Science 9–10

Chapter 12 — Earth and space sciences A: Earth's systems, carbon and climate

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Contents

Earth's four interrelated systems and the carbon cycle: photosynthesis and respiration

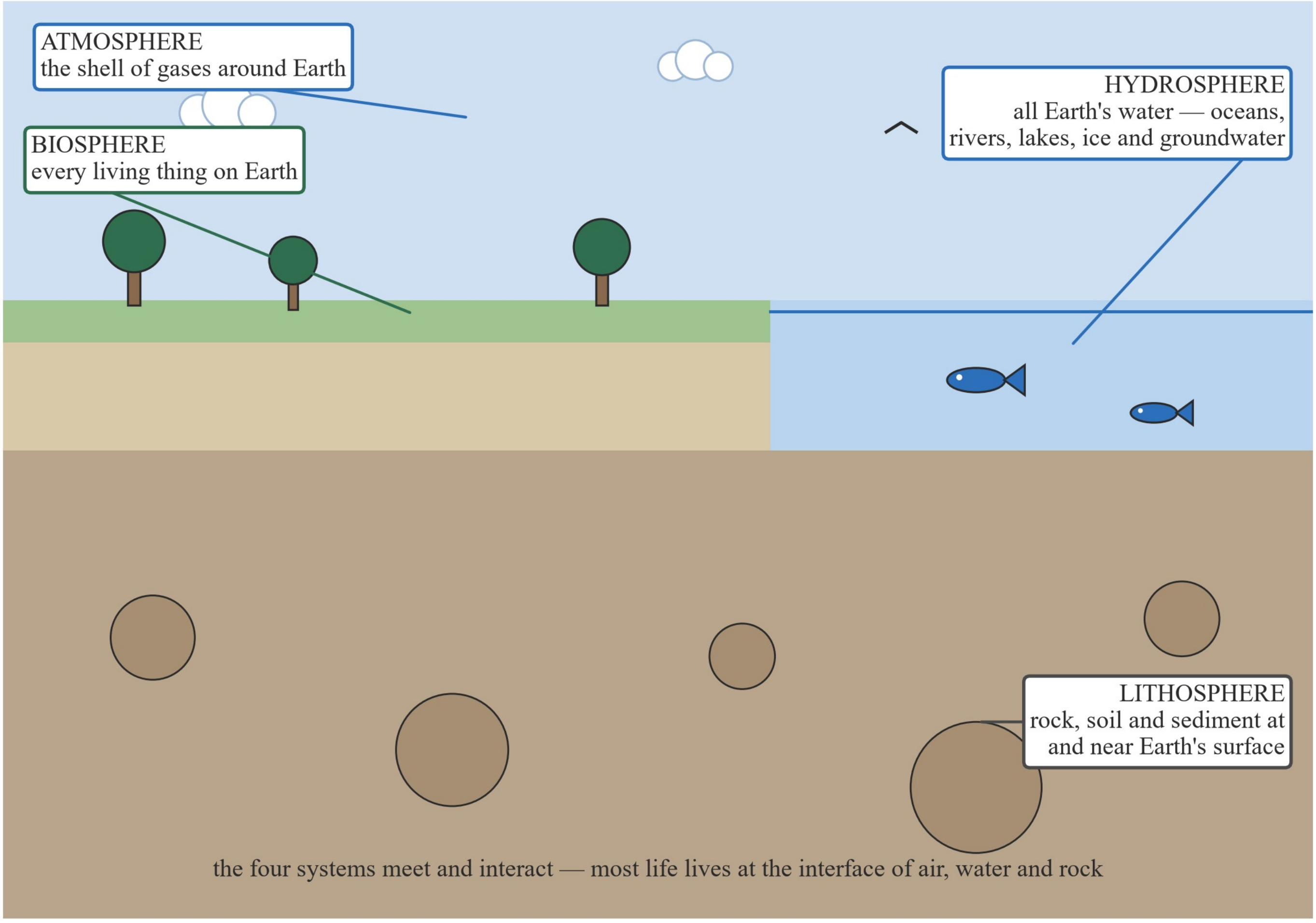
Subtopic 12A · VC2 Science Understanding — Earth and space sciences **CD code:** `VC2S10U10` (delivered in split with 12B — 12A owns Earth's four interrelated systems and the carbon cycle: photosynthesis and respiration; 12B owns fire, weathering, vulcanism and fossil-fuel combustion, and how the processes change system composition over time) **Content description (word for word):** "carbon is cycled on Earth through key processes including photosynthesis, respiration, fire, weathering, vulcanism and the combustion of fossil fuels; these processes change the composition of Earth's interrelated systems (atmosphere, biosphere, hydrosphere and lithosphere) over time" **Elaboration ids drawn on:** `VC2S10U10.E01` · `VC2S10U10.E02` (`VC2S10U10.E03`, `.E06` and `.E07` are delivered by subtopic 12B in this split; `VC2S10U10.E04` and `.E05` are withheld under the TOC's D10 ICIP decision and are not taught here.) **Achievement standard (extract served):** "They explain how interactions within and between Earth's interrelated systems affect the carbon cycle." (12A serves the explanation through the four systems and the photosynthesis–respiration pair; 12B completes it with the remaining processes and the change-over-time idea — TOC D6.) **Maths interlock (D11):** `VC2M9M02` — scientific notation and orders of magnitude, used here for the sizes of the carbon stores, which run from hundreds to tens of thousands of gigatonnes of carbon.

Theory

Earth as a system of four systems. Think of the Earth as one giant **system** — a set of parts that interact, so that a change in one part shows up in the others. For science, the Earth system is sorted into four interrelated systems:

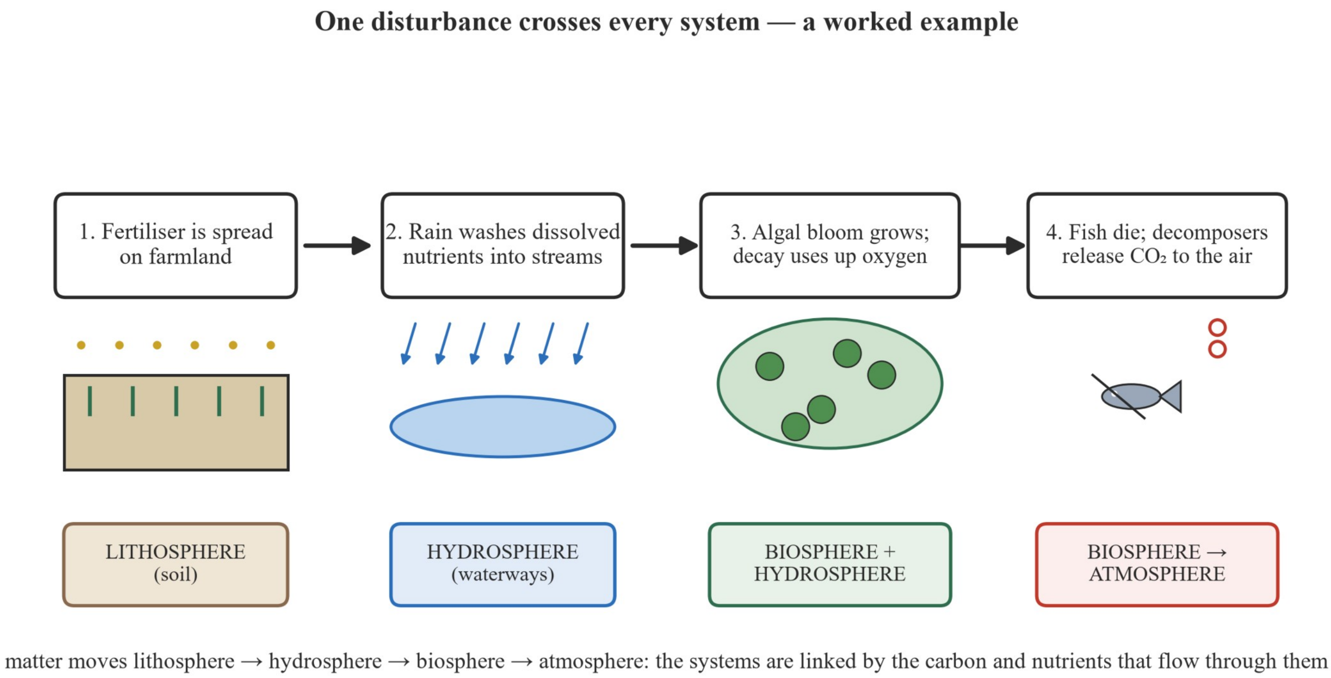
- The **atmosphere** is the layer of gases wrapped around the Earth — the air you breathe, including the carbon dioxide (CO_2) this subtopic keeps returning to.
- The **hydrosphere** is all the water on Earth: oceans, rivers, lakes, ice and groundwater. The ocean is by far the largest part of it.
- The **lithosphere** is the rocky outer part of the Earth — the crust, the rocks and the soils formed from them.
- The **biosphere** is every living thing on Earth — plants, animals, algae, fungi and microscopic organisms — together with the places they live.

The four systems are not sealed boxes. They share matter: water, gases and the elements that make up living things move from one system to another all the time. Carbon is the element we track in this subtopic, because the story of carbon touches all four systems at once.



A landscape cutaway showing Earth's four systems: the atmosphere as a sky band with clouds and birds, the biosphere as trees on a grass strip and fish in the sea, the hydrosphere as the ocean, and the lithosphere as the soil and rock beneath, with labelled boxes for ATMOSPHERE, BIOSPHERE, HYDROSPHERE and LITHOSPHERE and a caption noting that the four systems meet and interact

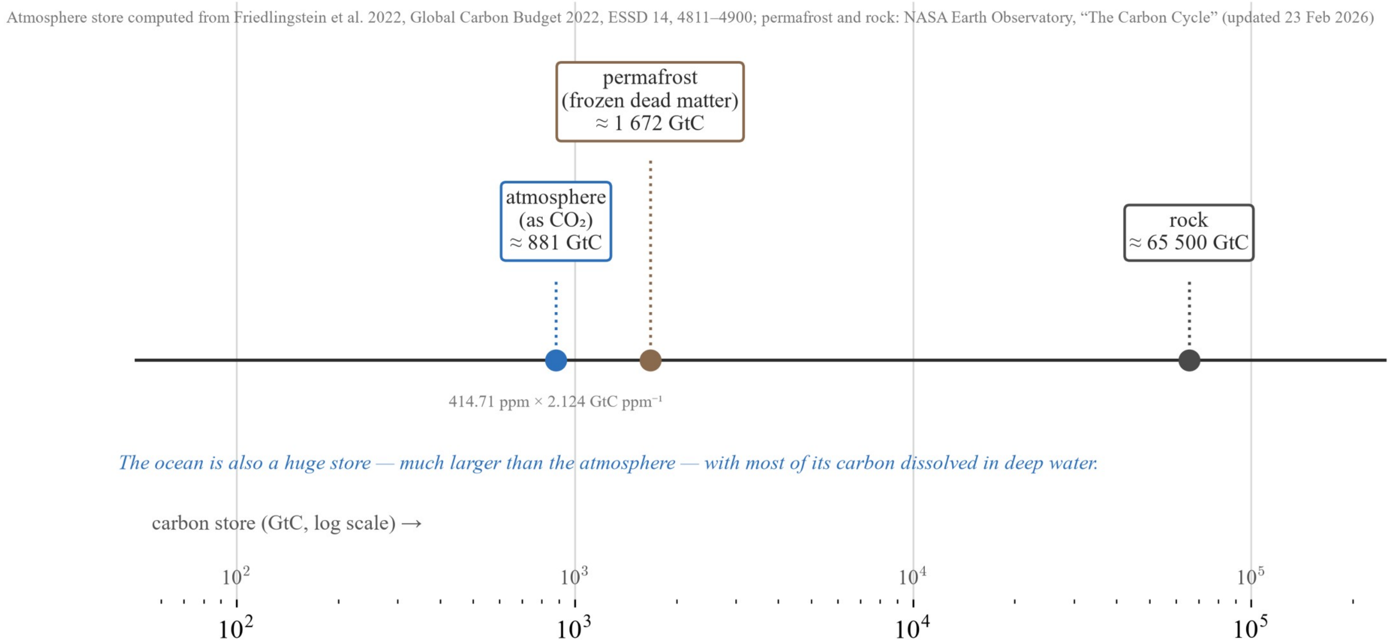
One disturbance crosses every system. The quickest way to see the interaction is to follow a disturbance. A farmer spreads **fertiliser** — nutrients added to soil to help crops grow. Rain washes some of those dissolved nutrients into a stream and then into a lake (hydrosphere). The extra nutrients feed an **algal bloom** — a sudden explosion in the number of algae. When the algae die, **decomposers** — organisms such as bacteria and fungi that break down dead remains — use up the water's dissolved oxygen as they work, and fish die. The decomposers then release CO_2 back to the air. One event on a paddock has now touched the lithosphere, the hydrosphere, the biosphere and the atmosphere.



A four-step flow chart titled "One disturbance crosses every system": 1, fertiliser is spread on farmland (lithosphere, soil); 2, rain washes dissolved nutrients into streams (hydrosphere); 3, algal bloom grows and decay uses up oxygen (biosphere plus hydrosphere); 4, fish die and decomposers release CO_2 to the air (biosphere to atmosphere)

The same reasoning works for carbon itself: carbon never stays in one system. It moves between the air, the water, the living things and the rock in a loop called the **carbon cycle**. Before drawing the whole loop, we need a feel for where carbon is stored and how big each store is.

Where carbon is stored. A **store** (also called a stock) is any place where carbon sits for a while: the air holds it as CO_2, the ocean holds it dissolved in water, the lithosphere holds it in rock and in frozen dead matter, and the biosphere holds it in living and recently dead organisms. The amounts are measured in **gigatonnes of carbon (GtC)** — one gigatonne is one billion tonnes (10^9 t), so 1 GtC = 10^9 t of carbon.

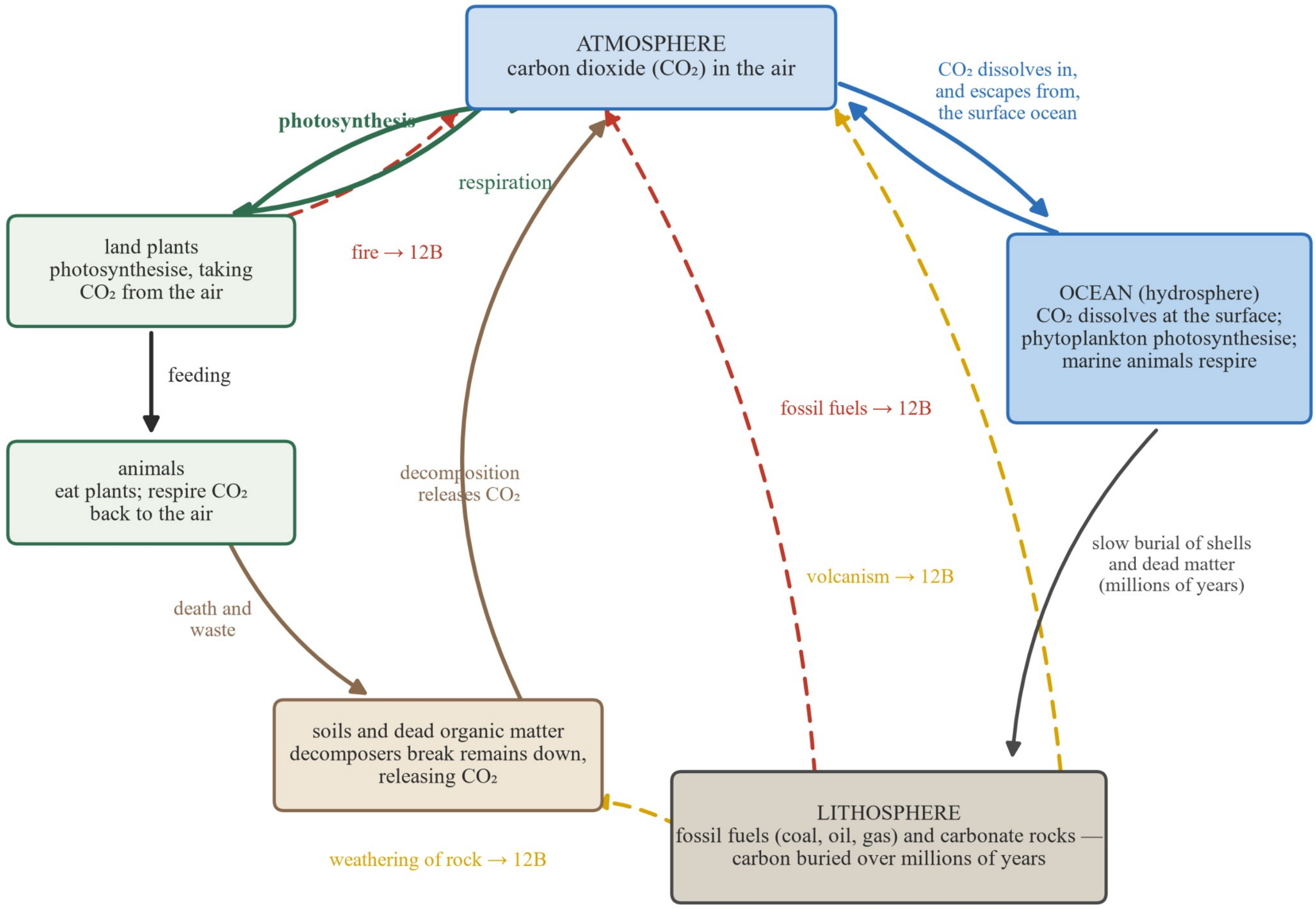


A log-scale number line of carbon store sizes in gigatonnes of carbon, from the atmosphere at about 881 GtC, through permafrost (frozen dead matter) at about 1 672 GtC, to rock at about 65 500 GtC, with a note that the ocean is also a huge store, much larger than the atmosphere

The stores differ by huge multiples, so they are best read in **scientific notation** and **orders of magnitude** (as in `VC2M9M02`): the atmosphere's store is about 8.8×10^2 GtC, permafrost about 1.7×10^3 GtC, and rock about 6.6×10^4 GtC. Each step of ten times is one order of magnitude: the rock store is about 74 times the atmosphere's store — between one and two orders of magnitude bigger. Notice the pattern: the bigger, slower stores sit in the lithosphere, while the small, lively store is the air. A small flow of carbon into or out of a small store changes that store a lot; the same flow makes almost no change to a big store. That is the key idea for reading any carbon diagram.

Source: atmosphere store computed from Friedlingstein et al. 2022, Global Carbon Budget 2022, ESSD 14, 4811–4900 (414.71 ppm × 2.124 GtC per ppm); permafrost and rock stores: NASA Earth Observatory, "The Carbon Cycle" (updated 23 Feb 2026).

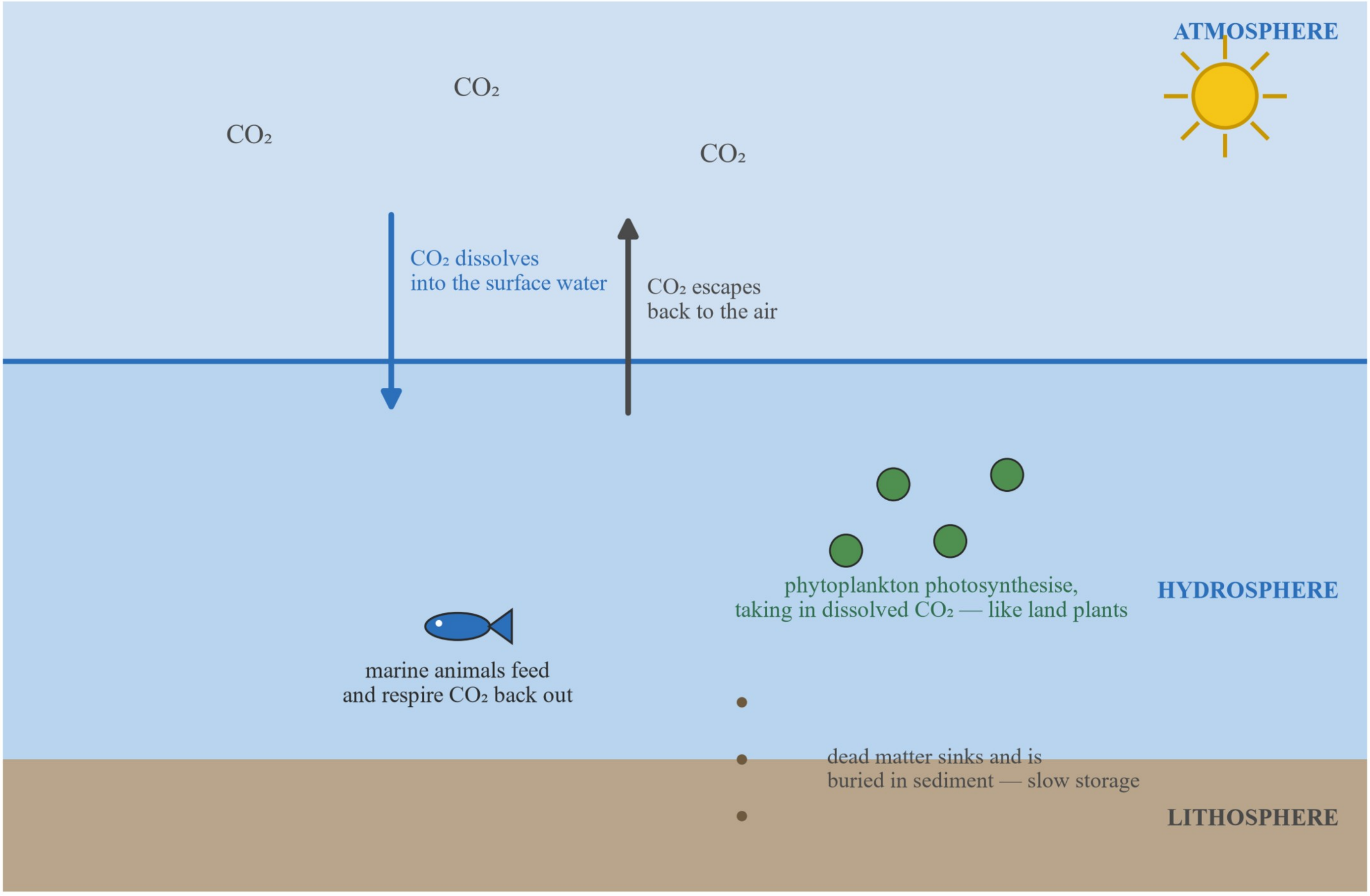
The carbon cycle. A **flow** is a movement of carbon from one store to another. The figure below joins the stores with their flows. The solid arrows are the fast biological cycle this subtopic teaches: plants take CO_2 from the air by **photosynthesis**, animals eat the plants, every organism returns CO_2 to the air by **respiration**, and decomposers release CO_2 as they break down dead matter and waste. The ocean constantly swaps CO_2 with the air at its surface. The dashed arrows — fire, the burning of fossil fuels, vulcanism and the weathering of rock — are real flows too, but they belong to Subtopic 12B, which examines how they change the systems' composition over time.



solid arrows: the fast biological cycle of this subtopic · dashed red and gold arrows: the processes delivered in Subtopic 12B

The carbon cycle: boxes for the atmosphere (CO_2 in the air), land plants, animals, soils and dead organic matter, the ocean, and the lithosphere (fossil fuels and carbonate rocks). Solid green arrows show photosynthesis taking CO_2 from air to plants and respiration returning it; feeding carries carbon from plants to animals; death and waste carry it to soils; decomposition releases CO_2; blue arrows show CO_2 dissolving into and escaping from the surface ocean; a dark arrow shows slow burial of shells and dead matter into the lithosphere over millions of years. Dashed red and gold arrows, labelled "to Subtopic 12B", mark fire, fossil-fuel burning, volcanism and weathering of rock

The ocean and the air swap carbon. At the sea surface, CO_2 from the air **dissolves** into the water, and dissolved CO_2 escapes back to the air — two flows running at the same time. Inside the water, **phytoplankton** — microscopic drifting organisms that photosynthesise, like land plants but suspended in sunlit surface water — take in the dissolved CO_2. Marine animals feed on them and respire CO_2 back out. Some dead matter sinks and is buried in **sediment** — the mud and sand that settle on the sea floor — where, over millions of years, it becomes part of the lithosphere's store. So the hydrosphere is not a side note to the carbon cycle: it is a busy exchange point between the air and the rock.



A cross-section of the ocean under the atmosphere: a blue arrow shows CO_2 dissolving into the surface water and a dark arrow shows CO_2 escaping back to the air; green dots of phytoplankton photosynthesise in the sunlit water; a fish stands for marine animals that feed and respire CO_2 back out; dots of dead matter sink into the sediment of the lithosphere, labelled slow storage

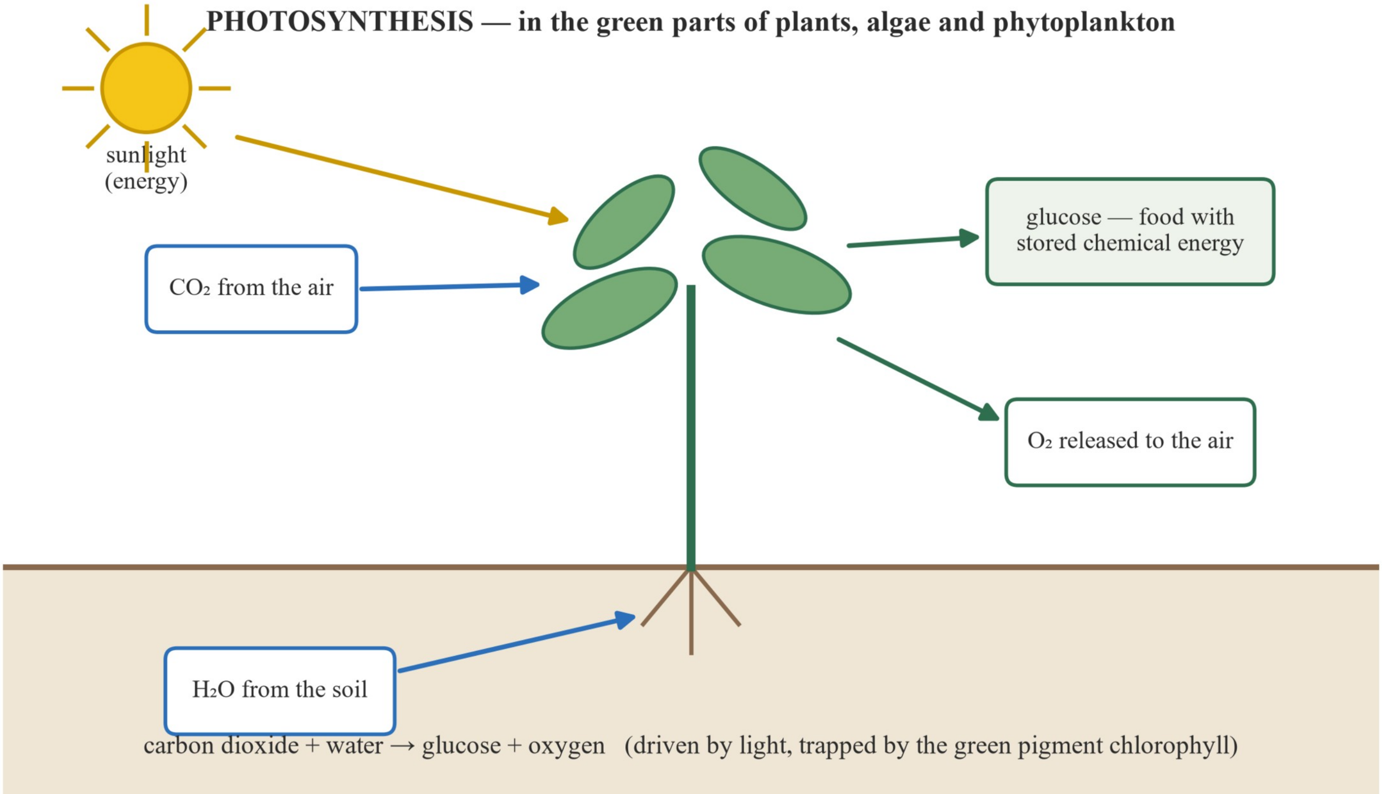
Photosynthesis. Photosynthesis is the process in which plants, algae and phytoplankton use light energy to make **glucose** — a sugar that stores chemical energy — from carbon dioxide and water, releasing oxygen as a by-product. It happens inside **chloroplasts**, the tiny structures in plant cells that contain **chlorophyll**, the green pigment that captures light energy. The word equation is:

carbon dioxide + water →(light, chlorophyll) glucose + oxygen

With chemical symbols — a molecule of glucose is $C_6H_{12}O_6$ — the same reaction is written:

$$6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2$$

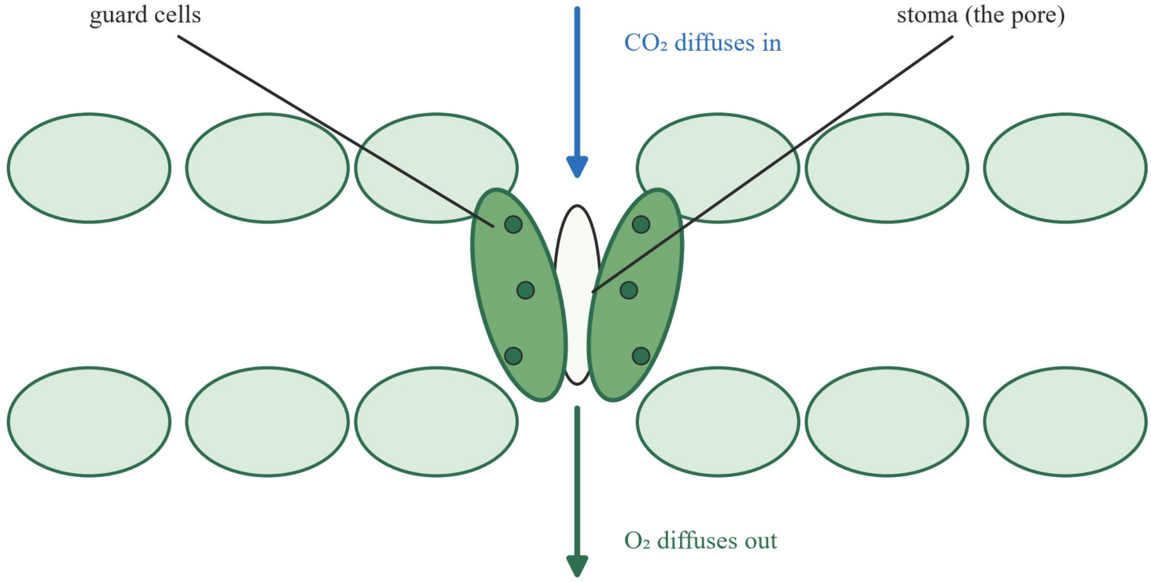
You are not asked to do any mole calculations with this equation (that is VCE chemistry, not this book); you *are* asked to check that it balances — the same count of each kind of atom on both sides (worked example 1).



