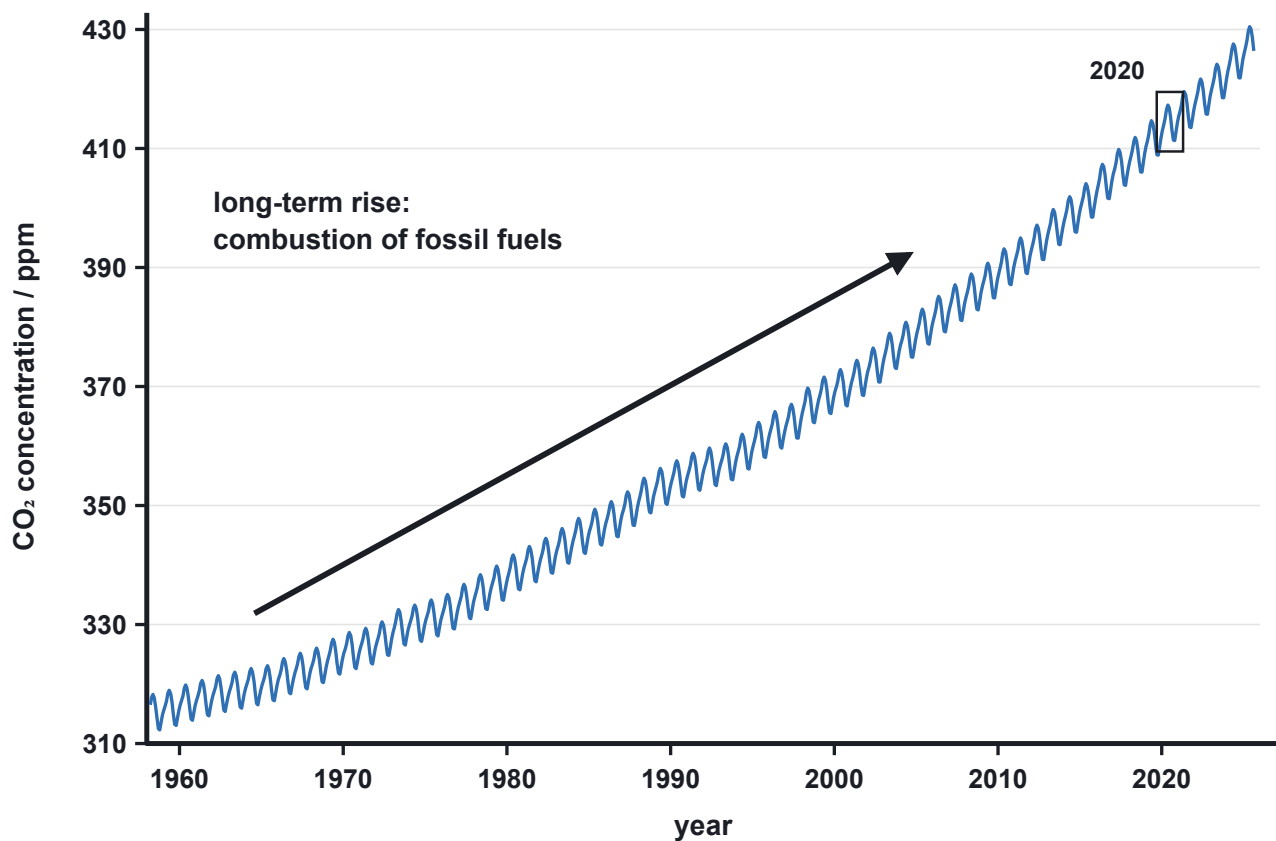
Carbon stores that release CO ₂ when burned	
Store	How and when it formed
Biomass (wood, crops)	Recent: from photosynthesis over years to centuries
Peat	Partly decomposed plant matter in waterlogged, acidic, anaerobic bogs, building up over thousands of years
Coal	Buried plant remains compressed over 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

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 .