A leaf-level diagram of photosynthesis: sunlight and carbon dioxide entering a leaf with water arriving from the roots, and glucose and oxygen leaving; the word equation carbon dioxide plus water, in the presence of light and chlorophyll, gives glucose plus oxygen is written beneath

The CO_2 a plant needs enters through **stomata** — tiny pores, mostly on the underside of a leaf, that open and close to let gases in and out. The oxygen made in photosynthesis leaves the same way, and so does water vapour. Stomata are the leaf's trading doors with the atmosphere.

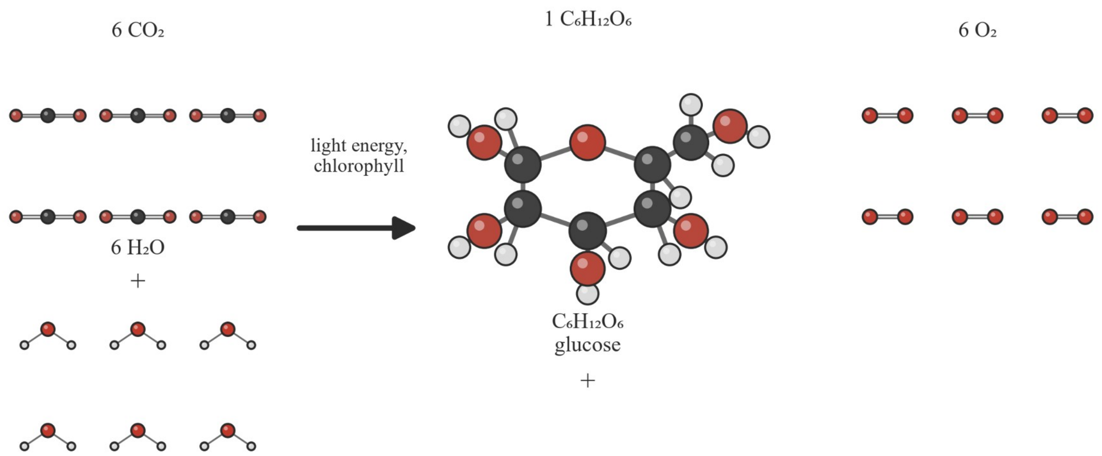
The underside of a leaf, enlarged: gases enter and leave through stomata



Each stoma is flanked by two guard cells; together, the stomata let CO_2 in for photosynthesis and O_2 out.

An enlarged view of the underside of a leaf showing one open stoma: two sausage-shaped guard cells around a pale pore, set among flat epidermal cells, with a blue arrow showing carbon dioxide diffusing in through the pore and a green arrow showing oxygen diffusing out, and a caption noting that each stoma is flanked by two guard cells

The molecule picture makes the balancing honest. Six molecules of CO_2 carry 6 carbon and 12 oxygen atoms; six of H_2O carry 12 hydrogen and 6 oxygen atoms. The products hold exactly those atoms rearranged: 6 carbon, 12 hydrogen and 18 oxygen in one glucose molecule plus six O_2 molecules. Nothing is created and nothing is lost — atoms are only rearranged, which is why the equation balances.



$6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2$ — count the atoms: 6 C, 12 H and 18 O on each side

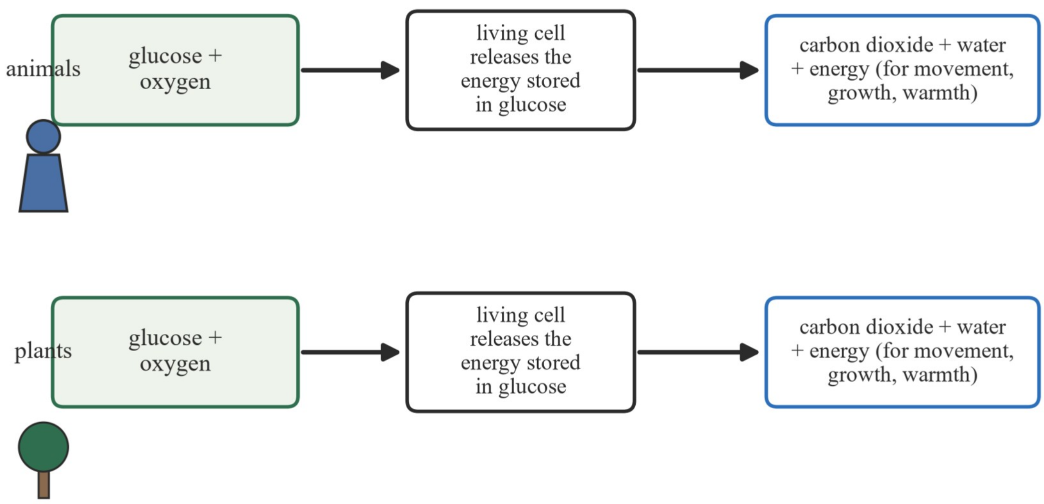
Ball-and-stick molecules drawn to the balanced equation: six CO_2 molecules and six H_2O molecules on the left, an arrow labelled light energy and chlorophyll, then one $C_6H_{12}O_6$ glucose molecule (a six-membered ring) and six O_2 molecules on the right, with the symbol equation $6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2$ and the atom count 6 C, 12 H and 18 O on each side written beneath

Respiration. Respiration is the process in which cells break down glucose with oxygen to release energy for life — growth, movement, repair — producing carbon dioxide and water as waste products. Its word equation is the reverse of photosynthesis:

glucose + oxygen → carbon dioxide + water (+ energy released)

Respiration is *not* the same thing as breathing: breathing moves air in and out of lungs, while respiration is the chemical process happening in cells. And it is not animals-only: **every living organism respires**, including plants. A plant photosynthesises in the light and respires all the time, day and night.

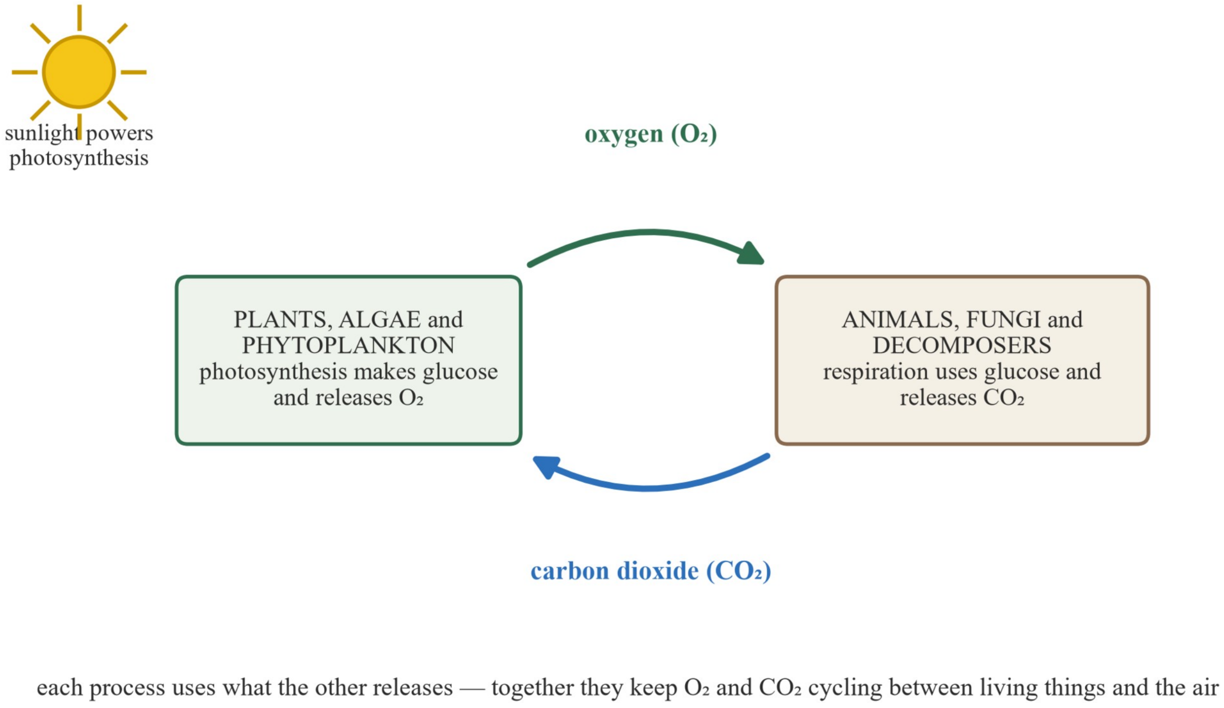
CELLULAR RESPIRATION — happens in every living cell, day and night



respiration is the reverse recipe of photosynthesis: it breaks glucose down and lets the stored energy out — plants respire too, not just animals.

Two parallel flow charts titled "Cellular respiration — happens in every living cell, day and night", one row for animals and one for plants: each runs from a "glucose + oxygen" box to a "living cell releases the energy stored in glucose" box to a "carbon dioxide + water + energy (for movement, growth, warmth)" box, with a caption noting that respiration is the reverse recipe of photosynthesis and that plants respire too, not just animals

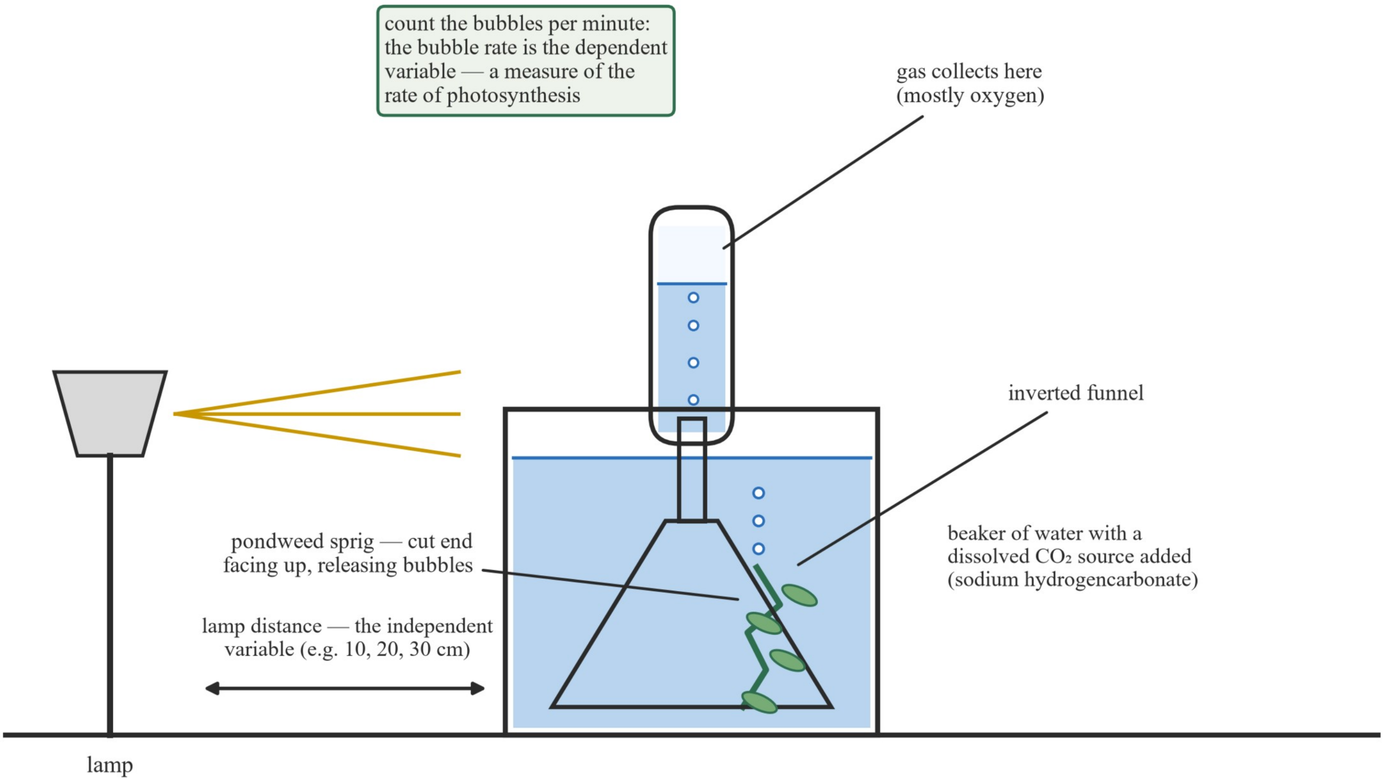
Two processes, one cycle. Photosynthesis and respiration are opposite trades of the same two gases. Photosynthesis takes CO_2 from the air and puts O_2 in; respiration takes O_2 from the air and puts CO_2 in. Each process uses what the other releases, so the two keep oxygen and carbon dioxide cycling between living things and the air. That loop — plants and phytoplankton on one side, animals, fungi and decomposers on the other — is the fast biological engine of the carbon cycle.



A two-box cycle: plants, algae and phytoplankton on the left (photosynthesis makes glucose and releases O_2) and animals, fungi and decomposers on the right (respiration uses glucose and releases CO_2), joined by a green arrow labelled oxygen (O_2) running left to right and a blue arrow labelled carbon dioxide (CO_2) running right to left, with a sun symbol marking that sunlight powers photosynthesis

Measuring the rate of photosynthesis. Because photosynthesis releases oxygen, a water plant (pondweed) under water gives off visible bubbles of oxygen, and counting bubbles per minute measures the **rate** of photosynthesis. In the classic setup, a pondweed sprig sits under an inverted funnel in a beaker of water with a dissolved CO_2 source added (sodium hydrogencarbonate), and an inverted test tube collects the gas. A lamp at a measured distance supplies the light. The **independent variable** — the one you change — is the lamp distance; the **dependent variable** — the one you measure — is the bubble rate; everything else (same pondweed, same water, same temperature) is kept the same. Moving the lamp closer makes the light stronger and the bubble rate rises; moving it away makes the rate fall. The method is drawn below, and Activity 3 gives you practice data to interpret.

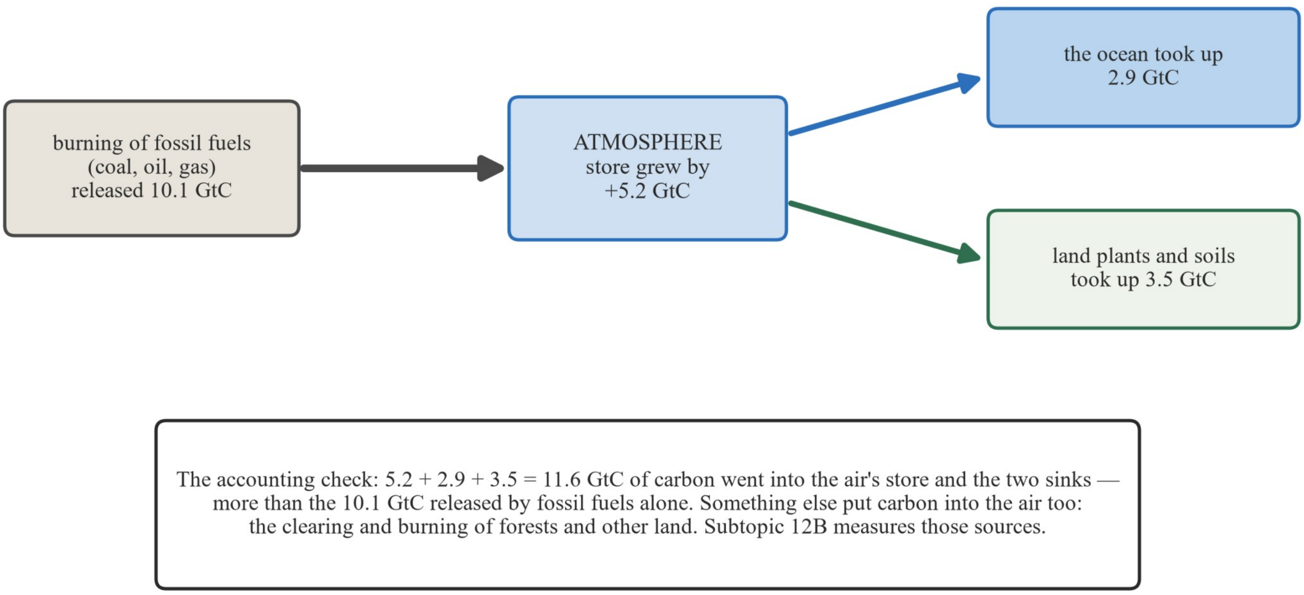
Measuring the rate of photosynthesis in a water plant (pondweed)



A labelled bench setup for measuring the rate of photosynthesis in pondweed: a lamp at a marked distance from a beaker of water with a dissolved CO_2 source added, an inverted funnel over a pondweed sprig with its cut end facing up, and an inverted test tube collecting the gas the plant releases; a note explains that counting the bubbles per minute is the dependent variable and the lamp distance is the independent variable

The carbon budget for 2021 — stocks and flows. A **stock-and-flow** picture reads a store as a tank with flows in and flows out; the store grows when the flows in exceed the flows out, even if every flow stays steady. The Global Carbon Budget works this way for the atmosphere, in GtC per year. In 2021, burning fossil fuels (coal, oil, gas) put 10.1 GtC into the air. The air's store grew by 5.2 GtC; the ocean took up 2.9 GtC; and land plants and soils took up 3.5 GtC. The accounting check: 5.2 + 2.9 + 3.5 = 11.6 GtC went into the store and the sinks — more than the 10.1 GtC from fossil fuels alone, so something else added carbon to the air as well. That something is the clearing and burning of forests and other land (about 1.1 GtC in 2021), which Subtopic 12B measures; the small leftover difference between the two totals is within the uncertainty of the estimates.

Where did the carbon go in 2021? A stock-and-flow picture

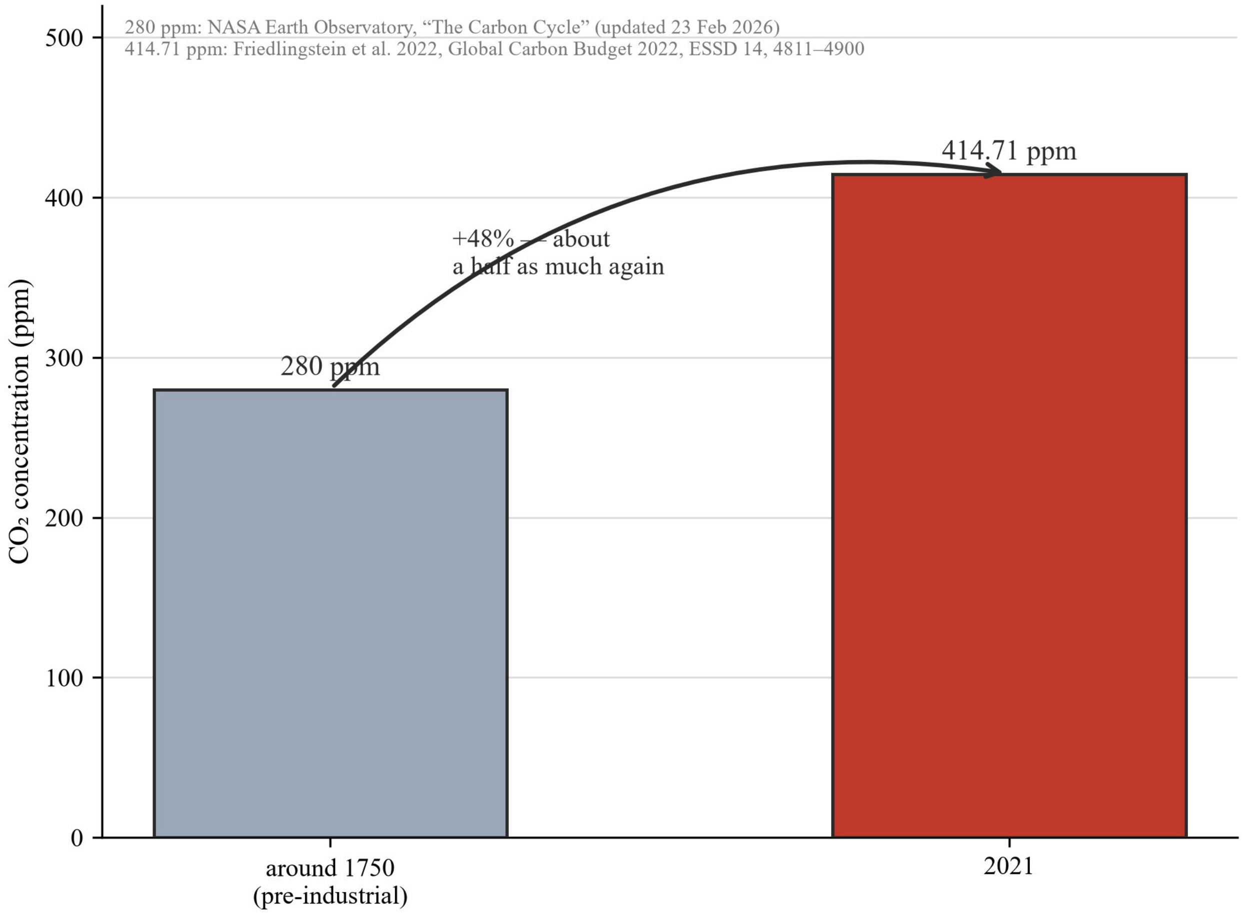


Friedlingstein et al. 2022, Global Carbon Budget 2022, ESSD 14, 4811–4900

A stock-and-flow diagram for 2021: burning of fossil fuels released 10.1 GtC; the atmosphere store grew by +5.2 GtC; the ocean took up 2.9 GtC; and land plants and soils took up 3.5 GtC; a box below shows the accounting check that 5.2 + 2.9 + 3.5 = 11.6 GtC, more than the fossil-fuel release alone, with the clearing and burning of forests named as the added source and measured in Subtopic 12B

Source: Friedlingstein et al. 2022, "Global Carbon Budget 2022", Earth System Science Data 14, 4811–4900.

Then and now. The same budget, repeated every year, is why the air's CO_2 store is not what it was. Around 1750, before large-scale fossil-fuel burning, the air held about 280 parts per million (ppm) of CO_2; in 2021 it held 414.71 ppm — a rise of about 48%, or about a half as much again. Read carefully: 414.71 ppm is a **level** (the size of the store at that moment), while 5.2 GtC per year is a **rate** (how fast the store was then growing). "Emissions fell" and "the CO_2 level fell" are different claims: a level only falls when the flows out of the store exceed the flows in.



A two-bar chart of CO_2 concentration in ppm: around 1750 (pre-industrial) at 280 ppm and 2021 at 414.71 ppm, with an arrow between the bar tops labelled +48%, about a half as much again

Source: 280 ppm: NASA Earth Observatory, "The Carbon Cycle" (updated 23 Feb 2026); 414.71 ppm: Friedlingstein et al. 2022, Global Carbon Budget 2022, ESSD 14, 4811–4900.

Activities

Activity 1 — Trace a carbon atom. Using the carbon cycle figure, write a travel diary for one carbon atom that visits all four systems in a single journey of at least six stops (for example: air → leaf → insect → soil → … → air). For each stop, name (i) which system the atom is sitting in, and (ii) which process moves it to the next stop. Mark which steps of your journey belong to the fast biological cycle and which would need a 12B process.

Activity 2 — Orders of magnitude of the carbon stores. Using the stores figure: (a) write the three store sizes (881; 1 672; 65 500 GtC) in scientific notation to two significant figures; (b) for each pair of stores, divide the larger by the smaller and say, in orders of magnitude, how far apart they are (remember: each factor of ten is one order of magnitude); (c) the atmosphere's store is the *smallest* of the major stores, yet it is the one the budget figure worries about. In one or two sentences, explain why a small store is the easiest one to change.

Activity 3 — Bubble-count data (simulated data for practice). A class ran the pondweed investigation at four lamp distances and recorded: 10 cm → 42 bubbles/min; 20 cm → 28 bubbles/min; 30 cm → 17 bubbles/min; 40 cm → 9 bubbles/min. (a) Identify the independent and dependent variables. (b) Describe the pattern in one sentence. (c) Suggest two things that must be kept the same for the test to be fair, and say what would go wrong if each one changed. (d) A student concludes "the plant is photosynthesising fastest at 10 cm, so light must be strongest there". Is the conclusion justified by the data? Explain.

Worked examples

Data in this section are quoted to the significant figures shown, and final answers match the precision of the given data unless the arithmetic is exact.

Example 1 — scaffolded

Check that the symbol equation for photosynthesis balances: 6 CO_2 + 6 H_2O → $C_6H_{12}O_6$ + 6 O_2. Count each kind of atom on both sides.

Step 1 — Left side. 6 CO_2 gives 6 C and 6 × 2 = 12 O. 6 H_2O gives 12 H and 6 O. Totals: C = 6; H = 12; O = 12 + 6 = 18.

Step 2 — Right side. $C_6H_{12}O_6$ gives 6 C, 12 H, 6 O. 6 O_2 gives 12 O. Totals: C = 6; H = 12; O = 6 + 12 = 18.

Step 3 — Compare. C: 6 = 6. H: 12 = 12. O: 18 = 18. Every count matches, so the equation balances — atoms are rearranged, not created or destroyed.

Example 2 — scaffolded

In 2021, fossil fuels released 10.1 GtC and land clearing about 1.1 GtC. The atmosphere grew by 5.2 GtC, the ocean took up 2.9 GtC and the land took up 3.5 GtC. Do the flows in and out of the air's store agree?

Step 1 — Flows into the air's story (sources). 10.1 + 1.1 = 11.2 GtC.

Step 2 — Where it went (growth + sinks). 5.2 + 2.9 + 3.5 = 11.6 GtC.

Step 3 — Compare. 11.6 − 11.2 = 0.4 GtC, a difference of less than the ±0.5–0.9 GtC uncertainty on each estimate. Within uncertainty, the budget balances — which is exactly what a stock-and-flow check is for.

Example 3 — unscaffolded

The rock store holds about 65 500 GtC and the atmosphere about 881 GtC. (a) Write both in scientific notation. (b) How many times larger is the rock store, and how does that compare with orders of magnitude?

(a) 65 500 ≈ 6.6×10^4 GtC; 881 ≈ 8.8×10^2 GtC.
(b) 65 500 ÷ 881 ≈ 74. Ten times is one order of magnitude and one hundred times is two, so 74 times is between one and two orders of magnitude — close to two.

Example 4 — unscaffolded

CO_2 was about 280 ppm around 1750 and 414.71 ppm in 2021. Calculate the percentage increase.

Increase = 414.71 − 280 = 134.71 ppm. Percentage increase = 134.71 ÷ 280 × 100 ≈ 48%. The 2021 level was about a half as much again as the pre-industrial level.

Practice questions

Scaffolded questions

Question 1 Name Earth's four interrelated systems and, for each, give one place or thing from the four-systems figure that belongs to it.

Question 2 Follow the fertiliser story of the system-links figure. Copy the four steps and write the system (or systems) each step mainly involves.

Question 3 (a) Write the word equation for photosynthesis, including the conditions written over the arrow. (b) Name the cell structure where it happens and the pigment that captures light.

Question 4 Using the molecule figure, count the carbon, hydrogen and oxygen atoms on each side of 6 CO_2 + 6 H_2O → $C_6H_{12}O_6$ + 6 O_2 and state what the equal counts show.

Question 5 (a) What are stomata? (b) Name the two gases that pass through them into and out of a leaf during photosynthesis.

Question 6 (a) Write the word equation for respiration. (b) A friend says “plants photosynthesise, animals respire”. Correct the sentence and give the reason.

Question 7 In the gas-cycle figure, which process removes CO_2 from the air and which returns it? Explain in one sentence why the two are called a cycle.

Question 8 The carbon cycle figure shows four dashed arrows that belong to Subtopic 12B. Name the four processes they mark.

Unscaffolded questions

Question 9 The atmosphere’s carbon store is about 881 GtC and the rock store about 65 500 GtC. (a) Write both in scientific notation to two significant figures. (b) Estimate, as a power-of-ten statement, how many orders of magnitude larger the rock store is.

Question 10 In the pondweed investigation, state (a) the independent variable, (b) the dependent variable, and (c) one factor to keep the same, with a reason.

Question 11 The 2021 budget: fossil fuels released 10.1 GtC; the atmosphere grew by 5.2 GtC; the ocean took up 2.9 GtC; the land took up 3.5 GtC. (a) Show that the sinks plus the growth exceed the fossil-fuel release. (b) Name the extra source that closes most of the gap, and say which subtopic measures it.

Question 12 CO_2 was about 280 ppm around 1750 and 414.71 ppm in 2021. Calculate the percentage increase, to two significant figures.

Question 13 A headline reads “emissions fell, so the CO_2 level in the air fell too”. Using the stock-and-flow idea, explain why the second half does not follow from the first.

Question 14 The stores figure puts the atmosphere at about 8.8×10^2 GtC — one of the smallest stores — yet the budget figure shows it changing the fastest. Explain why a small store changes more than a big one for the same flow of carbon.

Answers

Question 1 Atmosphere (the sky/air); hydrosphere (the ocean); lithosphere (soil, rock); biosphere (trees, grass, fish, birds). **Question 2** 1 lithosphere (soil); 2 hydrosphere; 3 biosphere + hydrosphere; 4 biosphere → atmosphere. **Question 3** (a) carbon dioxide + water →(light, chlorophyll) glucose + oxygen; (b) chloroplasts; chlorophyll. **Question 4** 6 C, 12 H, 18 O on each side; atoms are rearranged, not created or destroyed — the equation balances. **Question 5** (a) tiny pores, mostly on a leaf's underside, that open and close; (b) CO_2 in; O_2 out (water vapour also leaves). **Question 6** (a) glucose + oxygen → carbon dioxide + water (+ energy released); (b) all living organisms respire, including plants; plants also photosynthesise in the light. **Question 7** Photosynthesis removes CO_2; respiration returns it; each process uses what the other releases, so the gases loop. **Question 8** Fire; burning of fossil fuels; vulcanism; weathering of rock. **Question 9** (a) 8.8×10^2 GtC; 6.6×10^4 GtC; (b) about 74 times — between one and two orders of magnitude (close to two). **Question 10** (a) lamp distance; (b) bubbles per minute; (c) e.g. same water temperature — temperature also affects the rate, so changing it would hide the light effect. **Question 11** (a) 5.2 + 2.9 + 3.5 = 11.6 GtC > 10.1 GtC; (b) the clearing and burning of forests and other land (about 1.1 GtC) — Subtopic 12B. **Question 12** ≈ 48%. **Question 13** The level falls only when flows out exceed flows in; smaller emissions still add carbon while they exceed the sinks, so the store keeps growing (more slowly). **Question 14** The same flow is a bigger share of a small store than of a big one; 10 GtC shifts the air's 881 GtC store noticeably but would be invisible in the rock store.

Fully-worked solutions

Question 1 The sky with its clouds and birds is the **atmosphere**; the ocean is the **hydrosphere**; the soil band and the rock beneath are the **lithosphere**; the trees, grass strip and fish are the **biosphere**. (Any matching item from the figure scores.)

Question 2 Step 1, fertiliser on farmland — **lithosphere** (soil). Step 2, rain washing nutrients into streams — **hydrosphere**. Step 3, algal bloom and oxygen loss — **biosphere + hydrosphere**. Step 4, fish die and decomposers release CO_2 — **biosphere → atmosphere**.

Question 3 (a) carbon dioxide + water → glucose + oxygen, with light and chlorophyll written as the conditions. (b) Photosynthesis happens in **chloroplasts**, whose **chlorophyll** captures light energy.

Question 4 Left: 6 CO_2 → 6 C + 12 O; 6 H_2O → 12 H + 6 O; totals 6 C, 12 H, 18 O. Right: $C_6H_{12}O_6$ → 6 C, 12 H, 6 O; 6 O_2 → 12 O; totals 6 C, 12 H, 18 O. Equal counts show the equation balances: atoms are rearranged, never created or destroyed.

Question 5 (a) Stomata are tiny pores, mostly on a leaf's underside, that open and close. (b) During photosynthesis, CO_2 enters and O_2 leaves through them (water vapour also escapes).

Question 6 (a) glucose + oxygen → carbon dioxide + water, with energy released. (b) Corrected: "all living organisms respire, and plants also photosynthesise." Plants respire day and night; photosynthesis only runs in light.

Question 7 **Photosynthesis** removes CO_2 from the air; **respiration** returns it. They form a cycle because each process uses exactly the gas the other releases, keeping O_2 and CO_2 moving between living things and the air.

Question 8 Fire; the burning of fossil fuels; vulcanism; and the weathering of rock — the four dashed arrows, all delivered in Subtopic 12B.

Question 9 (a) 881 ≈ **8.8×10^2 GtC**; 65 500 ≈ **6.6×10^4 GtC**. (b) 65 500 ÷ 881 ≈ 74. Since $10^1 = 10$ and $10^2 = 100$, 74 times is **between one and two orders of magnitude**, close to two.

Question 10 (a) The **independent variable** is the lamp distance (what you change). (b) The **dependent variable** is the bubble rate in bubbles per minute (what you measure). (c) Example: keep the water temperature the same — warmth also speeds up the plant, so a changing temperature would hide the effect of the light.

Question 11 (a) Growth + sinks = 5.2 + 2.9 + 3.5 = **11.6 GtC**, which is more than the **10.1 GtC** released by fossil fuels alone. (b) The extra source is the clearing and burning of forests and other land (about 1.1 GtC in 2021); Subtopic **12B** measures those sources. The remaining ~0.4 GtC difference is within the uncertainty of the estimates.

Question 12 Increase = 414.71 − 280 = 134.71 ppm. Percentage = 134.71 ÷ 280 × 100 = 48.1… ≈ **48%** (2 s.f.).

Question 13 In stock-and-flow terms, the air's CO_2 **level** is the store and emissions are a flow in. A store only shrinks when flows out exceed flows in. "Emissions fell" means the flow in got smaller — but while it is still bigger than the sinks' flow out, the store keeps growing. So the level would keep rising, just more slowly; the headline's second half does not follow.

Question 14 A flow changes a store by its *share* of that store. 10 GtC is about 1% of the atmosphere's 881 GtC store — a visible yearly change — but about 0.015% of the 65 500 GtC rock store, far too small to notice. Same flow, small store: big effect; same flow, big store: almost no change.

Where this leads: within this book, the second half of `VC2S10U10` — fire, weathering, vulcanism and the combustion of fossil fuels, and how those processes change the composition of Earth's systems over time — is delivered by subtopic 12B, which takes over every dashed arrow in the carbon cycle figure. Beyond school, the destination is mainly VCE Environmental Science: U1 AoS1 ("How are Earth's systems organised and connected?") starts exactly where 12A ends, with the four spheres as an interacting system, and U4 AoS1 ("How can we respond to climate change?") quantifies the stock-and-flow picture of atmospheric CO_2 introduced here (TOC §5, reference-only, D12). The durable skills are the reading habits, not the facts: reading a store with its flows in and flows out, and telling a **rate** ("emissions fell") from a **level** ("concentration fell") — the confusion is endemic in student writing and is exactly what VCE assesses. No VCE content is pre-taught here (TOC D9): no mole calculations, no equilibrium, and the greenhouse mechanism itself is left for the later energy- balance treatment in subtopic 12C.

Fire, weathering, vulcanism and fossil-fuel combustion — how carbon processes change system composition over time

Chapter 12 — Earth and space sciences A: Earth's systems, carbon and climate (Science, Levels 9 and 10)

Subtopic 12B · VC2 Science Understanding — Earth and space sciences

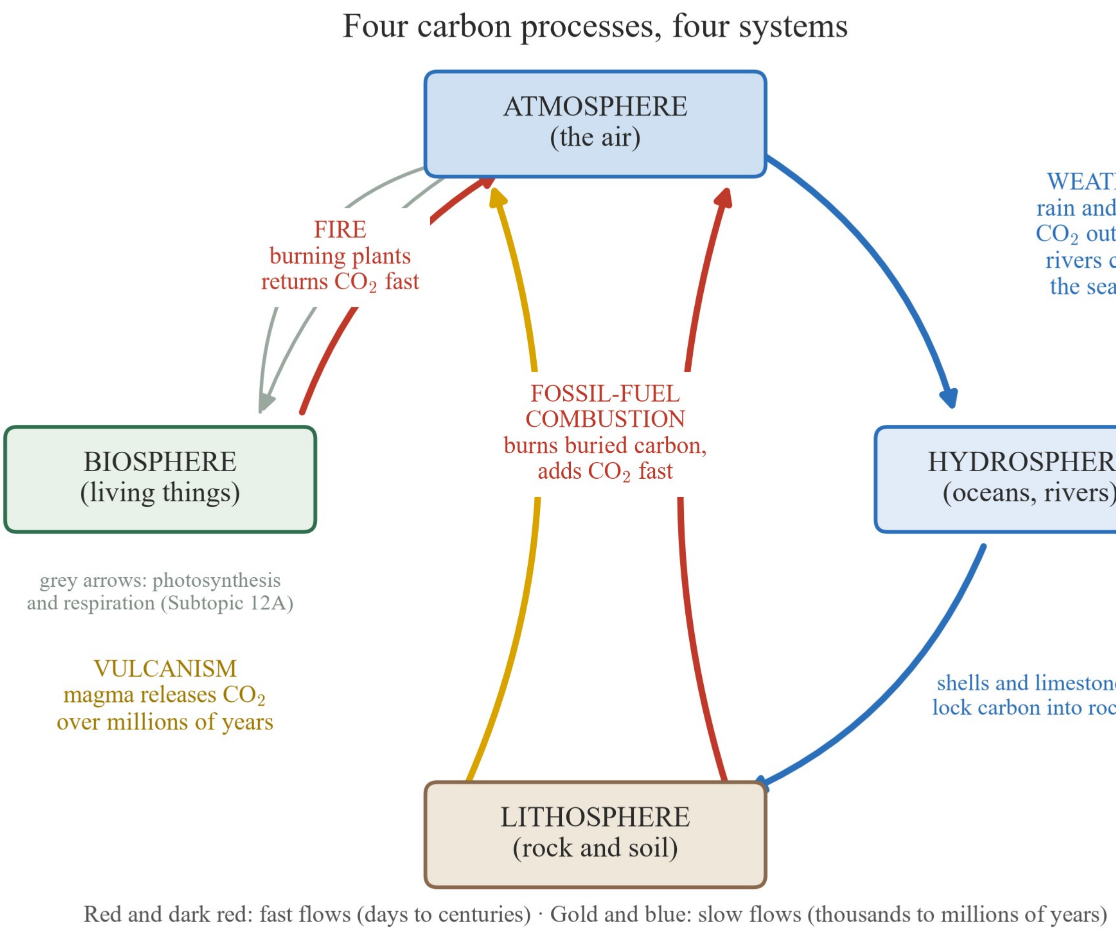
CD code: `VC2S10U10` (split delivery †; this subtopic is the partner, not the accountable owner) **Content description (verbatim):** "carbon is cycled on Earth through key processes including photosynthesis, respiration, fire, weathering, vulcanism and the combustion of fossil fuels; these processes change the composition of Earth's interrelated systems (atmosphere, biosphere, hydrosphere and lithosphere) over time" **This subtopic's limb (TOC §4 clause split):** fire, weathering, vulcanism and fossil-fuel combustion — how carbon processes change system composition over time. The accountable owner `12A` delivers the other limb: Earth's four interrelated systems and the carbon cycle: photosynthesis and respiration. **Elaboration ids drawn on:** `VC2S10U10.E03` · `VC2S10U10.E06` · `VC2S10U10.E07` (ids `VC2S10U10.E01` and `VC2S10U10.E02` are drawn on by Subtopic 12A; ids `VC2S10U10.E04` and `VC2S10U10.E05` are not authored, under the TOC's D10 ICIP decision) **Achievement standard (extract served):** "They explain how interactions within and between Earth's interrelated systems affect the carbon cycle." **Maths interlock (D11):** `VC2M9M05` — direct proportion, rates, ratio and scale.

Most worked numbers in this subtopic are simulated data for practice, and each dataset is labelled where it appears. A few values are real and carry source lines where they are used: the carbon-dioxide record from ice cores and the Cape Grim measurements, the two average temperatures of the natural greenhouse effect, the rule that about half of dry biomass is carbon, and the fact that the land and ocean absorb about half of the carbon dioxide human activities add each year. No real-world measurement is attributed to any person or place.

Theory

Carbon moves by more than two routes. In Subtopic 12A you traced how carbon moves between the air and living things: photosynthesis takes carbon dioxide out of the atmosphere and builds it into living material, and respiration returns it. Those two processes keep carbon moving quickly between the atmosphere and the biosphere — in the grey arrows of the figure below. They are not the whole story. This subtopic adds four more processes: **fire**, **weathering**, **vulcanism** and the **combustion of fossil fuels**. Every one of them changes the composition of Earth's interrelated systems over time — which is exactly the skill the achievement standard asks for.

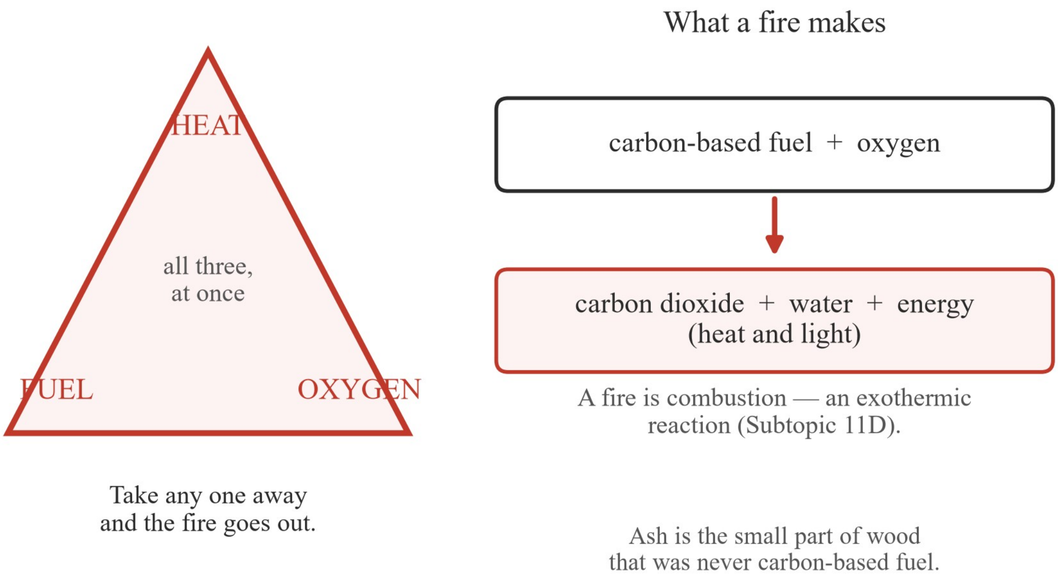
Read the carbon cycle as a set of accounts. Every process is either a **source** — a process that adds carbon dioxide to the atmosphere — or a **sink** — a process that removes it. The four processes here work at very different speeds: fire moves carbon in minutes, while weathering works over hundreds of thousands of years. What moves, and how fast it moves, decides what happens to the composition of the air, the sea, the living world and the rocks.



A map of the carbon cycle with Earth's systems as labelled boxes — the atmosphere, the biosphere, the hydrosphere and the lithosphere. Grey arrows show photosynthesis and respiration from Subtopic 12A. Coloured arrows show this subtopic's four processes: fire returns carbon from the biosphere to the atmosphere; weathering drains carbon from the atmosphere into the hydrosphere and on into the lithosphere; vulcanism returns carbon from the lithosphere to the atmosphere; fossil-fuel combustion burns buried carbon from the lithosphere and adds carbon dioxide to the atmosphere fast.

Fire returns carbon fast. A fire is combustion — the exothermic reaction you met in Subtopic 11D, running out in the open. Three things must be present together for a fire to burn: fuel, oxygen and heat. This is the **fire triangle**: take any one of the three away and the fire goes out. That is why water puts a fire out (it takes away heat), why a fire blanket works (it keeps oxygen away), and why a firebreak — a gap cleared of anything burnable — stops a fire spreading (it takes away fuel).

The fire triangle — and the reaction it stands for



The fire triangle: a triangle with its three sides labelled fuel, oxygen and heat. A note in the middle says a fire burns only while all three are present together, and taking any one of them away puts the fire out. A side panel gives the word equation carbon-based fuel + oxygen → carbon dioxide + water + energy (heat and light), and notes that a fire is combustion — an exothermic reaction (Subtopic 11D) — with a note that a little carbon is left behind as ash and charcoal.

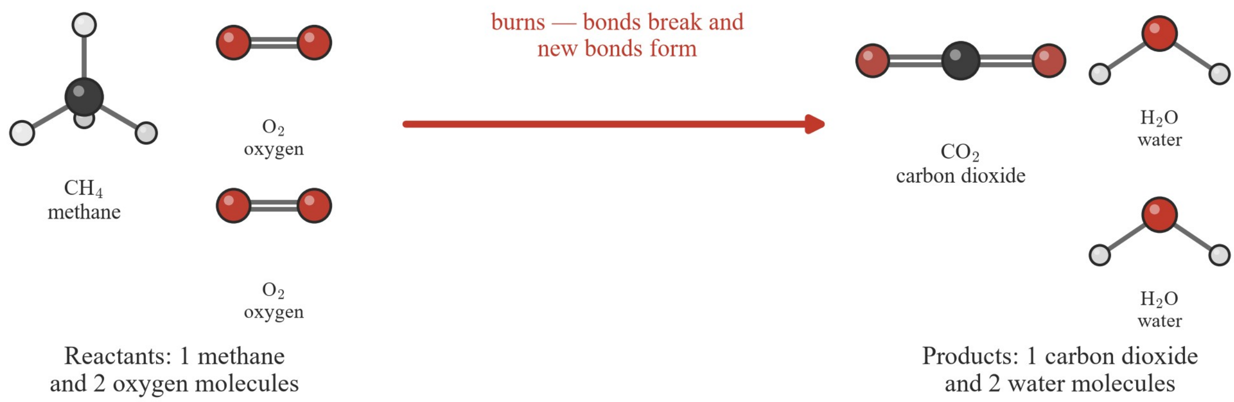
When a bushfire — usually started by a lightning strike — moves through forest or grassland, the fuel is biomass: wood, grass and leaf litter, all built from carbon dioxide taken out of the air by photosynthesis (Subtopic 12A). The carbon a tree spent decades building up returns to the atmosphere as carbon dioxide in minutes. The composition of two systems changes at once: the biosphere loses carbon and the atmosphere gains carbon dioxide. Some of the carbon is not burned completely — it is left behind as charcoal and ash, which break down much more slowly. Even so, next to the slow rotting of fallen wood, fire is a fast return.

In words, combustion is:

> fuel + oxygen → carbon dioxide + water (energy is released) — exothermic

At the particle level, the simplest fuel is methane, the main gas in natural gas. One molecule of methane — CH_4, one carbon atom joined to four hydrogen atoms — reacts with two molecules of oxygen, and the atoms rearrange into one molecule of carbon dioxide and two molecules of water, exactly the rearrangement idea of Subtopic 11A:

methane + oxygen → carbon dioxide + water (+ energy)

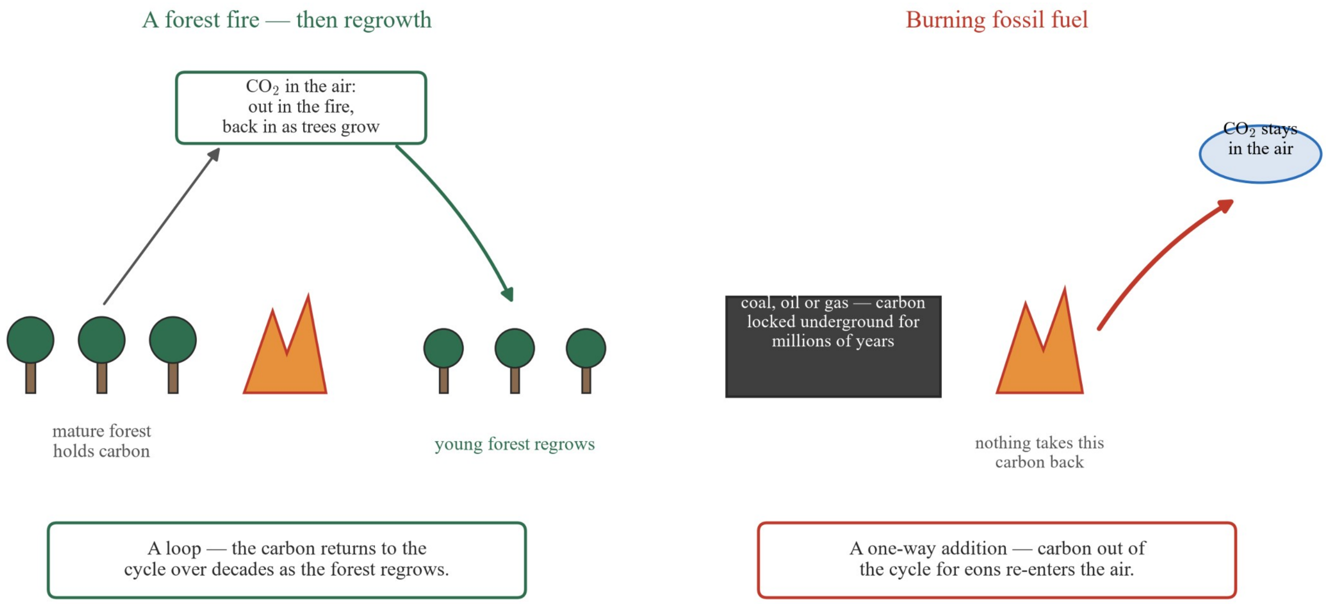


Count the atoms: 1 carbon, 4 hydrogens and 4 oxygens on each side — atoms are rearranged, not destroyed (Subtopic 11A).

A particle diagram of methane burning. One methane molecule — one black carbon atom joined to four small hydrogen atoms — reacts with two oxygen molecules, each made of two oxygen atoms. The atoms rearrange into one carbon dioxide molecule — one carbon atom joined to two oxygen atoms — and two water molecules, each one oxygen atom joined to two hydrogen atoms. Below the diagram, the word equation reads: methane + oxygen → carbon dioxide + water.

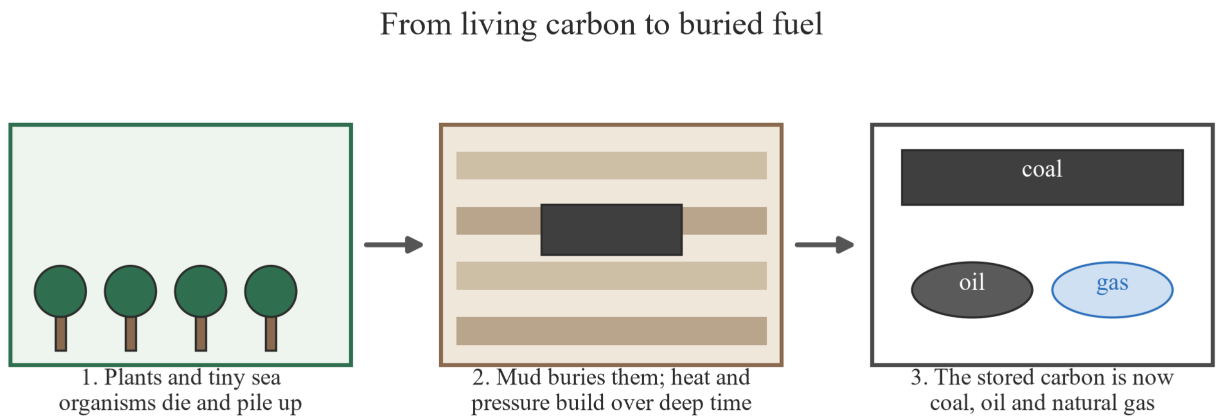
Two carbon accounts. A **store** is a place where carbon is kept, and each account tracks a store. In the first, a bushfire sends a pulse of carbon dioxide into the air in minutes — but as the forest regrows, photosynthesis takes about the same amount back over decades. The carbon goes round a loop and returns to the cycle. A forest that never burns stays in a loop too: photosynthesis takes carbon dioxide in, and respiration and the slow breakdown of dead material return about the same amount (Subtopic 12A), so year after year the forest adds little to the air and takes little from it, and the atmosphere's composition changes very little.

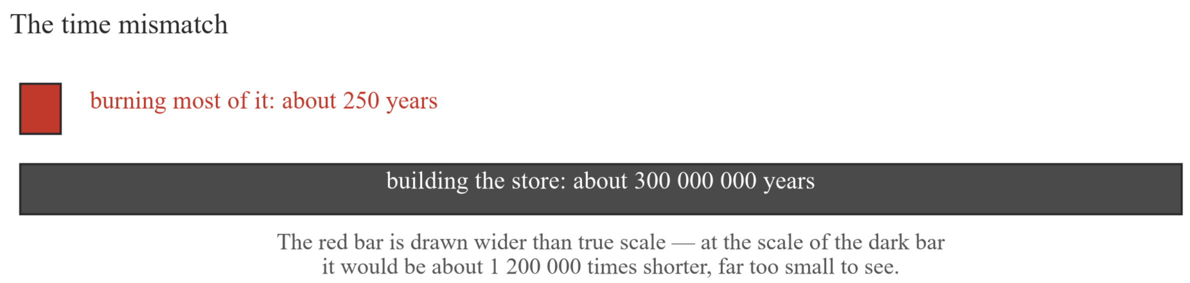
Burning fossil fuel is the other kind of account. The fuel is carbon that was locked in the lithosphere, out of the cycle. When it is dug up and burned, that carbon re-enters the air as carbon dioxide, and nothing takes it back on any human timescale — a one-way addition to the atmosphere. That contrast — carbon going round in a loop, and carbon on a one-way trip out of deep-time storage — is the key idea of this subtopic.



Two carbon accounts shown side by side. The left panel shows a forest fire and then regrowth: the fire sends carbon dioxide out into the air, and the regrowing forest takes it back in over decades, so the carbon moves in a loop and returns to the cycle. The right panel shows fossil fuel being burned: carbon locked in the lithosphere for eons, as coal, oil and gas, re-enters the air as carbon dioxide, and nothing takes this carbon back — a one-way addition.

Fossil fuels are deep-time carbon. Coal, oil and natural gas come from the buried remains of plants and tiny sea organisms. Layer after layer of **sediment** — sand, mud and silt carried by rivers and the sea — covered those remains. Over about 300 000 000 years, heat and pressure turned the buried carbon into the fuels we dig up today.





A sequence showing how fossil fuels form. The remains of plants and tiny sea organisms settle and are buried under layers of sediment; over about 300 000 000 years, heat and pressure slowly turn the buried carbon into coal, oil and gas, locked in the lithosphere. Below, two bars compare the time taken to build the store, about 300 000 000 years, with the time people have taken to burn most of it, about 250 years; the burning bar is drawn wider than true scale so that it can be seen.

Combustion runs that story backwards — and far faster. Burning coal, oil or gas returns their carbon to the atmosphere as carbon dioxide. The mismatch in times is the point: about 300 000 000 years were needed to bury this carbon, and people have been releasing it in the roughly 250 years since the mid-1700s. Carbon that left the atmosphere in deep time is coming back within a few human lifetimes.

The mass of carbon dioxide released is larger than the mass of carbon burned, because each carbon atom pairs with two oxygen atoms taken from the air. The mass ratio is fixed: for every 12 units of carbon burned, 44 units of carbon dioxide form. Burn 1.0 kg of carbon and $1.0 \times 44 \div 12 \approx 3.7$ kg of carbon dioxide enters the atmosphere. The extra mass is oxygen drawn in from the air during combustion.

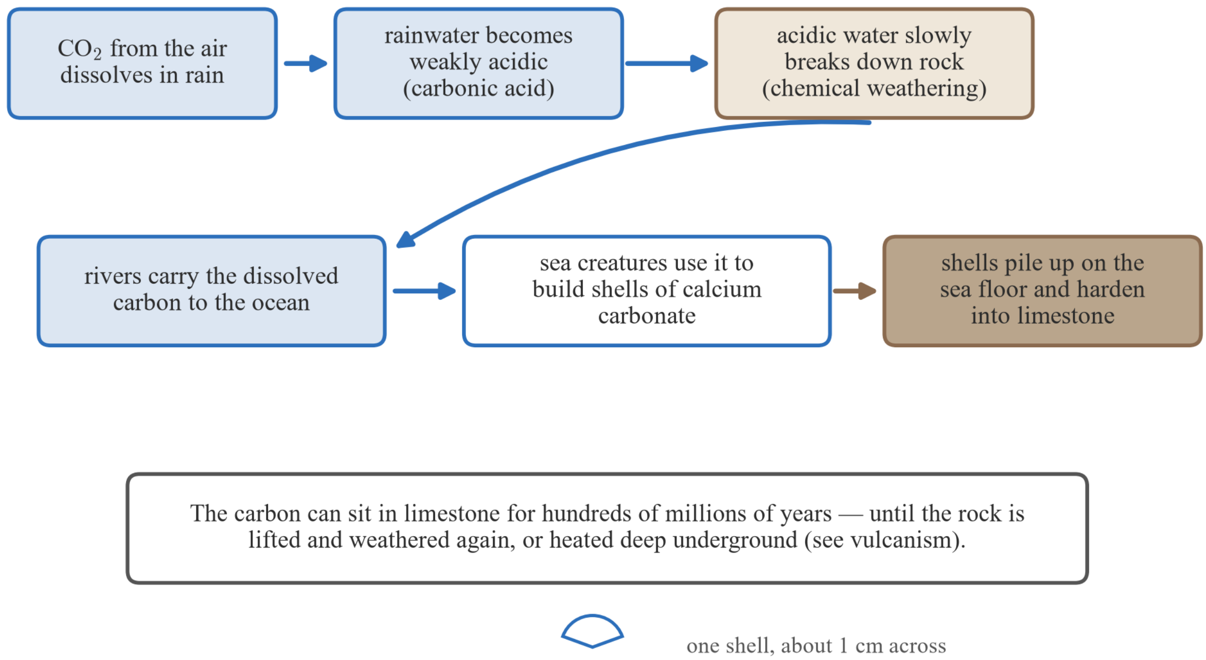
Weathering is a slow sink. Rainwater dissolves a little carbon dioxide from the air as it falls, becoming a weak acid. When that rain lands on rock, it slowly attacks it — especially rocks built of **calcium carbonate**, such as limestone, chalk and marble. Calcium carbonate is the compound that seashells and the shells of tiny sea animals are made of, and over Earth's long history, pressed-down layers of shells became limestone.

The reaction moves carbon out of the air and into dissolved form:

calcium carbonate + carbon dioxide + water → calcium hydrogen carbonate

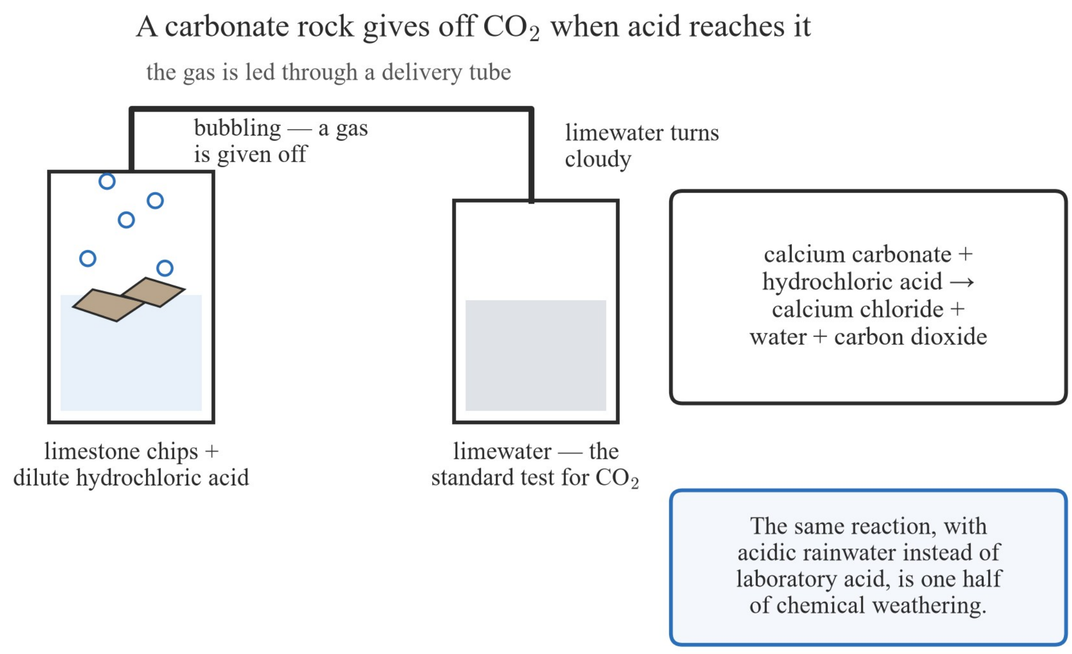
The calcium hydrogen carbonate dissolves and is carried by rivers to the sea, where sea animals use it to build new shells. When those animals die, their shells settle on the sea floor and, over long periods, form new limestone. The net effect: carbon leaves the atmosphere and ends up locked in rock. Weathering is a sink — but an extremely slow one, working over tens of thousands to hundreds of thousands of years.

Chemical weathering — where rain takes CO_2 out of the air



A flow diagram of chemical weathering. Carbon dioxide from the air dissolves in falling rainwater, making a weak acid. The acid slowly attacks rocks that contain calcium carbonate, such as limestone. The dissolved carbon is carried by rivers to the sea, where sea animals use it to build shells, and the shells slowly form limestone rock on the sea floor.

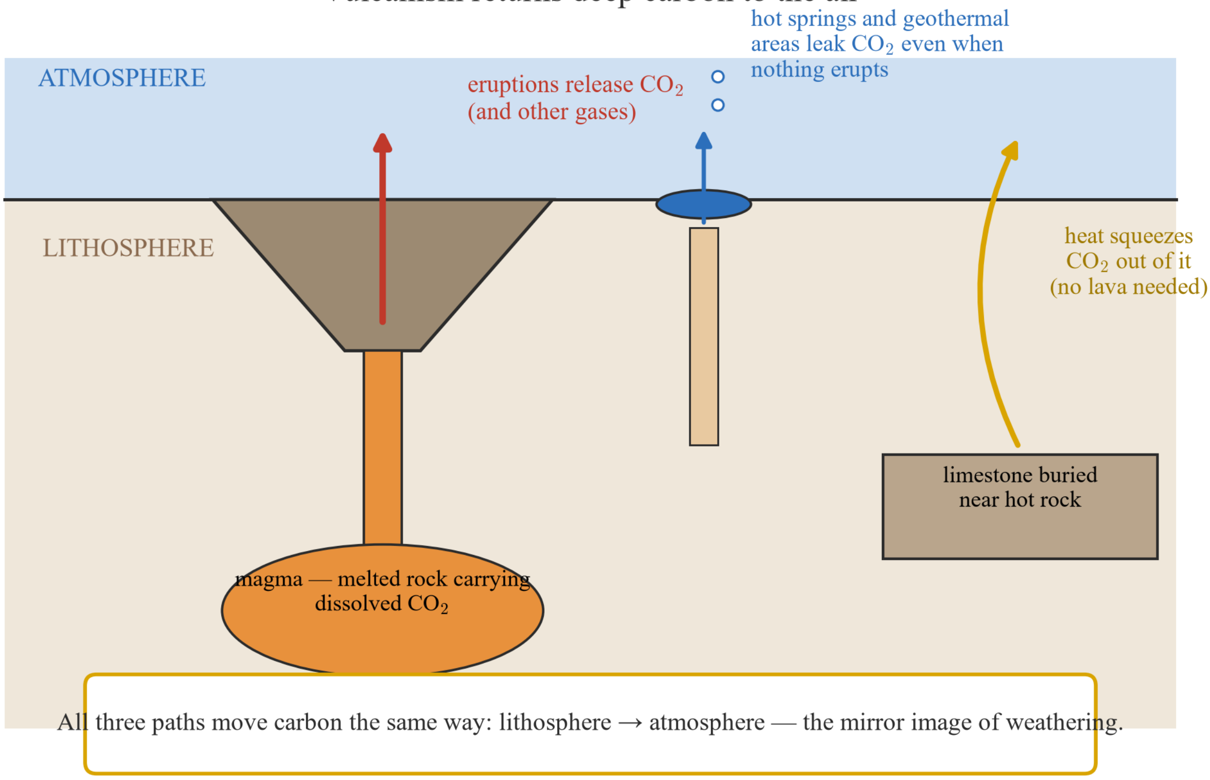
You can test that limestone really is a carbon store. Add dilute acid to a piece of limestone and it fizzes — a gas is given off. Pass the gas into **limewater** — a clear solution that turns cloudy when carbon dioxide is bubbled through it — and the cloudiness identifies the gas as carbon dioxide. The carbon came out of the rock.



A laboratory test for carbonate rock. On the left, dilute acid is added to a piece of limestone and bubbling shows a gas is given off. On the right, the gas is passed into limewater and the limewater turns cloudy, identifying the gas as carbon dioxide.

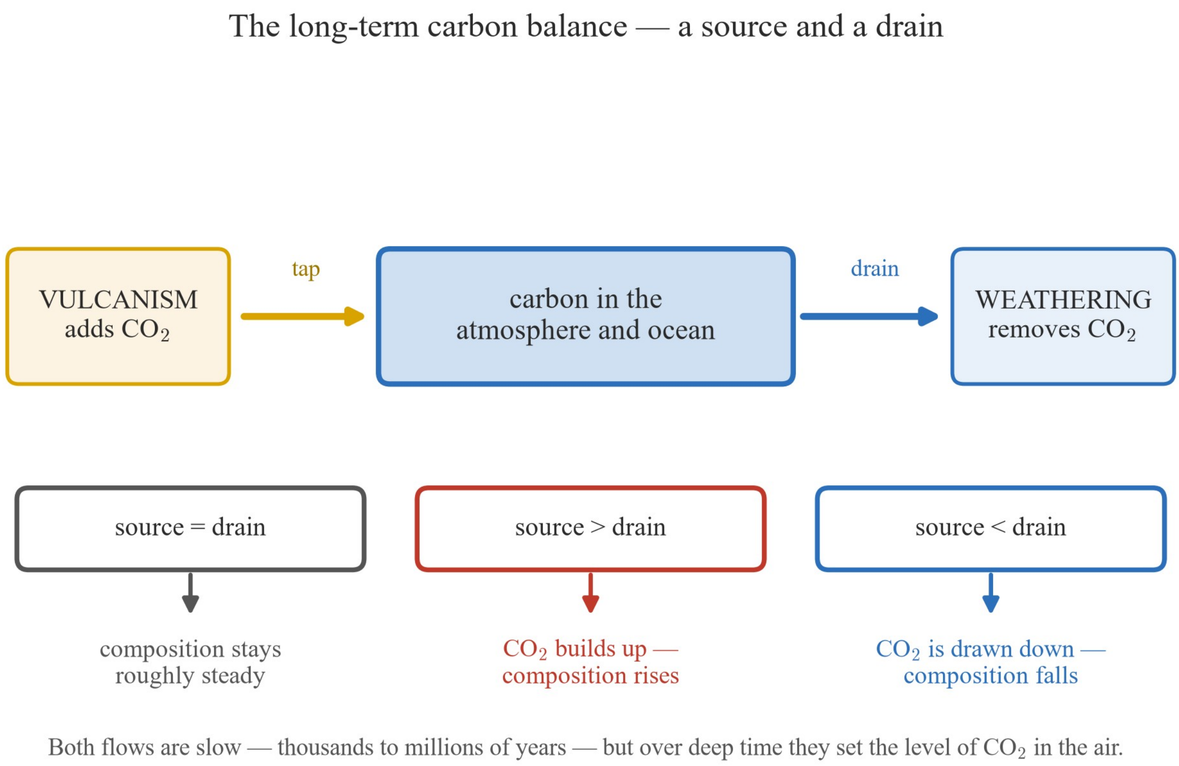
Vulcanism is a slow source. Carbon also finds its way back out of the lithosphere through volcanoes. Deep below the surface, **magma** — melted rock — carries dissolved carbon dioxide. As magma rises, pressure drops and the carbon dioxide escapes into the atmosphere during eruptions. Carbonate rocks heated at depth release carbon dioxide too, and volcanic regions leak the gas slowly even between eruptions. Vulcanism is a source: it adds carbon dioxide to the atmosphere slowly and steadily, over Earth’s long history.

Vulcanism returns deep carbon to the air



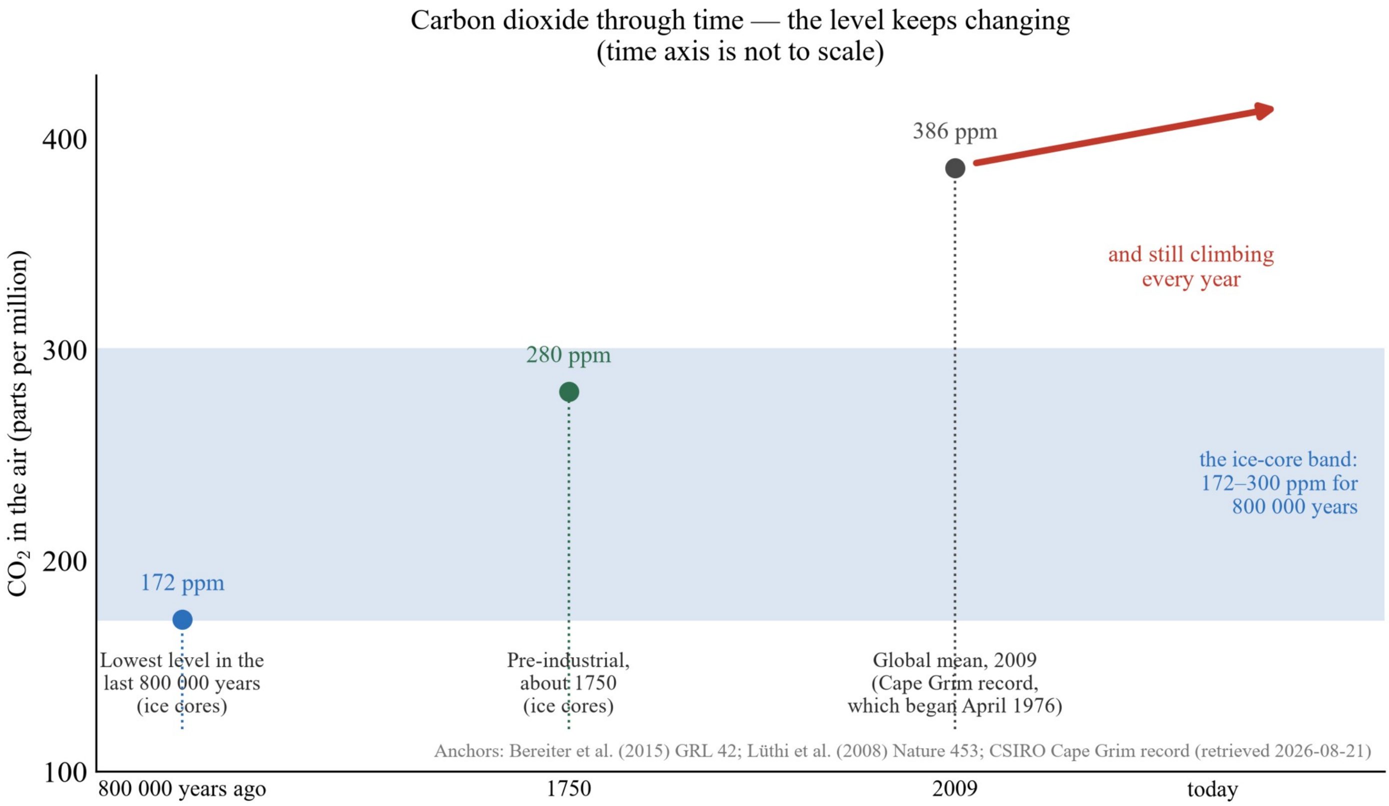
A cross-section showing three ways volcanic regions return carbon dioxide to the atmosphere. Eruptions release carbon dioxide that was carried dissolved in rising magma; hot springs and geothermal areas leak the gas even when nothing erupts; and limestone buried near hot rock has its carbon dioxide squeezed out by heat, with no lava needed. A note says all three paths move carbon the same way — lithosphere to atmosphere, the mirror image of weathering.

The long-term balance. For most of Earth's history the slow source and the slow sink have roughly balanced each other. Vulcanism adds carbon dioxide to the atmosphere, and weathering removes it, at about the same rate. Over hundreds of thousands of years the atmosphere's carbon dioxide level has stayed within a narrow band — long enough for the living world to depend on it being steady.



A tap-and-drain diagram of the long-term balance. Vulcanism adds carbon dioxide to the atmosphere and ocean like a tap, and weathering removes it like a drain; both flows are slow. Three cases are shown below: source equal to drain keeps the composition nearly steady; source greater than drain lets carbon dioxide accumulate; source less than drain lets it decrease.

The evidence comes from ice cores — long cylinders of ice drilled from the ice sheets of Antarctica. Tiny bubbles of ancient air, trapped when the ice formed, let scientists measure the carbon dioxide of hundreds of thousands of years ago. Concentrations are measured in **parts per million** (ppm): the number of carbon dioxide molecules in every million molecules of air.



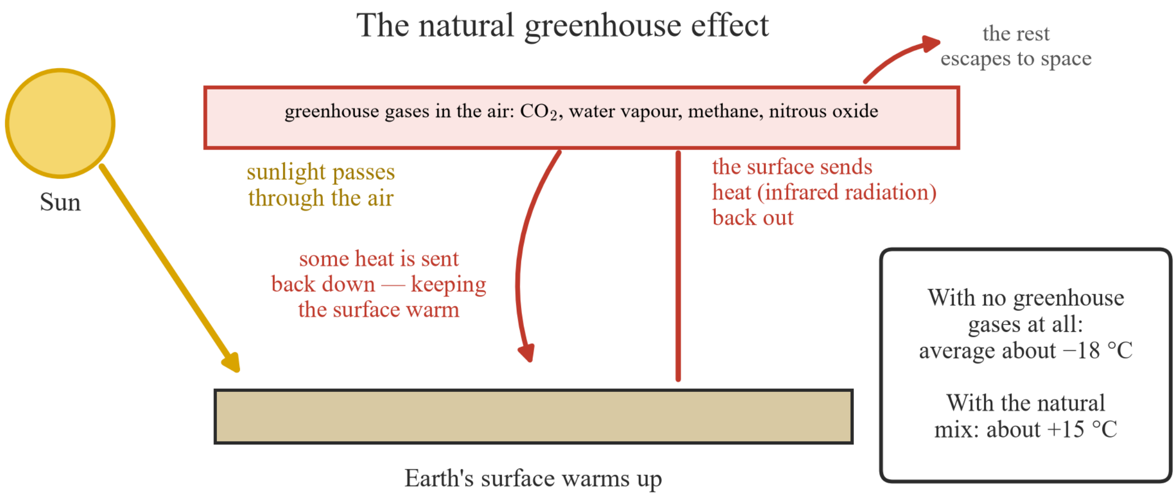
A chart of carbon dioxide concentration over time, with the time axis not to scale. A shaded band shows the ice-core range of about 172 to about 300 parts per million that held for 800 000 years, with anchor points at the lowest level of the record, 172 parts per million, and at the pre-industrial level near 280 parts per million about 1750. A third anchor at 386 parts per million marks the 2009 global average from the Cape Grim record, which began in April 1976, and an arrow shows the concentration still climbing every year.

For the last 800 000 years the concentration moved within a band of about 172 to 300 ppm, sitting near 280 ppm before 1750. Then, from about 1750 — when people began burning coal, oil and gas in large amounts — the line climbs steeply. By 2009 the global average had reached 386 ppm, and measurements taken in clean ocean air at Cape Grim in north-west Tasmania, running continuously since April 1976, show it still climbing. This record is real data:

D. Lüthi and others, Nature, vol. 453, pp. 379–382, 2008. B. Bereiter and others, Geophysical Research Letters, vol. 42, pp. 542–549, 2015. CSIRO and Bureau of Meteorology, "Cape Grim Baseline Air Pollution Station", 2026. csiro.au — retrieved 2026-08-21.

The rise tracks the combustion of fossil fuels. Carbon that weathering and burial spent deep time locking away is being returned to the atmosphere faster than the natural sinks can take it back in. That is how a process changes the composition of a system over time — and why the band of the last 800 000 years has broken open.

The natural greenhouse effect (elaboration `VC2S10U10.E03`). Carbon dioxide does more than move through the cycle — it shapes the temperature of the planet. Sunlight passes through the air and warms the surface. The warm surface sends energy back out as **infrared radiation** — energy that travels like light does but is felt as heat. Greenhouse gases in the atmosphere — carbon dioxide, water vapour and methane are the main ones — let most of the sunlight through, but they absorb some of the outgoing infrared radiation and send part of it back down. The result: the surface is kept warmer than it would otherwise be, the way the glass of a greenhouse keeps its inside warm.



This natural effect keeps Earth warm enough for life as we know it. How extra greenhouse gases change the balance is taken up in Subtopic 12C.

A diagram of the natural greenhouse effect. Sunlight passes through the air and warms the surface. The surface sends heat — infrared radiation — back out, but greenhouse gases in the air, including carbon dioxide, absorb some of it and send part of it back down, keeping the surface warm. A box compares the average surface temperature with no greenhouse gases at all, about −18 degrees Celsius, with the natural mix of greenhouse gases, about +15 degrees Celsius.

How big is the effect? With no greenhouse gases at all, Earth's average surface temperature would be about −18 °C. With the natural mix of greenhouse gases, the average is about +15 °C. Carbon dioxide is one of the gases that keeps those temperatures warm enough to support life as we know it: the natural greenhouse effect is not a problem to fix — it is the reason the planet is liveable. The temperatures come from an energy balance worked out by climate scientists:

J. T. Kiehl and K. E. Trenberth, Bulletin of the American Meteorological Society, vol. 78, pp. 197–208, 1997.

How adding extra greenhouse gases shifts this balance — and how climate is modelled — is taken up in Subtopic 12C, and the ways people can reduce emissions are taken up in Subtopic 12D. This subtopic stops at the natural effect.

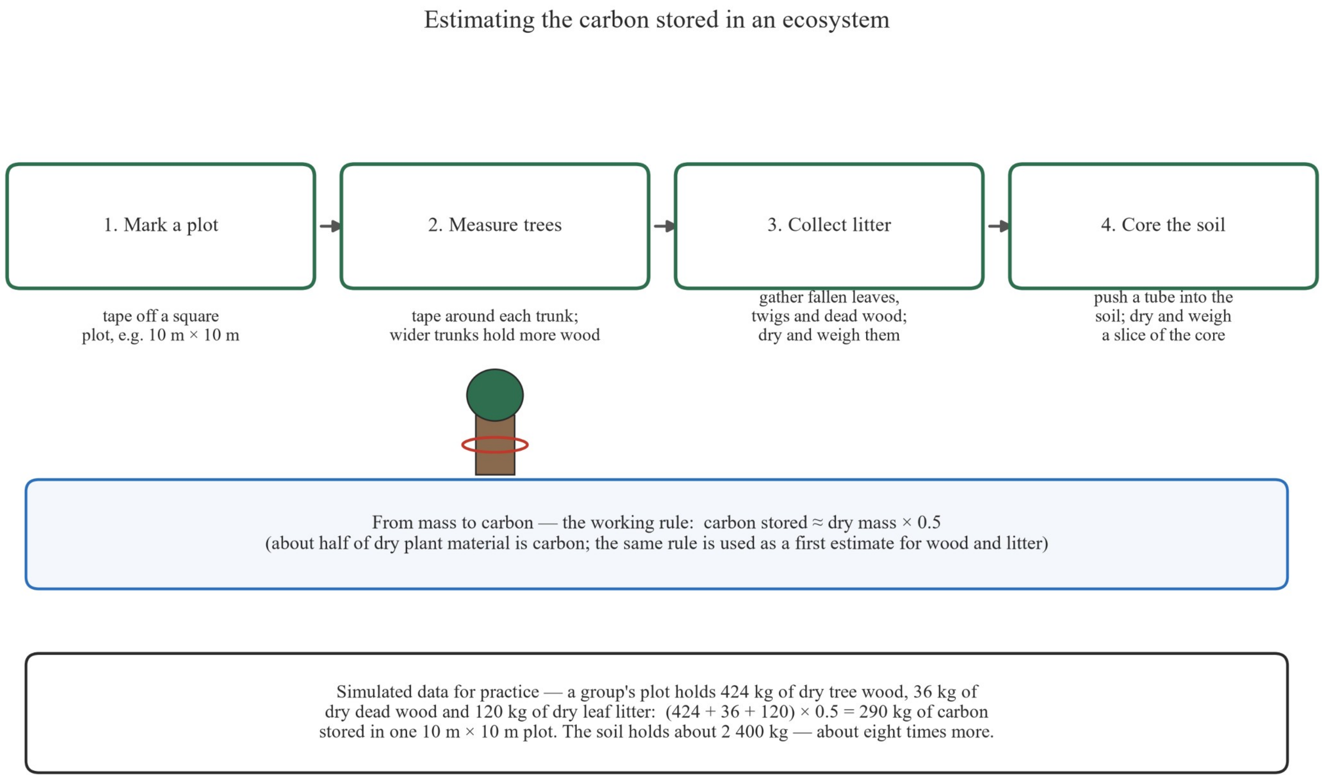
Measuring the carbon in an ecosystem (elaboration `VC2S10U10.E06`). If a forest stores carbon, how much does it store? You can estimate it with a field investigation. The carbon in an ecosystem is spread across several stores: the biomass of living trees, dead wood, leaf litter and the soil. A field survey samples each store:

- wrap a tape around each trunk — wider trunks hold more wood — and use the measurements to estimate the trees' dry biomass;
- collect samples of dead wood and leaf litter inside a **quadrat** — a square frame that marks off a fixed area — dry them, and weigh them;
- push a tube into the soil at several points to take a core, and note the soil depth, because deeper soils hold more carbon; dry and weigh a slice of the core.

Then the calculation is a simple ratio: about half of dry biomass is carbon, so the carbon in a store is about its dry mass multiplied by 0.5. Add the stores together and you have the ecosystem's approximate carbon storage. The half-as-carbon rule comes from measurements of real forests:

IPCC, "2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Other Land Use", https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html, retrieved 2026-08-21.

Notice the mathematics: multiplying by 0.5 is direct proportion, and scaling one small quadrat up to a whole site is ratio and scale. That is `VC2M9M05` — taught in Subtopic 4B and re-used here.

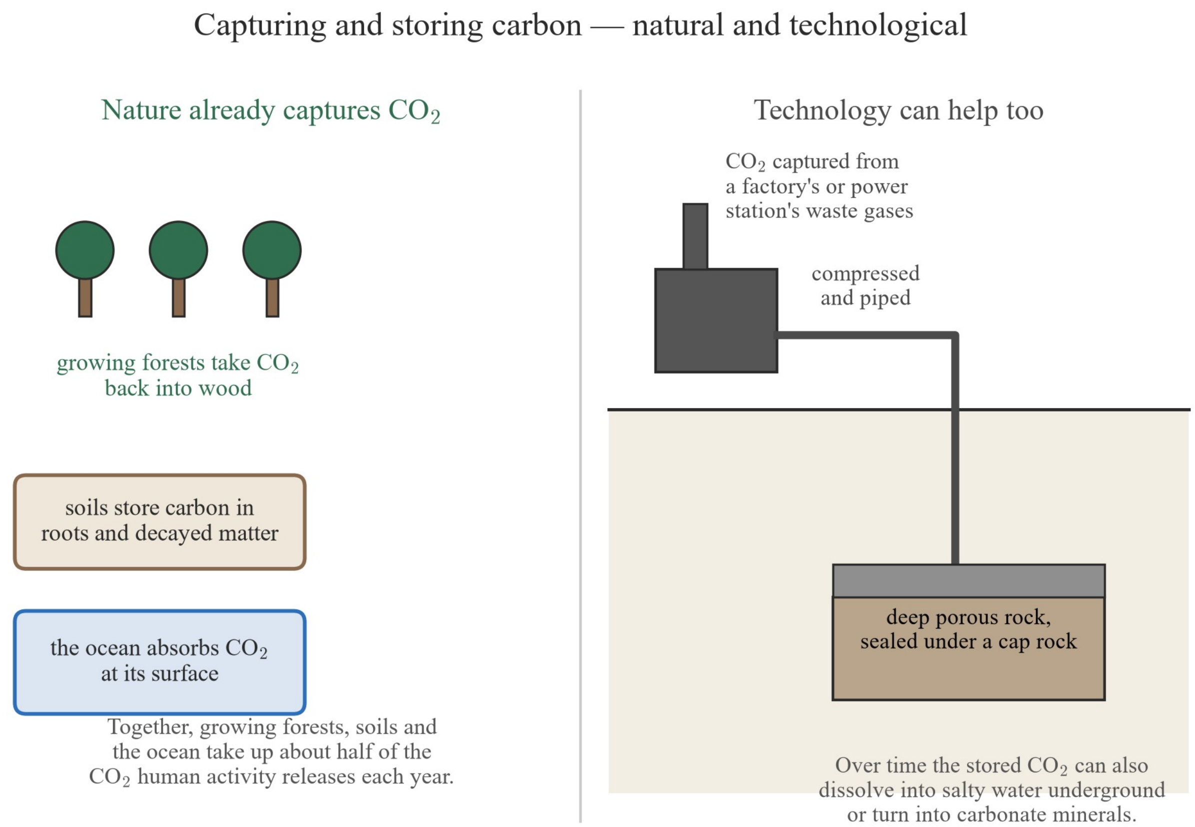


Steps of a field investigation of carbon storage, in four boxes joined by arrows. Mark a plot by taping off a square area such as 10 m × 10 m; measure the trees by wrapping a tape around each trunk, because wider trunks hold more wood; collect litter by gathering fallen leaves, twigs and dead wood, then drying and weighing them; core the soil by pushing a tube in, then drying and weighing a slice of the core. A rule box says the carbon stored is about the dry mass multiplied by 0.5, and a worked box applies the rule to simulated plot data: 424 kg of dry tree wood, 36 kg of dry dead wood and 120 kg of dry leaf litter give (424 + 36 + 120) × 0.5 = 290 kg of carbon in one plot, with the soil holding about eight times more.

Capturing and storing carbon (elaboration `VC2S10U10.E07`). Some processes — and some technologies — take carbon dioxide out of circulation and put it somewhere it stays. Natural capture happens all the time: forests take in carbon dioxide by photosynthesis, the ocean absorbs it, shells form limestone, and carbon is buried in sediment. The natural sinks are doing a large job right now: the land and the ocean together absorb about half of the carbon dioxide that human activities add to the atmosphere each year. The rest stays in the air, and that is why the concentration keeps rising.

P. Friedlingstein and others, Earth System Science Data, vol. 15, pp. 1675–1780, 2023.

Technologies can do the same job on purpose. **Carbon capture and storage** takes carbon dioxide from the waste gases of a factory or a power station before it reaches the atmosphere, compresses it, and pumps it deep underground into rock layers where it is trapped. The stored carbon is back in a one-way account — the same account the coal sat in before it was burned.



Ways carbon dioxide is captured and stored, natural and technological. On the left, nature already captures carbon dioxide: growing forests take it back into wood, soils store carbon in roots and decayed matter, and the ocean absorbs it at its surface — together taking up about half of the carbon dioxide human activity releases each year. On the right, technology captures carbon dioxide from a factory's or power station's waste gases, compresses it and pipes it into deep porous rock sealed under a cap rock; over time the stored carbon dioxide can dissolve into salty water underground or turn into carbonate minerals.

Where this leads: Subtopic 12C takes up how the extra greenhouse gases added by human activities shift Earth's energy balance, and how climate is modelled; Subtopic 12D takes up how emissions can be reduced across power generation, manufacturing, transport and food production. The chemistry of combustion itself — word and symbol equations — was taught in Chapter 11, and the energy change of combustion belongs to Subtopic 11D. Mole-ratio calculations for combustion are VCE-only and are not taught here (TOC D9); this subtopic works only with the fixed mass ratio, 44 units of carbon dioxide for every 12 units of carbon.

Activities

Activity 1 — Limestone is a carbon store (supports elaboration `VC2S10U10.E07`). Put a few small chips of limestone in a test tube, add dilute hydrochloric acid, and fit a delivery tube so any gas bubbles through a second test tube of limewater. Record what you see at each stage — the fizzing, then the change in the limewater — and state what the test proves about the carbon stored in the rock. Then explain in one sentence how that store connects to weathering and to the long-term balance of this subtopic. Wear eye protection; dilute hydrochloric acid is an irritant, and the teacher should prepare and dispense all solutions following Science ASSIST (ASTA) safety guidance.

Activity 2 — A field survey of carbon stores (elaboration `VC2S10U10.E06`). In the schoolyard or a nearby park, survey three stores. Wrap a tape around the trunks of five trees and record each girth — the distance around the trunk; the teacher provides a table that turns girth into an estimate of dry biomass. Inside a 1 m × 1 m quadrat, collect the dead wood and leaf litter, dry the samples, and weigh them. Push a thin rod into the ground at five points to measure soil depth. Use carbon ≈ 0.5 × dry mass to estimate the carbon in each store, then say which store holds the most at your site and which store you think would win at a different site, such as a forest. Wash your hands after handling soil and litter, leave living things and their homes undisturbed, and follow the teacher's risk assessment for outdoor work (planning safe fieldwork is covered in Subtopic 3B).

Activity 3 — What combustion gives off (supports elaboration `VC2S10U10.E03`). Hold a cold, dry beaker upside down above a candle flame for a few seconds and note what forms on the inside. Then rinse a second beaker with limewater, hold it above a fresh flame, and note the change. State the two products of combustion the tests show, write the word equation for the burning candle, and say where each product goes in the carbon cycle. Tie hair back and keep loose clothing clear of the flame; the teacher supervises all flames, following Science ASSIST (ASTA) guidance.

Activity 4 — A greenhouse model (elaboration `VC2S10U10.E03`). Stand two identical jars under a lamp, each holding a thermometer. In one jar, make extra carbon dioxide by adding a spoon of sodium hydrogen carbonate to a little vinegar; leave the other jar as the control (what a control is for — Subtopic 3A). Record both temperatures every minute for ten minutes while the lamp shines, then compare the two temperature changes and explain them using the greenhouse effect. Finish by naming two limits of the model — places where a jar of air is not like the real atmosphere (one place to start: a jar traps warm air from moving away, which the real atmosphere does not do in the same way). The lamp and the glass get hot; do not touch them while they are on or just after they are switched off.

Worked examples

Example 1 — scaffolded

A group surveys carbon storage in a 10 m × 10 m plot of bushland. The table is **simulated data for practice**.

Store	Estimated dry mass (kg)
Living trees	424
Dead wood	36
Leaf litter	120

(a) Calculate the mass of carbon stored in the living trees.
(b) Calculate the mass of carbon stored in the dead wood and in the leaf litter.
(c) Calculate the total carbon stored in these three stores.
(d) The soil of the plot is estimated to hold 2 400 kg of carbon. Compare the soil store with the three stores combined, and say what the comparison shows.

Working	Comment
(a) carbon ≈ 0.5 × dry mass = 0.5 × 424	About half of dry biomass is carbon.
= **212 kg**	Units are kilograms of carbon.
(b) dead wood: 0.5 × 36 = **18 kg**; leaf litter: 0.5 × 120 = **60 kg**	The same rule applies to each store.
(c) total = 212 + 18 + 60 = **290 kg**	Add the stores to get the plot's approximate carbon storage.

(d) 2 400 ÷ 290 ≈ 8.3, so the soil holds about **eight times** as much carbon as the trees, dead wood and leaf litter combined. Most of the carbon at this site is not in the wood you can see — it is in the soil, a store that is easy to overlook.

Example 2 — scaffolded

A fallen log of dry mass 84 kg burns completely in a bushfire. (a) Calculate the mass of carbon in the log. (b) Calculate the mass of carbon dioxide released, using the mass ratio 44 : 12. (c) State where the carbon goes, naming the two systems whose composition changes. (d) The tree took about 60 years to grow that wood. Compare the time the carbon was stored with the time the fire takes to release it.

Working	Comment
(a) carbon ≈ 0.5 × dry mass = 0.5 × 84	About half of dry biomass is carbon.
= **42 kg**	Kilograms of carbon.
(b) carbon dioxide = 42 × 44 ÷ 12	For every 12 units of carbon burned, 44 units of carbon dioxide form.

Working	Comment
= **154 kg**	The extra mass is oxygen drawn from the air.

(c) The carbon leaves the **biosphere** (the wood) and enters the **atmosphere** as carbon dioxide. The biosphere loses carbon and the atmosphere gains carbon dioxide, so the composition of both systems changes. In a real fire a little carbon stays behind as charcoal and ash; this estimate assumes complete combustion.

(d) Stored for about 60 years, released in minutes. Fire is a fast return: the same carbon that a tree built up over decades moves back into the air almost at once.

Example 3 — unscaffolded

The carbon in a coal seam was buried about 300 000 000 years ago. People have been burning coal at a large scale for about 250 years, since the mid-1700s. (a) How many times longer did the burying take than the releasing has taken so far? (b) State what that comparison means in one sentence. (c) Burning 3.0 kg of carbon releases how much carbon dioxide? (d) Explain why releasing deep-time carbon changes the atmosphere's composition, even though the amount burned is small next to all the carbon on Earth.

(a) 300 000 000 ÷ 250 = **1 200 000**. Burying the carbon took about one million two hundred thousand times longer than the time taken to release it so far.

(b) Carbon that took deep time to lock away is being released within a few human lifetimes — storage was extremely slow, release is extremely fast.

(c) 3.0 × 44 ÷ 12 = **11 kg** of carbon dioxide.

(d) Composition depends on what flows into and out of the atmosphere. The burned carbon had been locked in the lithosphere, out of the cycle, so burning it is a new source the atmosphere had not been receiving. The natural sinks — weathering and burial — are far too slow to take it back in on human timescales, so the extra carbon dioxide stays in the air and the concentration rises.

Example 4 — unscaffolded

The table is **simulated data for practice**. It shows the slow natural flows of carbon into and out of the atmosphere in one year.

Process	Carbon moved (million tonnes per year)
Vulcanism — adds carbon dioxide	150
Weathering — removes carbon dioxide	144

(a) Find the net change per year, and say whether the atmospheric carbon dioxide level is rising or falling.

(b) At that rate, how many years would it take to add an extra 300 million tonnes?

(c) Suppose weathering speeds up slightly, to 152 million tonnes per year. Find the new net change and say what happens to the level.

(d) Human activities add about 10 000 million tonnes of carbon per year through fossil-fuel combustion. How many times larger is that than the volcanic source? State what the comparison shows.

(e) 150 − 144 = **6 million tonnes per year** added. The source is bigger than the sink, so the level rises — slowly.

(f) 300 ÷ 6 = **50 years**. That is how gently the natural balance moves.

(g) 150 − 152 = **−2 million tonnes per year**. Now the sink is bigger than the source, so the level slowly falls. A small change in either flow flips the direction of change — which is what a balance does.

(h) 10 000 ÷ 150 ≈ **67**. Human combustion adds about 67 times as much carbon each year as all the world's volcanoes. That is why the recent rise in carbon dioxide is far outside the band the natural balance kept for 800 000 years.

Practice questions

Scaffolded questions

Question 1 The fire triangle. (a) Name the three things that must be present together for a fire to burn. (b) For each way of fighting a fire — pouring water, smothering with a fire blanket, clearing a firebreak — state which one of the three it removes. (c) Complete the word equation for combustion: fuel + oxygen → …

Question 2 Combustion, particle by particle. Methane burns in oxygen. (a) Name the two reactants and state how many molecules of oxygen react with one molecule of methane. (b) Name the two products. (c) State what happens to the atoms during the reaction. (d) Classify the reaction as exothermic or endothermic, and say what that classification means about energy.

Question 3 Weathering. (a) Complete the word equation: calcium carbonate + carbon dioxide + water → … (b) State whether weathering is a source or a sink for atmospheric carbon dioxide. (c) Name the system the carbon leaves at the start of the pathway and the system it ends up locked in. (d) State roughly how long weathering works over.

Question 4 The greenhouse effect, in order. (a) Put these four sentences in the correct order: A. Greenhouse gases absorb some of that outgoing radiation and send part of it back down. B. Sunlight passes through the air and warms the surface. C. The surface is kept warmer than it would otherwise be. D. The warm surface sends energy back out as infrared radiation. (b) State the average surface temperature with no greenhouse gases at all, and with the natural mix. (c) Name the three main greenhouse gases named in this subtopic.

Question 5 Carbon from dry mass. Use carbon ≈ 0.5 × dry mass. (a) A sample of dead wood has a dry mass of 260 kg. Calculate the mass of carbon it stores. (b) From the stores in Example 1 — living trees 212 kg of carbon, dead wood 18 kg, leaf litter 60 kg, soil 2 400 kg — state which store holds the most carbon. (c) Calculate the total carbon held in the trees, dead wood and leaf litter together.

Question 6 Reading the record. Use the figure of carbon dioxide through time. (a) State the band within which the concentration moved for the last 800 000 years. (b) State the concentration before about 1750. (c) State the global average concentration by 2009. (d) Name the measurements the graph comes from, and state where carbon dioxide has been measured continuously since April 1976.

Unscaffolded questions

Question 7 Deep-time fuel. Five steps from the air to the air again: 1. coal is dug up and burned 2. carbon dioxide returns to the atmosphere 3. plants take in carbon dioxide by photosynthesis 4. heat and pressure turn the buried remains into coal over about 300 000 000 years 5. the remains are buried under layers of sediment

(a) Write the steps in their correct order.
(b) State which step took by far the longest.
(c) Identify the two steps that changed the speed of the carbon cycle, and explain why.

Question 8 Car numbers. A car burns fuel containing 12 kg of carbon in one month. (a) Calculate the mass of carbon dioxide released in that month, using the mass ratio 44 : 12. (b) At that rate, calculate the mass of carbon dioxide released in one year. (c) The carbon dioxide released is heavier than the carbon burned. Explain where the extra mass comes from.

Question 9 Two accounts. (a) Explain why a mature forest keeps the atmosphere's composition roughly steady. (b) Explain why burning coal does not. (c) A forest burns in a bushfire, then regrows over the next 50 years. Explain why this is closer to the loop account than to the one-way account.

Question 10 Evaluating a claim about weathering. A student writes: "Weathering is so slow that it cannot possibly affect the carbon dioxide in the atmosphere." Evaluate the claim, using what weathering does and what it has done over Earth's long history.

Question 11 Vulcanism. (a) Name the store carbon leaves and the store it enters when a volcano releases carbon dioxide. (b) Describe two ways carbon dioxide reaches the atmosphere from volcanic regions. (c) State whether vulcanism is a source or a sink, and compare its speed with fossil-fuel combustion.

Question 12 The broken band. (a) For how long did the carbon dioxide concentration stay within about 172 to 300 ppm? (b) State what changed from about 1750. (c) Explain why the concentration is now rising, using the ideas of sources, sinks and timescale.

Question 13 Evaluating a claim about the greenhouse effect. A student writes: “Carbon dioxide causes the greenhouse effect, and the greenhouse effect is bad for life on Earth.” Evaluate the claim, using what you know about the natural greenhouse effect.

Question 14 Designing a field survey. Design a field investigation to compare carbon storage in a grassy paddock and a nearby forest. Include the stores you would measure, what you would measure for each store, how you would turn the measurements into carbon, and one thing you would do to make the results trustworthy (planning valid investigations — Subtopic 3A).

Question 15 Capture and storage. (a) Name two natural processes that capture carbon dioxide from the atmosphere. (b) Describe how carbon capture and storage works at a power station. (c) State where the captured carbon is put and why it stays there. (d) The land and the ocean together absorb about half of the carbon dioxide human activities add each year. State where the rest goes, and what that does to the concentration.

Question 16 The whole cycle. Copy and complete the table for the four processes of this subtopic.

Process	Carbon moves from … to …	Speed	Adds carbon dioxide to, or removes it from, the atmosphere
fire			
weathering			
vulcanism			
fossil-fuel combustion			

Answers

Question 1 (a) fuel, oxygen and heat; (b) water removes heat, a fire blanket removes oxygen, a firebreak removes fuel; (c) fuel + oxygen → carbon dioxide + water. **Question 2** (a) methane and oxygen; two molecules of oxygen; (b) carbon dioxide and water; (c) see solution; (d) exothermic — releases energy. **Question 3** (a) calcium hydrogen carbonate; (b) sink; (c) atmosphere; lithosphere; (d) see solution. **Question 4** (a) B, D, A, C; (b) about −18 °C; about +15 °C; (c) carbon dioxide, water vapour and methane. **Question 5** (a) 130 kg; (b) soil; (c) 290 kg. **Question 6** (a) about 172 to 300 ppm; (b) about 280 ppm; (c) 386 ppm; (d) ice-core measurements; Cape Grim, north-west Tasmania. **Question 7** (a) 3, 5, 4, 1, 2; (b) step 4; (c) see solution. **Question 8** (a) 44 kg; (b) 528 kg; (c) see solution. **Question 9** (a)–(c) see solution (loop versus one-way account). **Question 10** see solution (slow does not mean unimportant). **Question 11** (a) lithosphere; atmosphere; (b) see solution; (c) source; see solution. **Question 12** (a) about 800 000 years; (b) see solution; (c) see solution. **Question 13** see solution (the natural effect supports life; the extra gas is the issue). **Question 14** see solution. **Question 15** (a) any two of photosynthesis by forests, absorption by the ocean, shell and limestone formation, burial in sediment; (b)–(d) see solution. **Question 16** see solution.

Fully-worked solutions

Question 1 (a) **Fuel, oxygen and heat** — all three, together. (b) **Water removes heat** (it cools the fuel below the temperature at which it burns); **a fire blanket removes oxygen** (it keeps the air away); **a firebreak removes fuel** (it leaves the fire nothing to burn). (c) fuel + oxygen → **carbon dioxide + water** (energy is released).

Question 2 (a) The reactants are **methane** and **oxygen**; **two** molecules of oxygen react with one molecule of methane. (b) **Carbon dioxide** and **water**. (c) The atoms are **rearranged**: the carbon and hydrogen atoms of the methane and the oxygen atoms of the oxygen molecules rejoin in new combinations to form carbon dioxide and water molecules. No atoms are made or destroyed. (d) **Exothermic** — the reaction releases energy from the reacting chemicals into the surroundings, which is why a flame gives out heat and light.

Question 3 (a) calcium carbonate + carbon dioxide + water → **calcium hydrogen carbonate**. (b) A **sink** — it removes carbon dioxide from the atmosphere. (c) The carbon leaves the **atmosphere** (dissolved in rainwater) and ends up locked in the **lithosphere**, as limestone. (d) Weathering works over **tens of thousands to hundreds of thousands of years**.

Question 4 (a) **B, D, A, C**: sunlight warms the surface; the surface sends energy out as infrared radiation; greenhouse gases absorb some of it and send part back down; the surface is kept warmer than it would otherwise be. (b) With no greenhouse gases at all: about **−18 °C**. With the natural mix: about **+15 °C**. (c) **Carbon dioxide, water vapour and methane**.

Question 5 (a) 0.5 × 260 = **130 kg** of carbon. (b) The **soil**, with 2 400 kg of carbon — about eight times the other three stores combined (212 + 18 + 60 = 290 kg). (c) **290 kg**.

Question 6 (a) About **172 to 300 ppm**. (b) About **280 ppm**. (c) **386 ppm**. (d) The graph comes from **ice-core** measurements — ancient air trapped in Antarctic ice — combined with direct measurements of the atmosphere. Clean-air measurements have been made continuously at **Cape Grim** in north-west Tasmania since April 1976.

Question 7 (a) **3, 5, 4, 1, 2**: plants take in carbon dioxide by photosynthesis; the remains are buried under layers of sediment; heat and pressure turn the buried remains into coal over about 300 000 000 years; coal is dug up and burned; carbon dioxide returns to the atmosphere. (b) **Step 4** — the 300 000 000 years of heat and pressure. (c) The **burying** (steps 5 and 4) and the **burning** (steps 1 and 2). Burial moved carbon out of the cycle extremely slowly; burning moves the same carbon back into the cycle in minutes. The carbon is the same — the speed is what changed.

Question 8 (a) 12 × 44 ÷ 12 = **44 kg** of carbon dioxide. (b) 44 × 12 = **528 kg** of carbon dioxide in a year. (c) Each carbon atom pairs with **two oxygen atoms taken from the air** during combustion. The carbon dioxide molecule is heavier than the carbon atom because it carries that extra oxygen with it — for every 12 units of carbon burned, 44 units of carbon dioxide form.

Question 9 (a) A mature forest takes in carbon dioxide by photosynthesis and returns about the same amount by respiration and the slow breakdown of dead material. The carbon moves in a loop, so the forest adds little to the atmosphere and removes little from it: the composition stays roughly steady. (b) Coal is carbon that was locked in the lithosphere, out of the cycle. Burning it adds carbon dioxide that the atmosphere was not receiving, and nothing in the fast loop takes that carbon back — so the composition rises. (c) The fire releases the carbon fast, but the regrowing forest takes it back in by photosynthesis over the next 50 years. The carbon has gone round the loop — out of the trees, into the air, back into the trees — rather than being added from a store outside the cycle. That is the loop account. (A fossil fuel, once burned, is not regrown.)

Question 10 The claim is wrong. Speed and importance are not the same thing. Weathering is a sink: it removes carbon dioxide from the atmosphere and locks it away as carbonate rock. Over Earth's long history, weathering working against vulcanism is what kept the atmosphere's carbon dioxide within a narrow band — a balance that held for hundreds of thousands of years. A slow process running for a very long time has a very large total effect. The student is right that weathering is slow, and wrong to conclude that it cannot affect the atmosphere; it has shaped the atmosphere's composition more than almost anything else over deep time.

Question 11 (a) The carbon leaves the **lithosphere** (magma and carbonate rocks deep underground) and enters the **atmosphere**. (b) Any two of: carbon dioxide dissolved in **magma escapes during eruptions** as the magma rises and pressure drops; **carbonate rocks heated at depth** release carbon dioxide; volcanic regions **leak the gas slowly** even between eruptions. (c) Vulcanism is a **source** — it adds carbon dioxide to the atmosphere. It works slowly and steadily over Earth's long history; fossil-fuel combustion releases carbon at a far faster rate — roughly 67 times the volcanic source today.

Question 12 (a) About **800 000 years**. (b) People began **burning coal, oil and gas in large amounts**. The carbon dioxide that had been locked in fossil fuels began returning to the atmosphere. (c) Fossil-fuel combustion is a **source** that adds carbon dioxide much faster than the natural **sinks** — weathering, burial, and absorption by the land and ocean — can take it back in. When a source runs faster than the sinks, the amount in the atmosphere grows: the composition changes over time, and the natural band breaks open.

Question 13 The claim is half right and half wrong, and the wrong half matters. Carbon dioxide is indeed one of the gases that cause the greenhouse effect — that part is correct. But the natural greenhouse effect is not bad for life: with no greenhouse gases at all, Earth's average surface temperature would be about −18 °C; with the natural mix it is about +15 °C. The greenhouse effect is the reason the planet is warm enough to support life as we know it. The concern in Subtopics 12C and 12D is not the natural effect but the **extra** carbon dioxide added by burning fossil fuels, which shifts the balance the natural effect maintains.

Question 14 A sound design covers the stores, the measurements, the calculation and the reliability. For example: choose the same-sized plot in each site (say 10 m × 10 m); wrap a tape around every tree trunk in each plot and use a table that turns each girth into an estimate of the trees' dry biomass; collect all dead wood and leaf litter inside a 1 m × 1 m quadrat in each plot, dry the samples and weigh them; measure soil depth at several points in each plot; then estimate the carbon in each store with carbon ≈ 0.5 × dry mass and add the stores. To make the results trustworthy, repeat the quadrat sampling several times in each site and use the same method and the same-sized plots at both sites, so the comparison is fair (Subtopic 3A). Finally, compare the totals and state which ecosystem stores more carbon and which store holds most of it.

Question 15 (a) Any two of: **photosynthesis by forests** and other green plants; **absorption by the ocean**; **shells forming limestone**; **burial of carbon in sediment**. (b) The carbon dioxide is **captured from the waste gases** of the power station before it reaches the atmosphere, **compressed**, and **pumped deep underground** into rock layers where it is trapped. (c) It is put **deep underground in rock layers**. It stays there because it is locked back into a one-way account — the same kind of account that held the coal before it was burned — with no fast pathway back to the atmosphere. (d) The rest **stays in the atmosphere**, which is why the concentration keeps rising even though the natural sinks are absorbing so much.

Question 16

Process	Carbon moves from … to …	Speed	Adds carbon dioxide to, or removes it from, the atmosphere
fire	biosphere to atmosphere	fast (minutes to hours)	adds it
weathering	atmosphere to hydrosphere, then	very slow (tens of thousands to hundreds of	removes it

Process	Carbon moves from … to …	Speed	Adds carbon dioxide to, or removes it from, the atmosphere
	lithosphere	thousands of years)	
vulcanism	lithosphere to atmosphere	slow and steady	adds it
fossil-fuel combustion	lithosphere to atmosphere	fast (the burning); from deep-time storage	adds it

Climate dynamics: greenhouse gas emissions, energy exchange between Earth's systems, and how climate is modelled

Chapter 12 — Carbon and climate (Science, Levels 9 and 10)

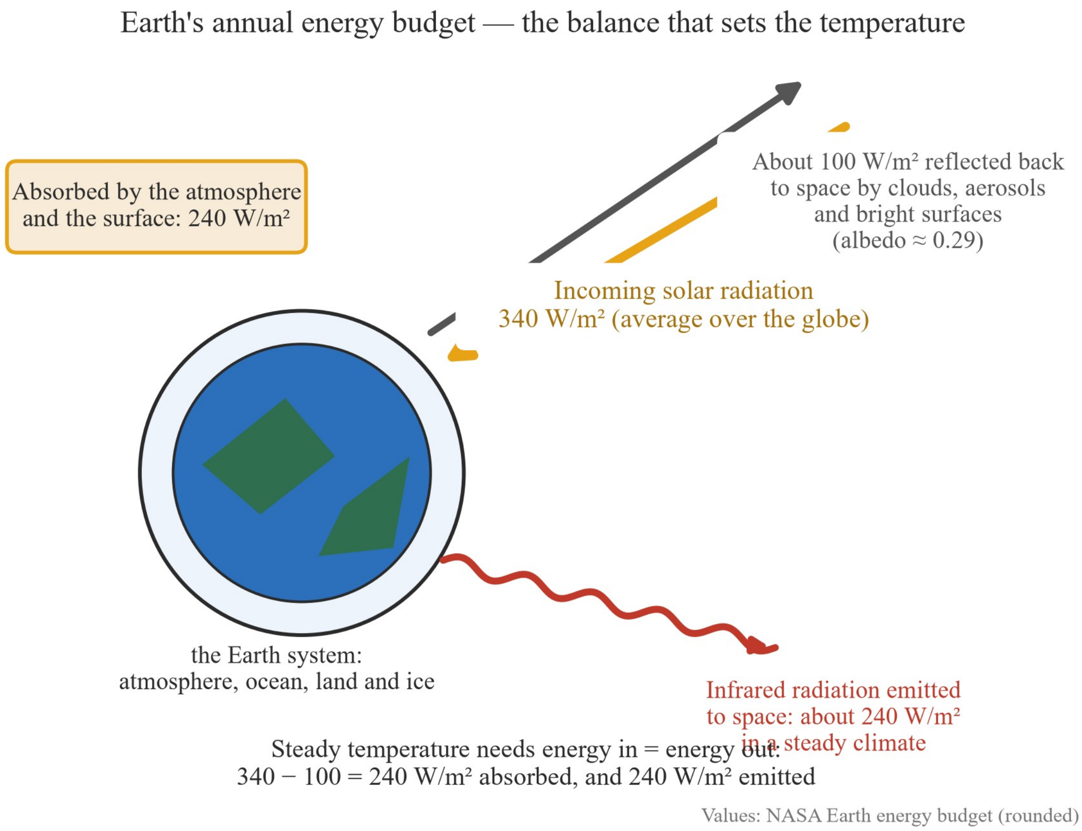
Subtopic 12C · VC2 Science Understanding — Earth and space sciences

CD code: `VC2S10U11` (delivered in split with 12D — 12C owns the climate dynamics limb: greenhouse gas emissions, energy exchanges within and between Earth's systems, and how climate is modelled; 12D owns the mitigation limb: power generation, deforestation, manufacturing, transport, food production and resource consumption) **Content description (word for word):** "the dynamics of global climate change can be modelled and explained by examining the interactions between greenhouse gas emissions and energy exchanges within and between Earth's systems; mitigating human-induced climate change requires addressing various activities including power generation, deforestation, manufacturing, transportation, food production and resource consumption" **Elaboration ids drawn on:** `VC2S10U11.E01` · `VC2S10U11.E02` · `VC2S10U11.E03` · `VC2S10U11.E04` (`VC2S10U11.E05` and `VC2S10U11.E06` — predicting changes, mitigation strategies and carbon footprints — are delivered by subtopic 12D. No elaboration of this CD is withheld under the TOC's D10 ICIP decision.) **Achievement standard (extract served):** "They describe trends in patterns of global climate change and propose strategies to mitigate contributing factors." (12C serves the first half — describing trends in patterns of global climate change; 12D serves the proposing-strategies half — TOC D6.) **Maths interlock (D11):** `VC2M9M05` — rates and percentage change are used here as scientific reasoning (the rate of sea level rise, the percentage rise in CO_2); the formal maths treatment of rates and percentages sits with 12D.

Theory

The climate system: one engine, several parts. Weather is what the atmosphere does over hours to days — a cold front on Tuesday, a heatwave next month. **Climate** is the pattern of weather averaged over a long period, conventionally about 30 years: a single hot day tells you almost nothing about a climate, and a single cold winter does not erase a warming trend. The engine of both weather and climate is radiation from the Sun. Elaboration `VC2S10U11.E01` is the starting point of this subtopic: the interactions of the Sun's radiation with the **atmosphere** (the layer of gases), the **ocean**, and the **land** are the foundation of the global climate system.

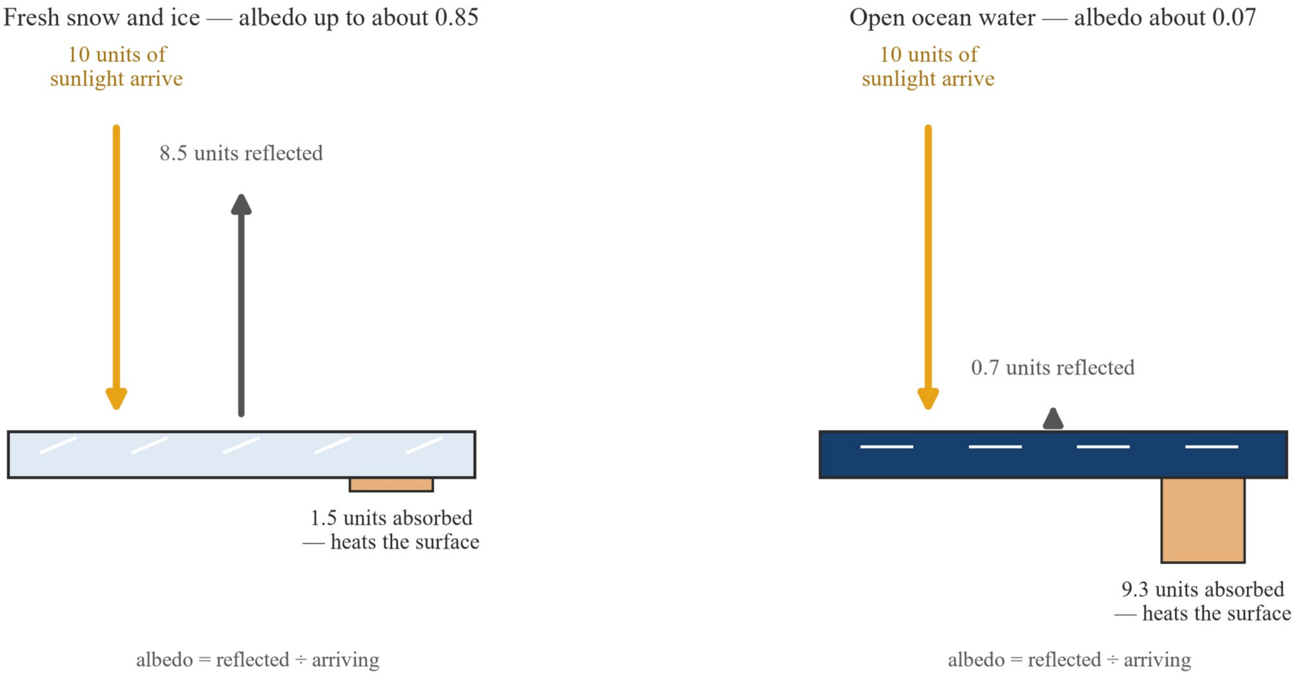
The numbers of that foundation are shown in the energy budget figure. Averaged over the whole planet, about 340 W/m² of solar power arrives at the top of the atmosphere. (The watt, W, is the unit of power; 340 W/m² means 340 watts for every square metre of the Earth's area facing the Sun.) Of the arriving energy, about 100 W/m² is reflected straight back to space by clouds, particles and bright surfaces, and about 240 W/m² is absorbed by the surface and the air. A healthy energy budget balances: the Earth sheds the absorbed 240 W/m² again by emitting **infrared radiation** — the invisible heat radiation that every warm object gives out. When incoming and outgoing energy balance, the global temperature is steady; when they do not, the planet warms or cools.



A vertical energy budget diagram of the Earth: 340 W/m² of sunlight arrives at the top of the atmosphere, about 100 W/m² is reflected back to space by clouds and bright surfaces, and about 240 W/m² is absorbed and then re-emitted as infrared radiation so that the budget balances

How much of the arriving sunlight a surface reflects is its **albedo** — the reflected share of the arriving energy, a number between 0 and 1. Fresh snow and ice are the brightest natural surfaces, with an albedo of up to about 0.85; open ocean water is one of the darkest, at about 0.07.

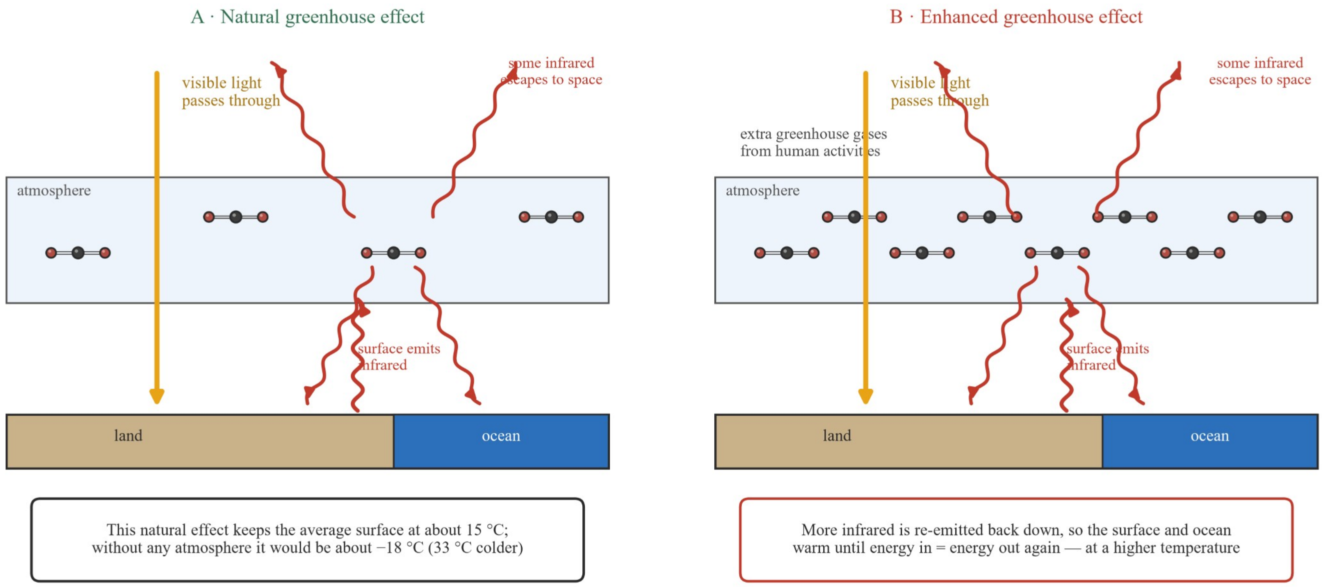
Albedo: why bright ice keeps a region cool and dark water warms it



Two side-by-side panels comparing albedo: fresh snow and ice reflecting 8.5 of 10 arriving units of sunlight (albedo up to about 0.85) and absorbing 1.5, while open ocean water reflects only 0.7 of 10 units (albedo about 0.07) and absorbs 9.3, heating the surface

The same sunlight falling on ice and on water therefore does very different work: the ice reflects most of it away and stays cool, while the water absorbs almost all of it and warms. This is why albedo matters for climate, and why a change in ice cover changes how much energy the Earth absorbs — more on that in the feedback section.

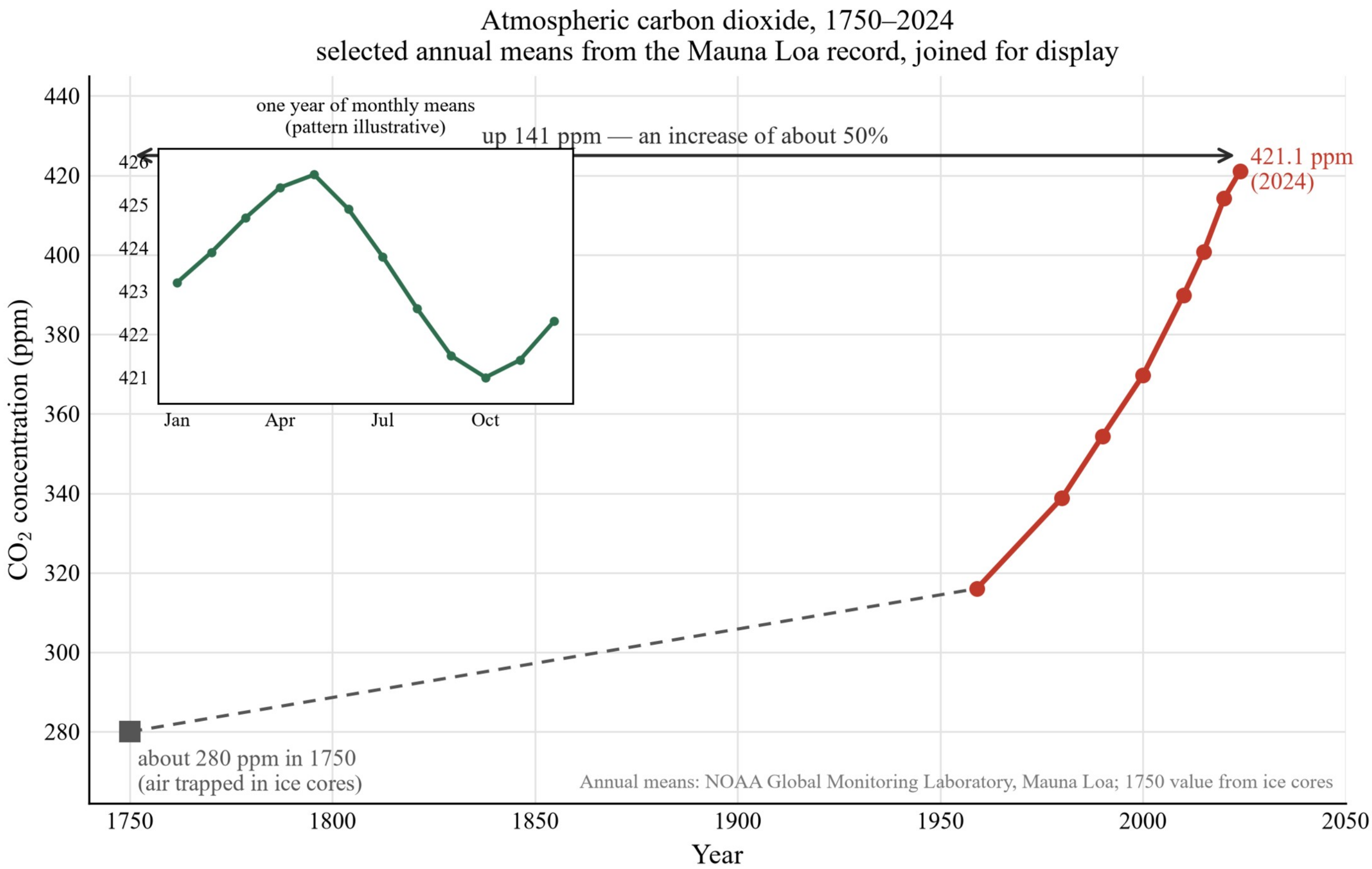
The greenhouse effect — natural and enhanced. The atmosphere is mostly nitrogen and oxygen, but it also contains trace **greenhouse gases**: water vapour, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). These gases behave differently from the rest of the air towards radiation. Incoming visible light from the Sun passes through them almost as if they were not there, and warms the surface. The warmed surface then emits infrared radiation — and greenhouse gases absorb that infrared and re-emit it in all directions, sending a share back down towards the surface. The energy is briefly held in the lower atmosphere instead of escaping straight to space. This is the **greenhouse effect**, and it is natural and life-saving: without it the Earth's average surface temperature would be about −18 °C instead of the roughly 15 °C it actually is — a difference of about 33 °C.



Two side-by-side panels of the greenhouse effect: with the natural amount of greenhouse gas molecules the surface sits at about 15 °C, whereas a planet with no greenhouse gases would be about −18 °C; a second comparison shows that adding extra greenhouse gas molecules (the enhanced greenhouse effect) re-emits more infrared back to the surface and warms it further

The **enhanced greenhouse effect** is the same mechanism with more gas. Burning fossil fuels, clearing forests and farming add CO_2, CH_4 and N_2O to the air on top of the natural amounts, so more of the outgoing infrared is absorbed and re-emitted back to the surface. The outgoing side of the budget no longer quite matches the absorbed side, and the extra energy warms the ocean, the land and the air. It is important to keep the two effects separate in your head: the natural greenhouse effect makes the planet liveable, and the enhanced greenhouse effect is the human addition on top of it that is changing the climate.

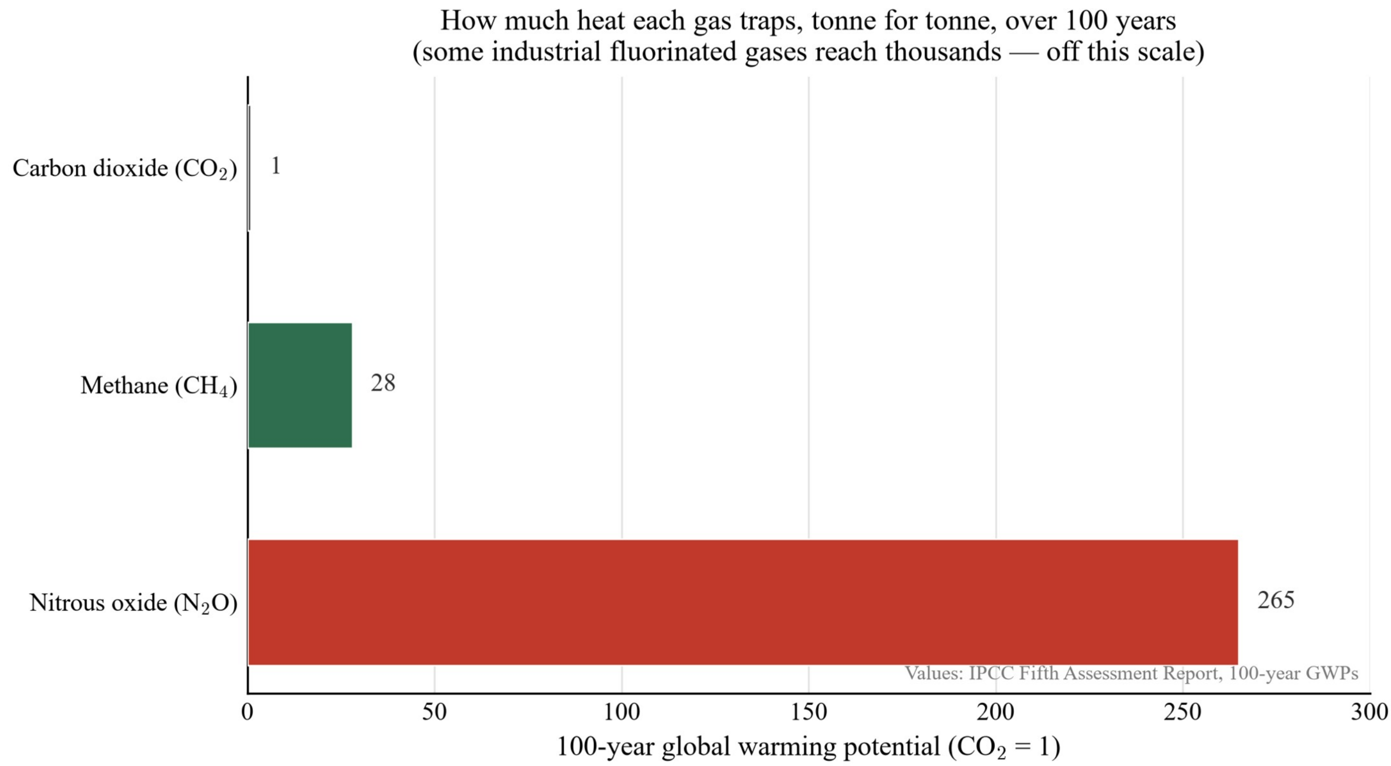
Emissions and concentrations: reading the CO_2 record. Human activity has changed the composition of the atmosphere, and the cleanest record of that change is the concentration of carbon dioxide. Concentrations this small are quoted in **parts per million (ppm)** — one molecule in every million molecules of air. Before about 1750, at the start of large-scale fossil-fuel burning, the air held about 280 ppm of CO_2; that older value is read from air bubbles trapped in polar ice cores. Direct measurement at Mauna Loa in Hawai'i shows the annual mean for 2024 at 421.1 ppm — a rise of 141 ppm, an increase of about 50 %.



Line graph of atmospheric carbon dioxide from 1750 to 2024: an ice-core anchor at about 280 ppm in 1750 joined by a dashed line to the Mauna Loa record of selected annual means, rising slowly at first and then steeply to 421.1 ppm in 2024, with an inset showing one illustrative year of monthly means saw-toothing up and down

Two features of the record matter. The long-term **trend** is sharply upward, and it is the trend that changes the energy budget. On top of it sits a small yearly **cycle** (the inset): each northern summer, forests grow and draw CO_2 out of the air by photosynthesis, and each winter, respiration and decay give some back — the carbon cycle of subtopics 12A and 12B breathing once a year. A cycle of a few ppm does not change the climate; a trend of 141 ppm does.

Not all greenhouse gases are equal. To compare them, scientists use the **global warming potential (GWP)** — how much heat one tonne of a gas traps over 100 years compared with one tonne of CO_2 (GWP = 1 by definition). Over 100 years, methane has a GWP of about 28 and nitrous oxide about 265. Multiplying tonnes of a gas by its GWP gives **carbon dioxide equivalent (CO_2-e)** — the tonnes of CO_2 that would trap the same heat.



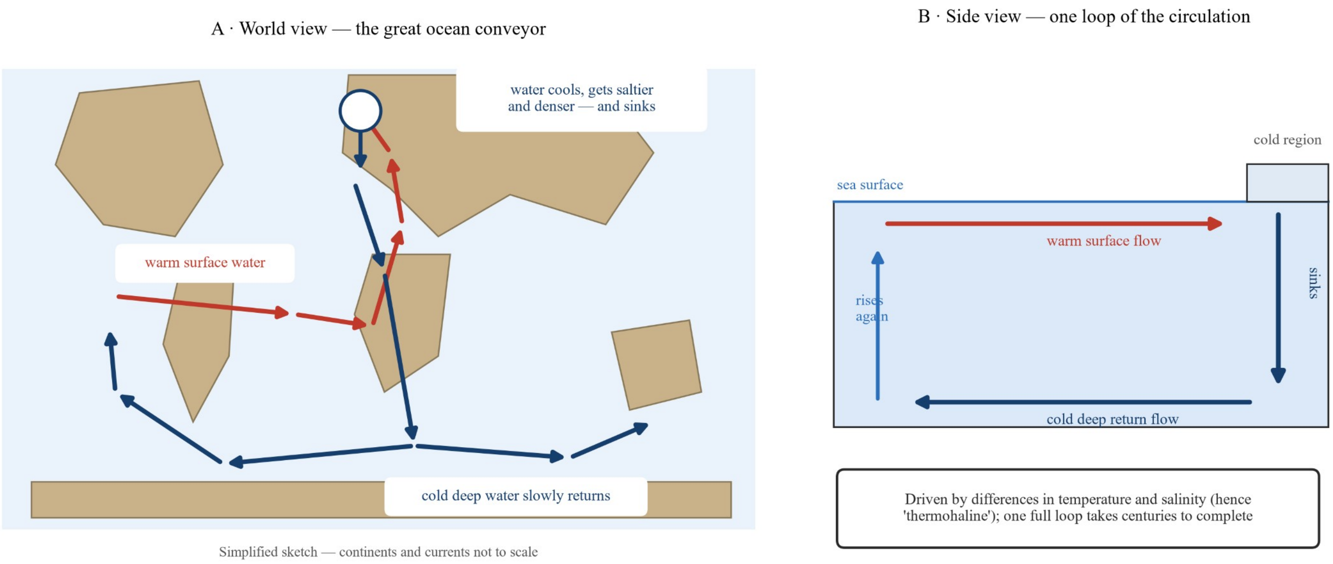
Horizontal bar chart of 100-year global warming potentials with carbon dioxide at 1, methane at 28 and nitrous oxide at 265, noting that some industrial fluorinated gases reach thousands and are off the scale

Source for GWP values: IPCC, "Climate Change 2013: The Physical Science Basis", 2013. https://www.ipcc.ch/report/ar5/wg1/ — retrieved 2026-08-21.

Energy exchange between Earth's systems. The absorbed solar energy does not stay where it lands. The ocean, the atmosphere, the land and the ice exchange energy constantly: winds and ocean currents carry warm air and warm water from the equator towards the poles, evaporation moves heat from the surface into the air, and the ocean gives heat back to the air in winter. This exchange is why the climate of a coastal city is milder than a desert at the same latitude, and it is the "energy exchanges within and between Earth's systems" named in the content description.

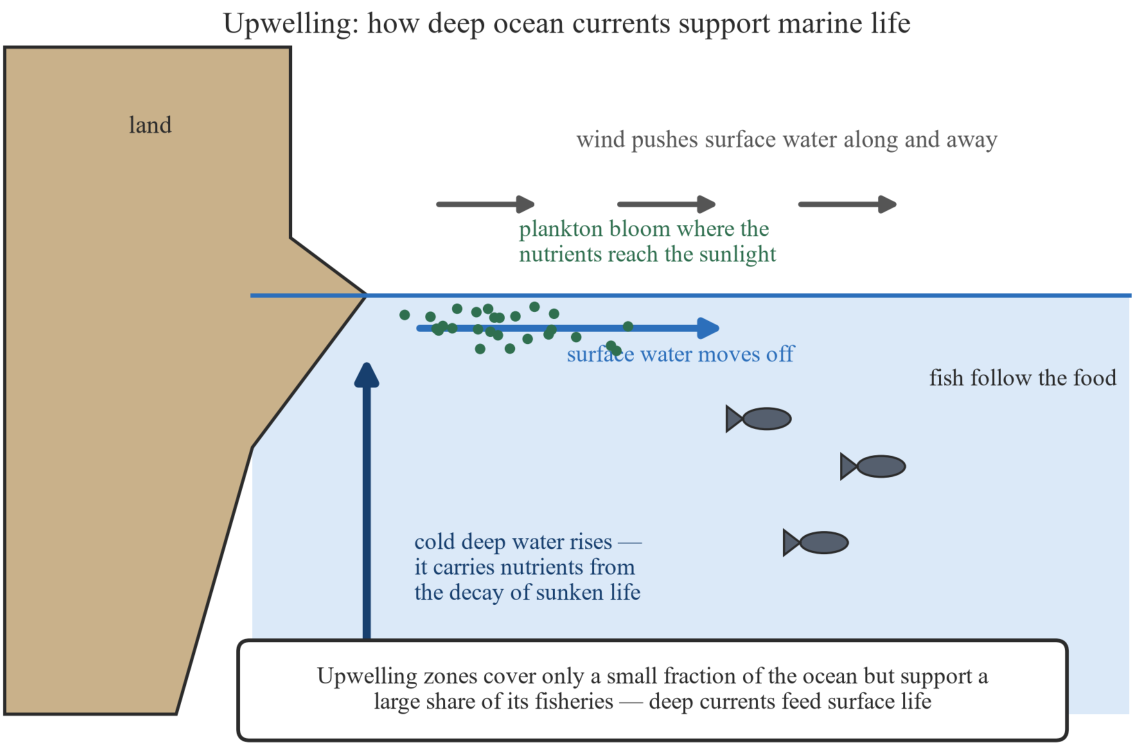
The most important exchange for climate change is the least visible one: the ocean is absorbing more than 90 % of the extra heat trapped by the enhanced greenhouse effect. Water takes a great deal of energy to warm — far more than air or rock for the same mass — so the ocean soaks up the imbalance slowly and steadily. That is good news in one sense (the ocean has slowed the warming of the air) and bad news in another: the stored heat will warm the climate for centuries even if concentrations stabilise, and warm water expands, adding to sea level rise.

Deep ocean currents: the global conveyor and upwelling. Differences in density drive the deep ocean. How salty the water is — its **salinity** — matters as much as its temperature: cold water is denser than warm water, and salty water is denser than fresh water; where surface water becomes cold and salty enough — mainly near the poles — it sinks, and the whole ocean slowly circulates. This density-driven deep circulation is sometimes called the thermohaline circulation (from *thermo*, heat, and *haline*, salt), and it moves water, heat and dissolved gases around the globe over hundreds to a thousand years, regulating the global climate by storing heat and carbon in the deep ocean.



Two panels showing deep ocean circulation: a simplified world map with warm surface currents flowing towards the North Atlantic and cold deep water returning around the globe, and a side view of the Atlantic loop in which warm surface water cools, sinks near the poles and returns at depth

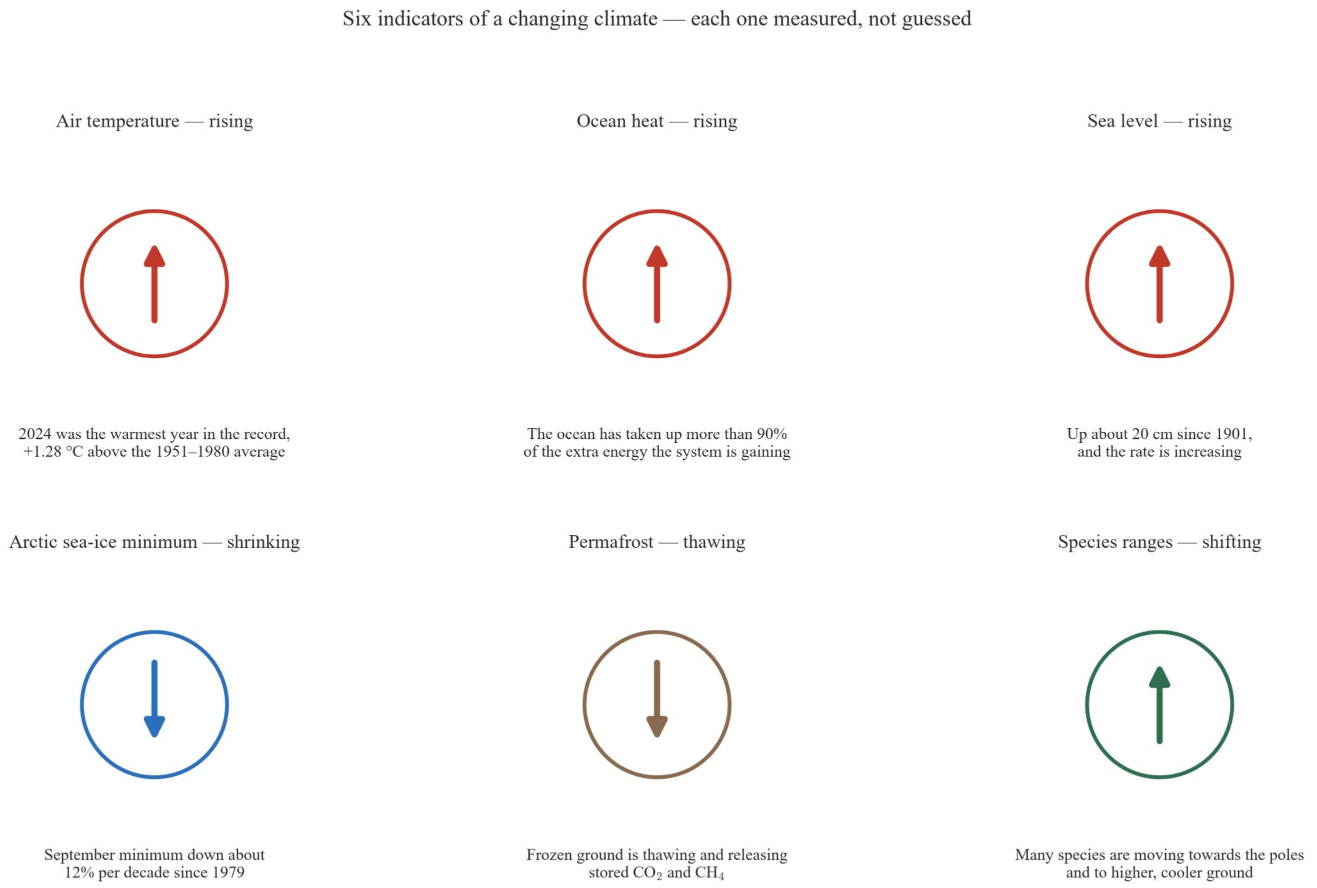
The second connection between deep currents and life is **upwelling**. Where winds push surface water along and away from a coast, deep water rises to replace it. That deep water carries nutrients released by the decay of sunken life; in the sunlight at the surface the nutrients feed plankton, and plankton feed fish. Upwelling zones cover only a small fraction of the ocean but support a large share of its fisheries.



Cross-section of a coastline showing upwelling: wind pushes surface water offshore, cold nutrient-rich deep water rises to replace it, plankton bloom where the nutrients reach sunlight, and fish gather where the plankton is dense

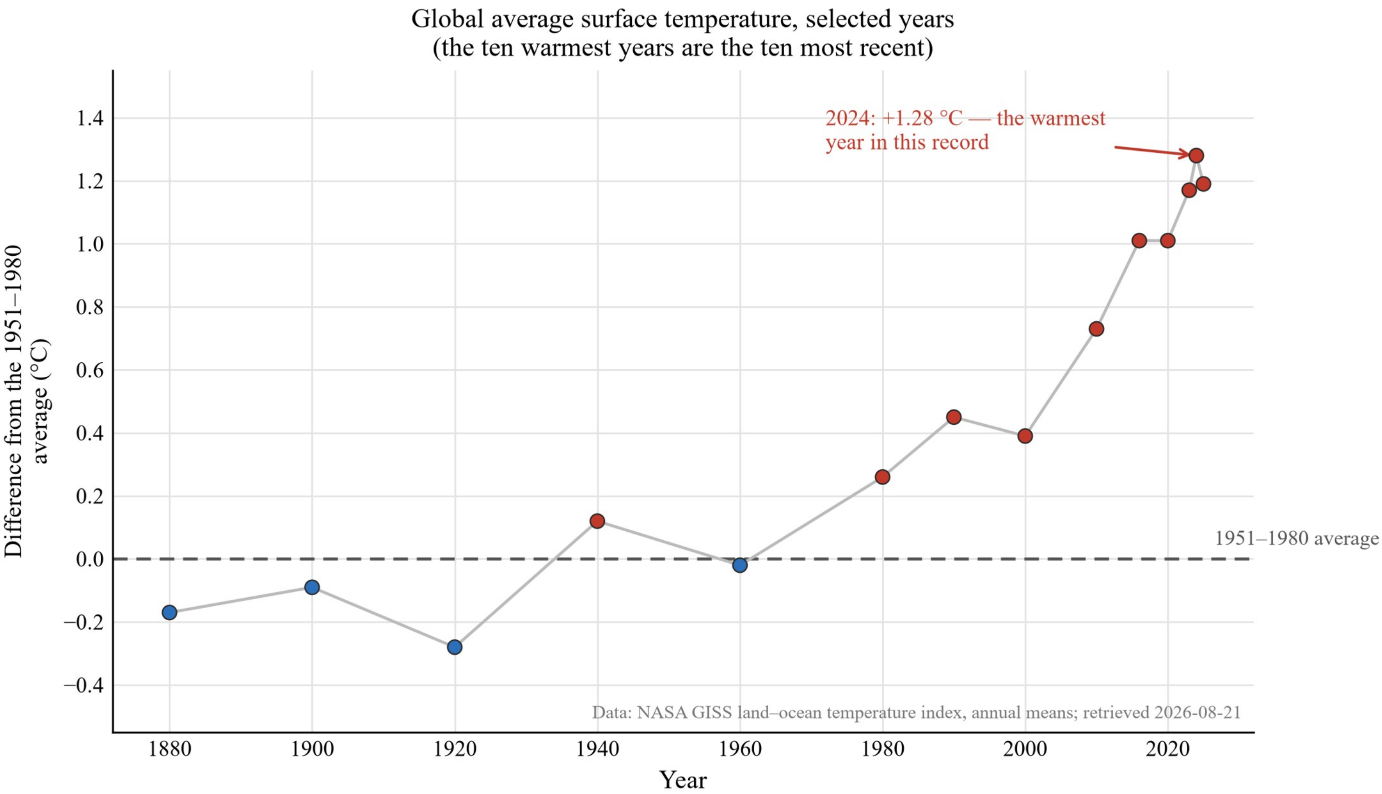
Both currents and upwelling show the pattern of `VC2S10U11.E04`: energy (as heat and as density differences) drives the deep circulation; the circulation regulates climate by moving and storing heat; and it directly affects marine life.

Indicators of climate change. Because climate is a system, it is measured with several independent **indicators** (`VC2S10U11.E02`). Six are standard, and all six point the same way:



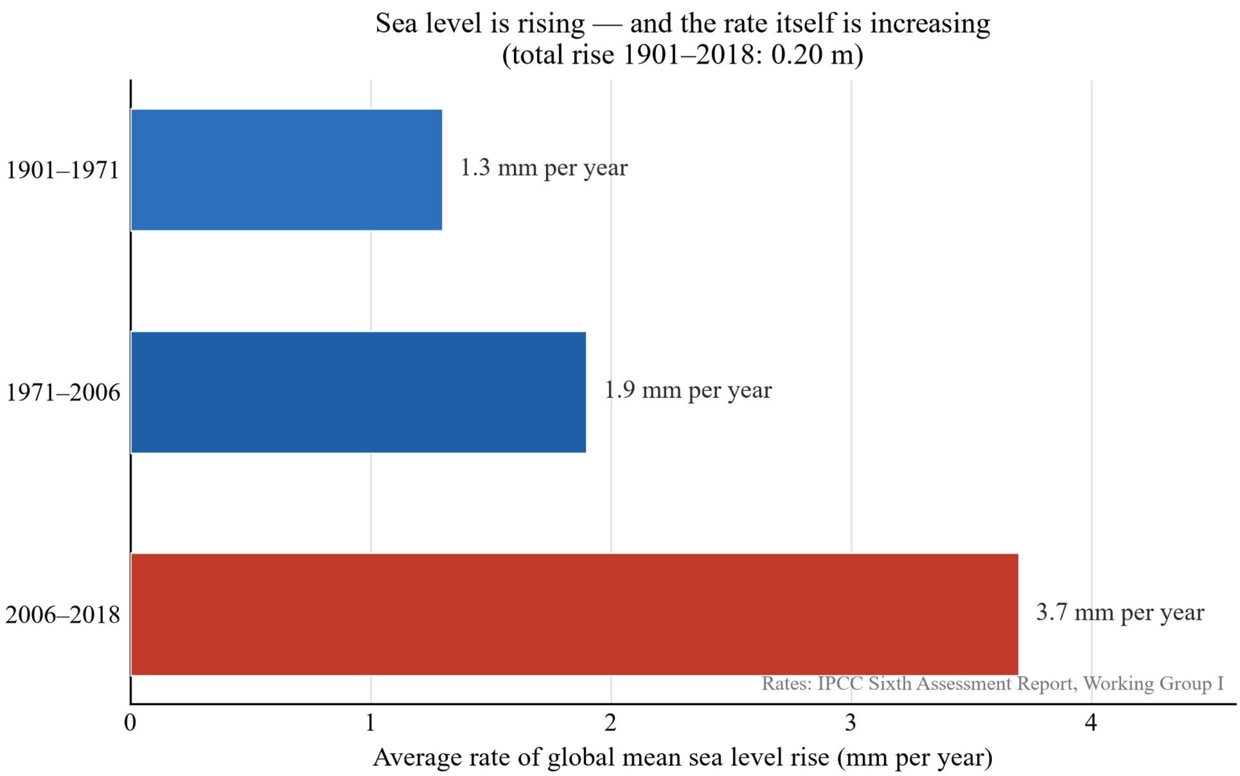
A grid of six indicator tiles, each with a small sketch and a one-line trend: ocean temperature rising, atmospheric temperature rising, sea level rising, biodiversity and species distributions shifting, permafrost thawing, and Arctic sea ice shrinking

- **Atmospheric temperature.** The global average surface temperature has risen by a little over 1 °C since the late 1800s, and the ten warmest years in the record are the ten most recent.
- **Ocean temperature.** More than 90 % of the extra heat is stored in the ocean, and ocean heat content has risen steadily.
- **Sea level.** Global mean sea level has risen about 0.20 m since 1900 — from expanding warm water and melting land ice — and the rate itself is increasing.
- **Sea ice.** The area of Arctic sea ice at its September minimum has declined by about 12 % per decade since satellites began watching in 1979.
- **Permafrost.** Permanently frozen ground in the far north is thawing, releasing CO_2 and CH_4 from the decay of ancient organic matter.
- **Biodiversity and species distribution.** Species are shifting towards the poles and upslope as their climate envelopes move, changing the mix of life in a region.



Line graph of global average surface temperature for selected years since 1880, shown as differences from the 1951–1980 average: values wobble below and about zero until the mid-twentieth century, then climb steeply, with 2024 at +1.28 °C the warmest year in the record and the ten warmest years the ten most recent

Read the temperature graph the way a scientist reads it: individual years wobble up and down because of natural variability (El Niño years, volcanic eruptions), but the trend across decades is steeply upward, and every recent decade sits above the one before it.

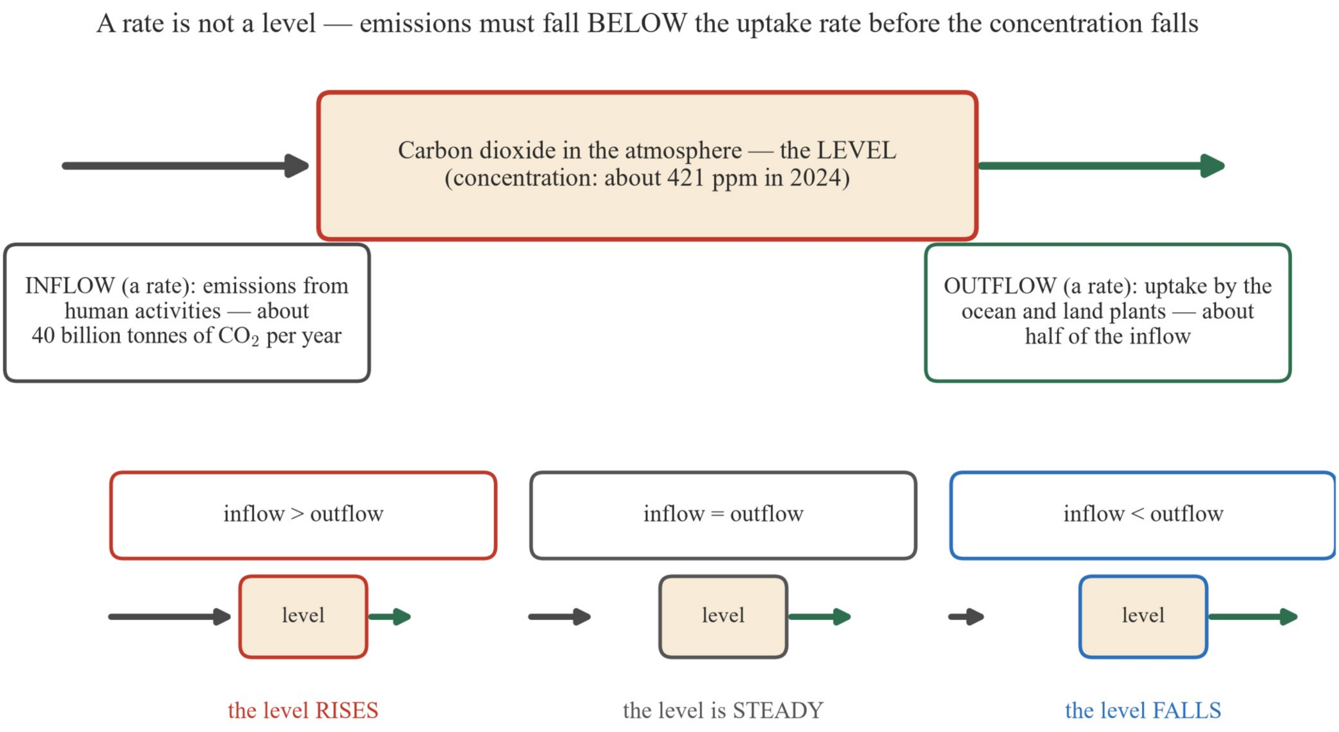


Horizontal bar chart of the average rate of global mean sea level rise in three periods: 1.3 mm per year in 1901–1971, 1.9 mm per year in 1971–2006 and 3.7 mm per year in 2006–2018, with the total rise 1901–2018 of 0.20 m noted

The sea level bars carry a message beyond the rise itself: the **rate** of rise has almost tripled from the twentieth century to the 2000s. A rising level with a rising rate is a system accelerating, not coasting.

Source for temperature: NASA Goddard Institute for Space Studies, "GISTEMP v4 — Global Surface Temperature", n.d. https://data.giss.nasa.gov/gistemp/ — retrieved 2026-08-21. Source for sea level rates and ocean heat: IPCC, "Climate Change 2021: The Physical Science Basis (Sixth Assessment Report)", 2021. https://www.ipcc.ch/report/ar6/wg1/ — retrieved 2026-08-21. Source for the CO_2 record: NOAA Global Monitoring Laboratory, "Trends in Atmospheric Carbon Dioxide", n.d. https://gml.noaa.gov/ccgg/trends/ — retrieved 2026-08-21. Source for sea ice and the ~1.1 °C warming since 1850–1900: NASA, "Vital Signs of the Planet", n.d. https://climate.nasa.gov/vital-signs/ — retrieved 2026-08-21.

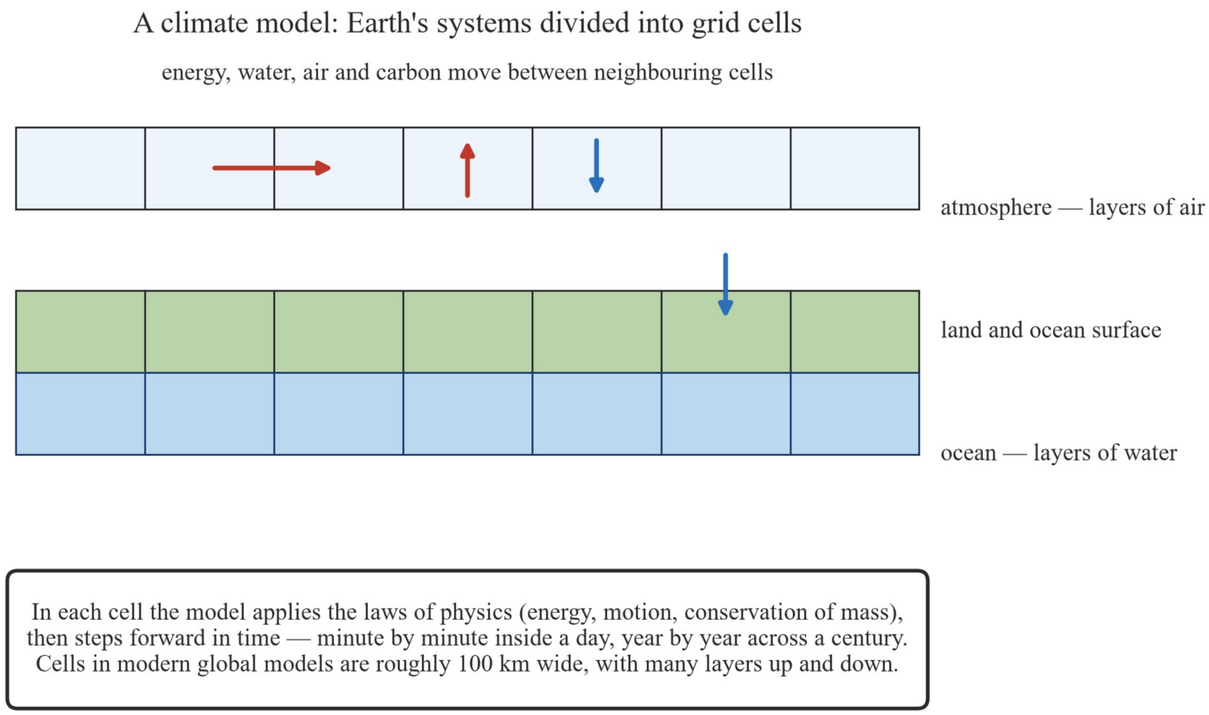
Rate and level: the stock-and-flow idea. One idea organises almost all of climate arithmetic, and it is worth naming precisely. A **stock** (or level) is an amount that accumulates — the CO_2 in the air, the heat in the ocean, the height of the sea. A **flow** (or rate) is something entering or leaving the stock per unit of time — tonnes of CO_2 emitted per year. The level changes according to the difference between the flow in and the flow out: while the flow in is bigger, the level rises; when the flows match, the level is steady; only when the flow out is bigger does the level fall.



A stock-and-flow diagram: a tub labelled "CO_2 in the atmosphere (the level)" with an inflow of about 40 Gt of CO_2 per year from human emissions and an outflow of about half that taken up by the ocean and land, plus three mini panels showing that the level rises when inflow exceeds outflow, is steady when they are equal, and falls only when outflow exceeds inflow

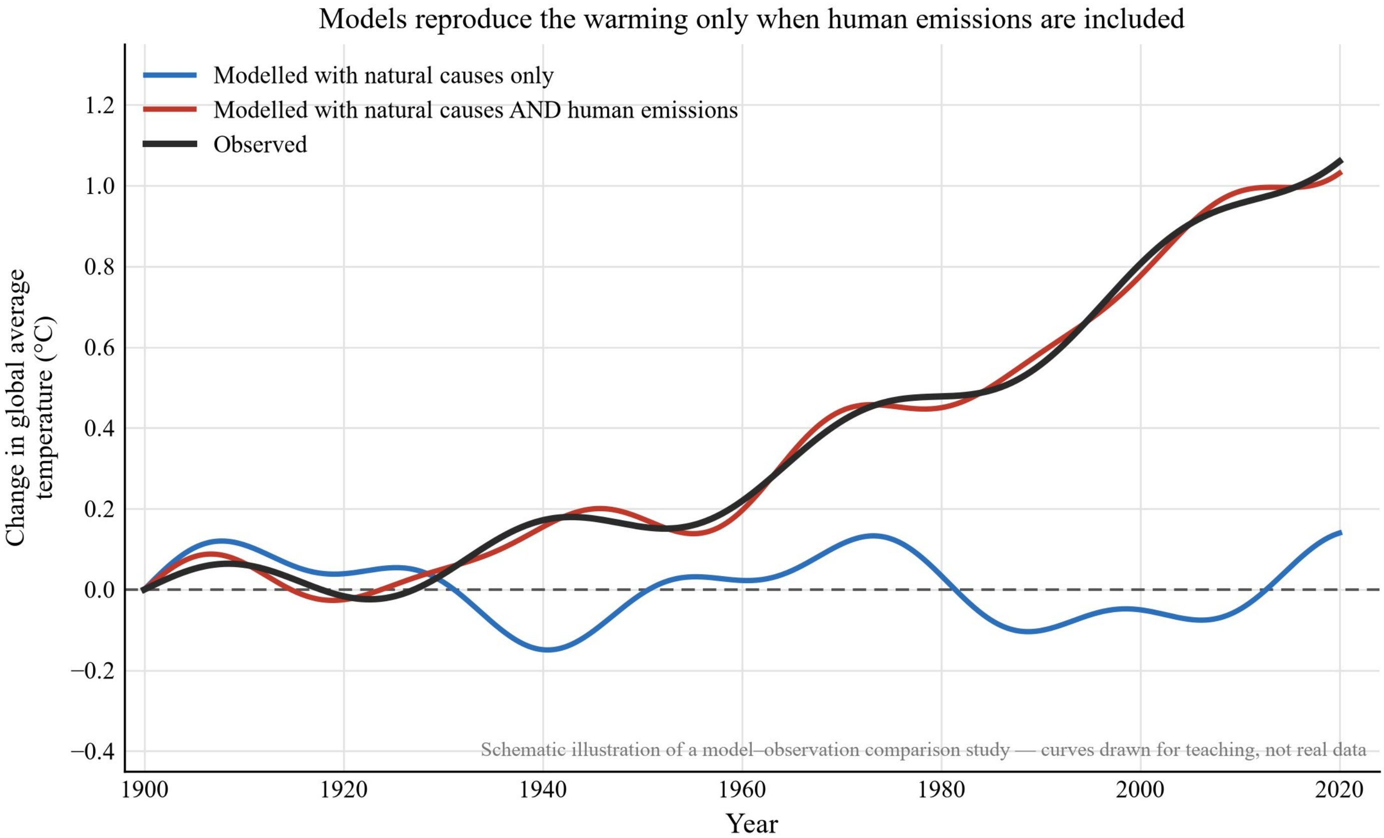
Human activity currently adds roughly 40 Gt of CO_2 to the air each year (one gigatonne, Gt, is a thousand million tonnes), and the ocean and land together take up about half of it. The level therefore keeps rising by about 20 Gt a year — exactly what the CO_2 record shows. The practical consequence is the one most often missed in public debate: cutting emissions makes the inflow smaller, but as long as the inflow is still bigger than the outflow, the concentration keeps rising. "Emissions fell" and "concentration fell" are different claims, and the first does not imply the second.

How climate is modelled. `VC2S10U11.E03` asks how scientists identify changes in global climate over time and *why* the energy balance has changed — and the tool for the "why" is the **climate model**. A model divides the atmosphere, the ocean and the land surface into a three-dimensional grid of cells, and in every cell the physics of radiation, clouds, winds, currents and the exchanges between surface and air are computed step by step on a supercomputer. Each cell is large — typically a hundred kilometres or so across — so small things like individual clouds are represented by their average effect within a cell rather than drawn one by one.



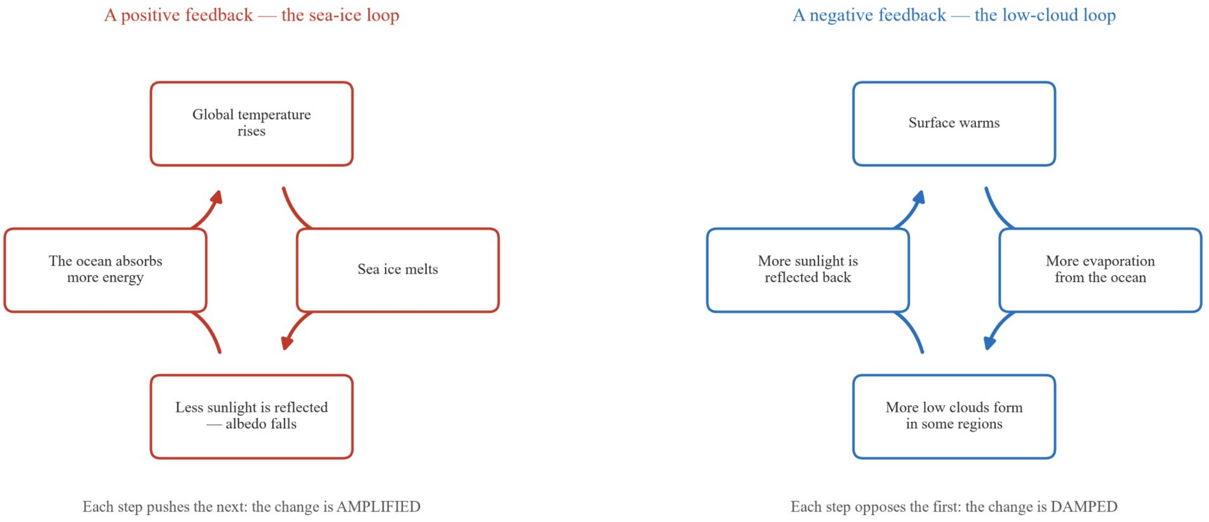
A diagram of a climate model grid: columns of cells stacked in layers through the atmosphere, a surface row of land and ocean, and layers of ocean cells below, with arrows showing energy and material exchanged between neighbouring cells and the physics computed in each cell

A model is only as good as its testing, and the testing is where the fingerprint method comes in. Models are run over the twentieth century twice: once driven by natural causes alone (the Sun's small variations and volcanic eruptions), and once driven by natural causes *and* human emissions. Only the runs that include human emissions reproduce the observed warming. The shape of the observed trend is, in that sense, a fingerprint: the pattern matches the signature of greenhouse gases, not the signature of the Sun or of volcanoes.



Schematic line graph of global average temperature change since 1900 with three curves: the observed record climbing about 1 °C, a model curve with natural and human causes together tracking the observed record closely, and a model curve with natural causes only wobbling about zero — labelled as a teaching illustration, not real data

Models also contain **feedbacks** — loops in which a change causes further change. A **positive feedback** amplifies: as sea ice melts, dark water replaces bright ice, the albedo falls, more sunlight is absorbed, and more ice melts. A **negative feedback** damps: in some regions a warmer surface drives more low cloud, and low cloud reflects sunlight, cooling the surface again. The size of the feedbacks, not the basic greenhouse physics, is the main source of the spread between model projections — which is why models are run many times and compared against the observed record before their projections are trusted.



Two loop diagrams of feedback: a positive loop in which warming melts sea ice, the darker surface absorbs more sunlight and the warming amplifies; and a negative loop in which warming increases low cloud in some regions, the brighter surface reflects more sunlight and the warming is damped

Running the tested models forward under different emissions **scenarios** — storylines of high or low future emissions — gives the projections used to describe coming climate. Under every scenario the models agree that the warming continues for some decades; how fast and how far it goes after mid-century depends mostly on the emissions path the world chooses. That is the modelling answer to the subtopic's central question: the dynamics of global climate change can indeed be modelled and explained, and the explanation runs through emissions, the energy budget, and the exchanges between the ocean, the air, the land and the ice.

Activities

Activity 1 — Albedo and the ice feedback. Place two identical shallow dishes in full sun or under an identical lamp: one lined with white paper (the "ice"), one filled with dark water (the "ocean"). Put a thermometer in each, read both temperatures every minute for ten minutes, and plot the two warming curves on the same axes. (a) Which surface warms faster, and by how much after ten minutes? (b) Identify the pair's albedos in the albedo figure and use them to explain your result. (c) Now argue the loop: if a warming region melts its ice and exposes dark water, what happens to the absorbed energy, and what does that do to the warming? Name the kind of feedback this loop is.

Activity 2 — Trend versus cycle in a CO_2 record. The table below is *simulated data for practice*, built to the same shape as the real Mauna Loa record (a seasonal cycle sitting on an upward trend).

month	ppm	month	ppm
Jan Yr 1	421.0	Jan Yr 2	423.2
Apr Yr 1	422.6	Apr Yr 2	424.8
Jul Yr 1	421.6	Jul Yr 2	423.8
Oct Yr 1	420.2	Oct Yr 2	422.4

Plot all eight points on one set of axes (ppm against time), join them in order, and answer: (a) what is the size of the seasonal cycle (the swing from a year's highest to lowest value)? (b) what is the trend (the change from a month in Year 1 to the same month in Year 2)? (c) explain the cycle using the carbon cycle of subtopics 12A and 12B, and explain why the cycle does not cancel the trend.

Activity 3 — A conveyor in a tank. Fill a clear tank or large glass dish with room-temperature fresh water and let it settle. In a small bottle, prepare cold, strongly salted water coloured with food dye, and gently rest the open bottle on the bottom at one end of the tank. Observe for two to three minutes. (a) Describe the path the coloured water takes and explain it using density. (b) Predict what would happen if the coloured water were warm and salty instead of cold and salty, and test your prediction. (c) Connect the demo to the conveyor figure: in the real ocean, where does surface water become cold and salty enough to sink, and what does the sinking start?

Worked examples

Data in this section are quoted to the significant figures shown, and final answers match the precision of the given data unless the arithmetic is exact.

Example 1 — scaffolded

Averaged over the planet, 340 W/m² of solar power arrives at the top of the atmosphere, and the Earth's albedo is about 0.29. (a) Calculate the reflected power per square metre. (b) Calculate the absorbed power per square metre. (c) State the outgoing infrared power per square metre when the budget balances.

Working	Comment
(a) reflected = 340 × 0.29 = 98.6 ≈ 100 W/m²	The albedo is the reflected share of the arriving energy, so multiply the arriving power by the albedo.
(b) absorbed = 340 − 98.6 = 241.4 ≈ 240 W/m²	Whatever is not reflected is absorbed.
(c) outgoing = absorbed ≈ 240 W/m²	A balanced budget means the Earth re-emits what it absorbs.

Example 2 — scaffolded

The CO_2 concentration was about 280 ppm in 1750 and 421.1 ppm in 2024. (a) Calculate the rise in ppm. (b) Show that this rise is an increase of about 50 %.

Working	Comment
(a) rise = 421.1 − 280 = 141.1 ≈ 141 ppm	A concentration change is the later value minus the earlier value.
(b) percentage increase = 141.1 ÷ 280 × 100 ≈ 50.4 % ≈ 50 %	A percentage increase is always the change divided by the *starting* value, not the final value.

Example 3 — unscaffolded

Global mean sea level rose 0.20 m between 1901 and 2018. (a) Calculate the average rate of rise over that period in mm per year. (b) Compare your answer with the 2006–2018 rate of 3.7 mm per year by writing the later rate as a multiple of the 1901–2018 average.

The period 1901–2018 is 117 years, and 0.20 m = 200 mm.

$$200 \div 117 = 1.7 \text{ mm per year (2 s.f.).}$$

(b) Divide the later rate by the long average:

$$3.7 \div 1.7 = 2.2.$$

The recent rate is about **2.2 times** the century average — the rise is accelerating.

Example 4 — unscaffolded

Human activity emits roughly 40 Gt of CO_2 per year, and the ocean and land take up about 20 Gt of it per year. (a) Calculate the net addition to the atmospheric stock each year. (b) If emissions were halved to 20 Gt per year while the uptake stayed at 20 Gt per year, state what happens to the concentration, and explain the word "steady" in your answer.

(a) net addition = 40 − 20 = **20 Gt per year**. The stock rises by that amount every year while the flows are unequal.

(b) With 20 Gt in and 20 Gt out, the flows balance, so the concentration is **steady — it stops rising, but it does not fall**. “Emissions halved” is not the same as “concentration falling”: the level falls only if the outflow exceeds the inflow.

Practice questions

Scaffolded questions

Question 1 Statement A: “Brisbane’s average rainfall over 1991–2020 was higher than over 1961–1990.” Statement B: “It rained 22 mm in Brisbane yesterday.” (a) Which statement is about climate and which is about weather? (b) Give the defining difference between the two terms. (c) State the conventional averaging period used for climate.

Question 2 Use the energy budget figure: 340 W/m² arrives and the Earth’s albedo is taken as 0.30. (a) Calculate the reflected power per square metre. (b) Calculate the absorbed power per square metre. (c) State the outgoing infrared power per square metre when the budget balances, and name the type of radiation that carries it.

Question 3 (a) Name the three main greenhouse gases added by human activity. (b) State which kind of incoming radiation passes through these gases, and which kind of outgoing radiation they absorb and re-emit. (c) State the Earth’s average surface temperature with the natural greenhouse effect and without it.

Question 4 Use the CO_2 record figure. (a) State the concentration in 1750 and in 2024. (b) Calculate the rise in ppm. (c) Show that the rise is an increase of about 50 %.

Question 5 Use the sea level figure. (a) State the average rate of rise in 2006–2018. (b) Calculate how many times larger that rate is than the 1901–1971 rate of 1.3 mm per year (to 2 s.f.). (c) State the total rise over 1901–2018.

Question 6 Use the stock-and-flow figure. (a) With an inflow of about 40 Gt of CO_2 per year and an outflow of about 20 Gt per year, calculate the net addition to the stock each year. (b) State what happens to the level when inflow equals outflow. (c) If emissions fell to exactly 20 Gt per year, would the concentration fall? Explain in one sentence.

Unscaffolded questions

Question 7 Explain the mechanism of the enhanced greenhouse effect. Your answer should state what happens to incoming visible light, what the surface emits in response, what greenhouse gases do with that emission, and what changes when more gas is added.

Question 8 (a) State roughly what share of the extra trapped heat the ocean absorbs. (b) Give two consequences of that stored heat. (c) Explain why the ocean’s slowness to warm means the air warms more slowly than it otherwise would — and why that is only a delay, not a rescue.

Question 9 About deep ocean currents and marine life: (a) Name the two properties of sea water that set its density and so drive the deep circulation. (b) Explain how upwelling supports productive fisheries. (c) State one way the deep circulation regulates the global climate.

Question 10 Describe the sea-ice feedback loop shown in the feedback figure, and explain why it is called a *positive* feedback. In your explanation, use the word albedo correctly at least once.

Question 11 A politician says: “Our emissions fell last year, so the CO_2 problem is on its way to being solved.” Using the stock-and-flow idea, identify the error in the statement and state what would have to be true of the two flows for the concentration to actually fall.

Question 12 Use the temperature trend figure. (a) State the warmest year in the record and its value against the 1951–1980 average. (b) Describe the pattern formed by the ten warmest years. (c) Explain why a single cold year would not contradict the warming trend, using the distinction between weather and climate.

Question 13 About climate models: (a) Describe how a model divides up the atmosphere, ocean and land. (b) Summarise the fingerprint test of the fingerprint figure, and state what it shows about the cause of the observed warming. (c) State what must be chosen before a model can project the climate of 2100, and why different choices give different answers.

Question 14 Use the GWP values (CH_4 28; N_2O 265). (a) Calculate the CO_2-e of 2 t of methane. (b) Calculate the CO_2-e of 0.2 t of nitrous oxide. (c) Which parcel — 2 t of CH_4 or 0.2 t of N_2O — traps more heat over 100 years?

Question 15 (a) List four of the six standard indicators of climate change. (b) Choose two of them and state how each is measured in practice. (c) Explain why scientists trust the conclusion more because the indicators are independent of one another.

Question 16 Measurements put the Earth's current energy imbalance at roughly 1 W/m^2 — one extra joule per second for every square metre of the planet. (a) Using one year $\approx 3.16 \times 10^7$ s, calculate the extra energy absorbed per square metre in one year. (b) The Earth's surface area is about 5.1×10^{14} m^2. Calculate the total extra energy absorbed in one year, and comment on what the ocean does with it.

Answers

Question 1 (a) A is climate; B is weather; (b) climate is the long-run pattern, weather is the short-run state; (c) about 30 years. **Question 2** (a) 102 ≈ 100 W/m²; (b) 238 ≈ 240 W/m²; (c) ≈ 240 W/m², infrared. **Question 3** (a) CO_2, CH_4, N_2O; (b) visible passes through; infrared absorbed and re-emitted; (c) about 15 °C with it, about −18 °C without. **Question 4** (a) 280 ppm; 421.1 ppm; (b) 141.1 ≈ 141 ppm; (c) 141.1 ÷ 280 × 100 ≈ 50 %. **Question 5** (a) 3.7 mm per year; (b) 3.7 ÷ 1.3 ≈ 2.8 times; (c) 0.20 m. **Question 6** (a) 20 Gt per year; (b) steady; (c) no — steady, not falling. **Question 7** see solution. **Question 8** (a) more than 90 %; (b) thermal expansion raising sea level; warming marine environments (and stored heat warming the climate for centuries); (c) see solution. **Question 9** (a) temperature and salinity; (b) see solution; (c) see solution. **Question 10** see solution. **Question 11** see solution. **Question 12** (a) 2024, +1.28 °C; (b) the ten most recent years; (c) see solution. **Question 13** (a) a 3-D grid of cells in layers; (b) see solution; (c) an emissions scenario. **Question 14** (a) 56 t CO_2-e; (b) 53 t CO_2-e; (c) the methane parcel (56 > 53). **Question 15** (a) any four of: atmospheric temperature, ocean temperature, sea level, sea ice, permafrost, biodiversity/species distribution; (b) see solution; (c) see solution. **Question 16** (a) ≈ 3.2×10^7 J per m²; (b) ≈ 1.6×10^{22} J — over 90 % stored in the ocean.

Fully-worked solutions

Question 1 (a) Statement A is about **climate** (a comparison of 30-year averages); statement B is about **weather** (a single day's rain). (b) Weather is the state of the atmosphere over hours to days; climate is the pattern of weather averaged over a long period. (c) About **30 years**.

Question 2 (a) reflected = 340 × 0.30 = **102 W/m²** (about 100 W/m² on the figure). (b) absorbed = 340 − 102 = **238 W/m²** (about 240 W/m² on the figure). (c) When the budget balances, outgoing = absorbed ≈ **240 W/m²**, carried away as **infrared** radiation.

Question 3 (a) Carbon dioxide (**CO_2**), methane (**CH_4**) and nitrous oxide (**N_2O**). (b) Incoming **visible** light passes through; the warmed surface emits **infrared**, which the gases absorb and re-emit in all directions, including back down. (c) About **15 °C** with the natural greenhouse effect; about **−18 °C** without it.

Question 4 (a) **280 ppm** in 1750 (ice cores); **421.1 ppm** in 2024 (Mauna Loa). (b) 421.1 − 280 = **141.1 ppm** (about 141 ppm). (c) 141.1 ÷ 280 × 100 = 50.4 % ≈ **50 %**.

Question 5 (a) **3.7 mm per year.** (b) 3.7 ÷ 1.3 = **2.8 times** (2 s.f.). (c) **0.20 m.**

Question 6 (a) 40 − 20 = **20 Gt per year** added to the stock. (b) The level is **steady** — neither rising nor falling. (c) No. With inflow equal to outflow the level is steady; halving emissions stops the rise but does not make the concentration fall.

Question 7 Incoming **visible light** passes through the atmosphere almost unhindered and warms the surface. The warm surface emits **infrared radiation**. Greenhouse gas molecules absorb that infrared and **re-emit it in all directions**, so a share returns to the surface and the lower atmosphere holds more energy. Adding more gas (the **enhanced** effect) absorbs and re-emits back a larger share of the outgoing infrared, so the surface and lower atmosphere warm until the outgoing side of the budget balances again at a higher temperature.

Question 8 (a) **More than 90 %** of the extra trapped heat. (b) Any two of: warm water **expands**, raising sea level; the stored heat will keep **warming the climate for centuries**; marine environments warm, shifting species distributions. (c) Water takes much more energy to warm than air, so the ocean soaks up heat that would otherwise sit in the atmosphere — the air warms more slowly than it otherwise would. It is a delay, not a rescue, because the heat is *stored*, not removed: it leaks back into the climate over centuries.

Question 9 (a) **Temperature and salinity** — cold, salty water is dense and sinks. (b) Wind pushes surface water offshore; **nutrient-rich deep water rises** to replace it; in sunlight the nutrients feed **plankton**, and plankton feed fish — so upwelling zones support a large share of the world's fisheries. (c) Any one of: it **moves heat** around the globe (warming high latitudes); it **stores heat and carbon** in the deep ocean for hundreds to a thousand years, slowing the pace of surface warming.

Question 10 Warming **melts sea ice**; dark open water replaces bright ice, so the **albedo falls** and more sunlight is **absorbed**; the extra absorbed energy causes **more warming**, which melts more ice. It is a **positive** feedback because each turn of the loop *amplifies* the change that started it — the output (more warming) reinforces the input, instead of damping it as a negative feedback would.

Question 11 The error is confusing a **flow** with a **stock**. Falling emissions mean a smaller inflow, but while the inflow (about 40 Gt/yr) is still larger than the outflow (about 20 Gt/yr), the concentration **keeps rising** — more slowly, but rising. For the concentration to fall, the **outflow would have to exceed the inflow** — emissions below the uptake of the ocean and land.

Question 12 (a) **2024**, at **+1.28 °C** above the 1951–1980 average. (b) The ten warmest years are **the ten most recent** — the top of the record is the end of the record. (c) Weather varies from year to year (El Niño, volcanoes), so a single cold year is *wobble about the trend*, not a change in the trend. Climate is the 30-year pattern; a trend is judged on decades, and every recent decade sits above the one before it.

Question 13 (a) The atmosphere, ocean and land are divided into a **three-dimensional grid of cells**, stacked in layers, and the physics of radiation, clouds, winds and currents is computed in every cell at each time step. (b) Models run over the twentieth century with **natural causes only** fail to reproduce the observed warming — they wobble about zero — while runs with **natural plus human** causes track the observed record closely. The observed trend therefore carries the **fingerprint of human emissions**, not of the Sun or volcanoes. (c) An **emissions scenario** — a storyline of future emissions. Different scenarios put different amounts of greenhouse gas into the modelled atmosphere, so the projected warming differs; the physics is the same, the input is not.

Question 14 (a) $2 \times 28 =$ **56 t CO_2-e**. (b) $0.2 \times 265 =$ **53 t CO_2-e**. (c) The **2 t of methane** (56 t CO_2-e) traps slightly more heat over 100 years than the 0.2 t of nitrous oxide (53 t CO_2-e) — even though nitrous oxide is the more powerful gas tonne for tonne.

Question 15 (a) Any four of: **atmospheric temperature; ocean temperature; sea level; sea ice; permafrost; biodiversity and species distribution**. (b) Any two, sensibly matched: atmospheric temperature — thermometer stations, ships and satellites combined into a global average; ocean temperature — instruments on floats and ships measuring heat content; sea level — tide gauges and satellite altimeters; sea ice — satellite images; permafrost — borehole temperature stations; species distribution — surveys and monitoring records. (c) The indicators are measured by **different instruments and different methods**, yet all point the same way; a single faulty instrument could mislead on one indicator, but independent lines of evidence agreeing makes the conclusion robust.

Question 16 (a) Energy per square metre = power × time = $1\ \text{W/m}^2 \times 3.16 \times 10^7\ \text{s} =$ **3.2×10^7 J** (2 s.f.) — about 32 million joules for every square metre, every year. (b) Total = $3.16 \times 10^7\ \text{J/m}^2 \times 5.1 \times 10^{14}\ \text{m}^2 \approx$ **1.6×10^{22} J per year**. That enormous flow of energy is the imbalance of the energy budget figure in absolute terms — and **more than 90 % of it is stored in the ocean**, which is why ocean heat content is one of the steadiest indicators of a changing climate.

Where this leads: within this book, the second limb of `VC2S10U11` — predicting changes and identifying strategies to reduce or mitigate climate change, including carbon footprints and the activities named in the content description (power generation, deforestation, manufacturing, transport, food production and resource consumption) — is delivered by subtopic 12D, which builds directly on the emissions, energy budget and stock-and-flow reasoning introduced here. Beyond school, be precise about the destination: the energy-balance account of the greenhouse effect taught here is the one Environmental Science Unit 4 Area of Study 1 later quantifies and models, and the implicit prerequisites VCE assumes — reading a stock-and-flow diagram, separating a trend from a superimposed cycle, and distinguishing a rate from a level — are exactly the skills this subtopic practises (TOC §5, Ch12 row, reference-only, D12). No VCE content is pre-taught here (TOC D9).

Mitigation: power generation, deforestation, manufacturing, transport, food production and consumption

Chapter 12 — Earth and space sciences A: Earth's systems, carbon and climate (Science, Levels 9 and 10)

Subtopic 12D · VC2 Science Understanding — Earth and space sciences

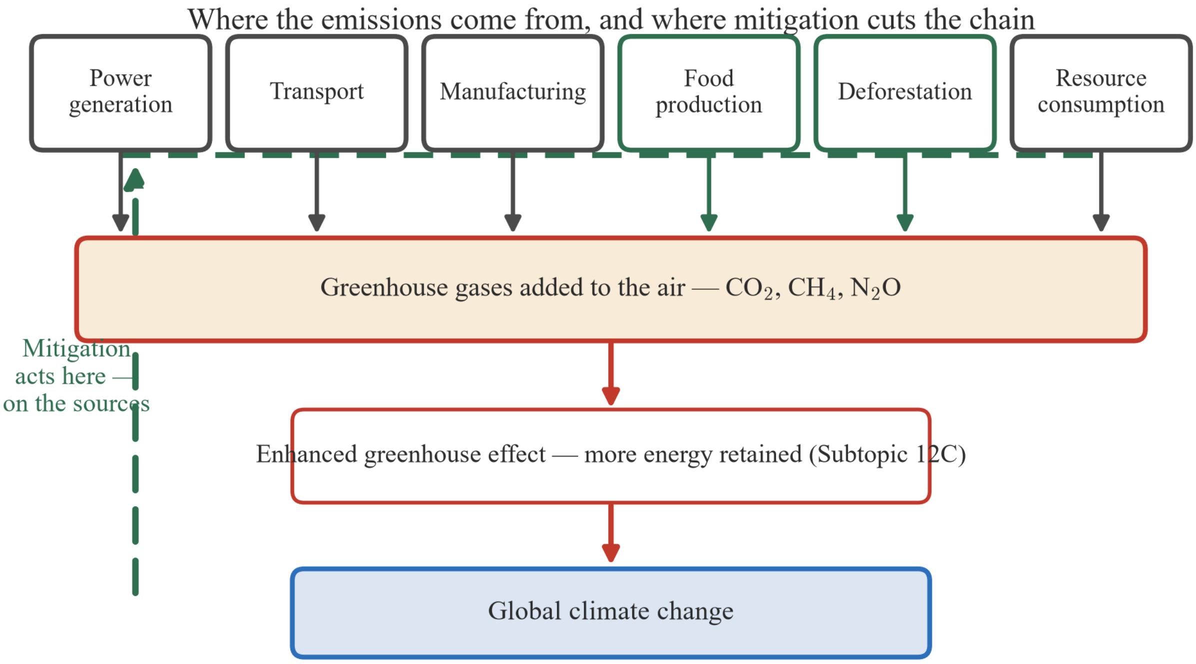
CD code: `VC2S10U11` (split delivery † — subtopic 12C owns this code and teaches the climate-dynamics limb; this subtopic delivers the sectoral-mitigation limb) **Content description (word for word):** "the dynamics of global climate change can be modelled and explained by examining the interactions between greenhouse gas emissions and energy exchanges within and between Earth's systems; mitigating human-induced climate change requires addressing various activities including power generation, deforestation, manufacturing, transportation, food production and resource consumption" **This subtopic delivers (clause split):** mitigating human-induced climate change requires addressing various activities including power generation, deforestation, manufacturing, transportation, food production and resource consumption **Elaboration ids drawn on:** `VC2S10U11.E05` · `VC2S10U11.E06` **Achievement standard (extract served):** "They describe trends in patterns of global climate change and propose strategies to mitigate contributing factors." **Maths interlock (D11):** `VC2M9M05` — direct proportion, rates, ratio and scale, used here for emission-factor calculations, percentage change and per-person (per-capita) comparisons.

Theory

Where this subtopic fits. Subtopic 12C models the dynamics: greenhouse gas emissions change the energy exchanges within and between Earth's systems, and that drives global climate change. This subtopic takes the next step the achievement standard asks for — proposing strategies to **mitigate** the contributing factors. Everything here is about the human activities that add greenhouse gases to the air, and about what can be done in each one.

Mitigation and adaptation — two different responses. Mitigation means acting on the causes of climate change: reducing greenhouse gas emissions at their sources, or strengthening the **sinks** (such as forests and oceans) that remove greenhouse gases from the air. **Adaptation** means adjusting to the effects of climate change that are already happening — for example, designing drains for heavier rainfall or planting shade trees for hotter summers. Both matter, but they are not the same thing: mitigation changes the future trend, adaptation copes with it. This subtopic is about mitigation, in the six activities the content description names: power generation, deforestation, manufacturing, transport, food production and resource consumption.

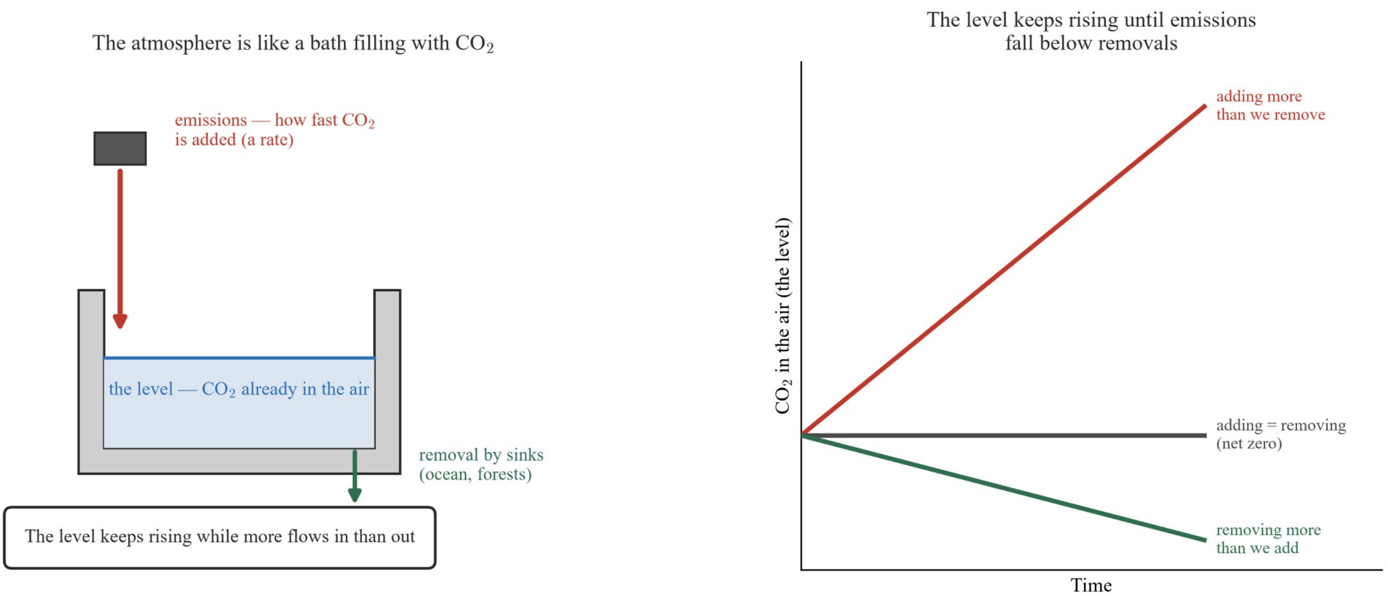
The cause chain, and where mitigation cuts it. The chain runs from human activities to greenhouse gases to climate change:



Flow diagram: six activity boxes for power generation, transport, manufacturing, food production, deforestation and resource consumption each arrow into a greenhouse gas box, then to the enhanced greenhouse effect, then to global climate change; a green dashed mitigation arrow crosses all six source flows.

Every mitigation measure in this subtopic does one of two things: it shrinks one of the flows into the greenhouse-gas box (burning less fuel, clearing less forest, wasting less material), or it enlarges a flow out of the box (growing and protecting forests that take CO_2 in). A measure that does neither is not mitigation.

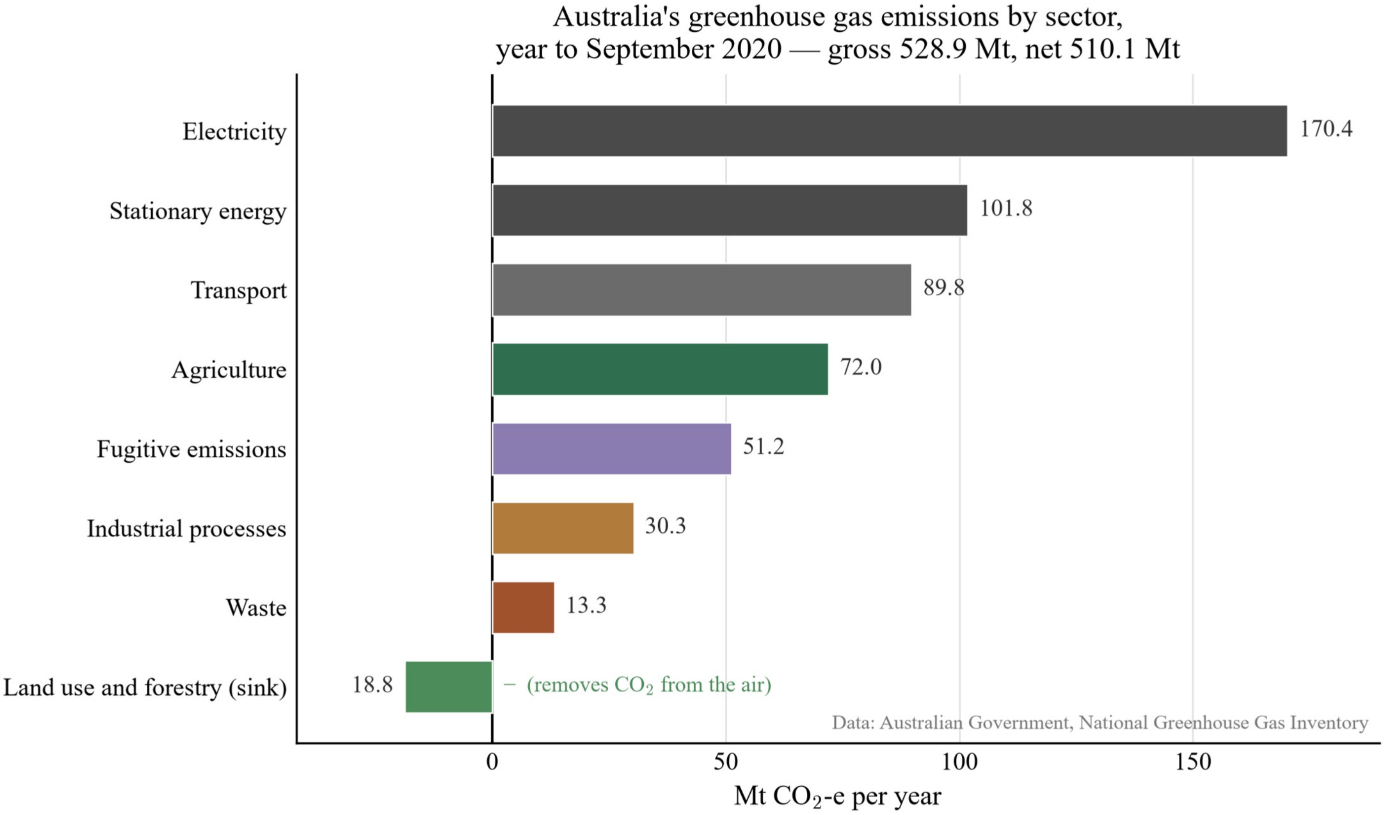
A rate is not a level. Before reading any emissions data, one distinction must be clear, because it is the most common confusion in this topic. **Emissions are a rate** — an amount of CO_2 added *per year*. **The CO_2 already in the atmosphere is a level** — a stored amount (concentration) that the rate adds to. A bath makes the idea visible:



Two-panel diagram: left, a bath with a tap labelled emissions, the rate, filling water labelled the level of CO2 already in the air, and a drain labelled removal by sinks such as the ocean and forests; right, three lines showing the level rising while adding is more than removing, steady when adding equals removing at net zero, and falling when removing is more than adding.

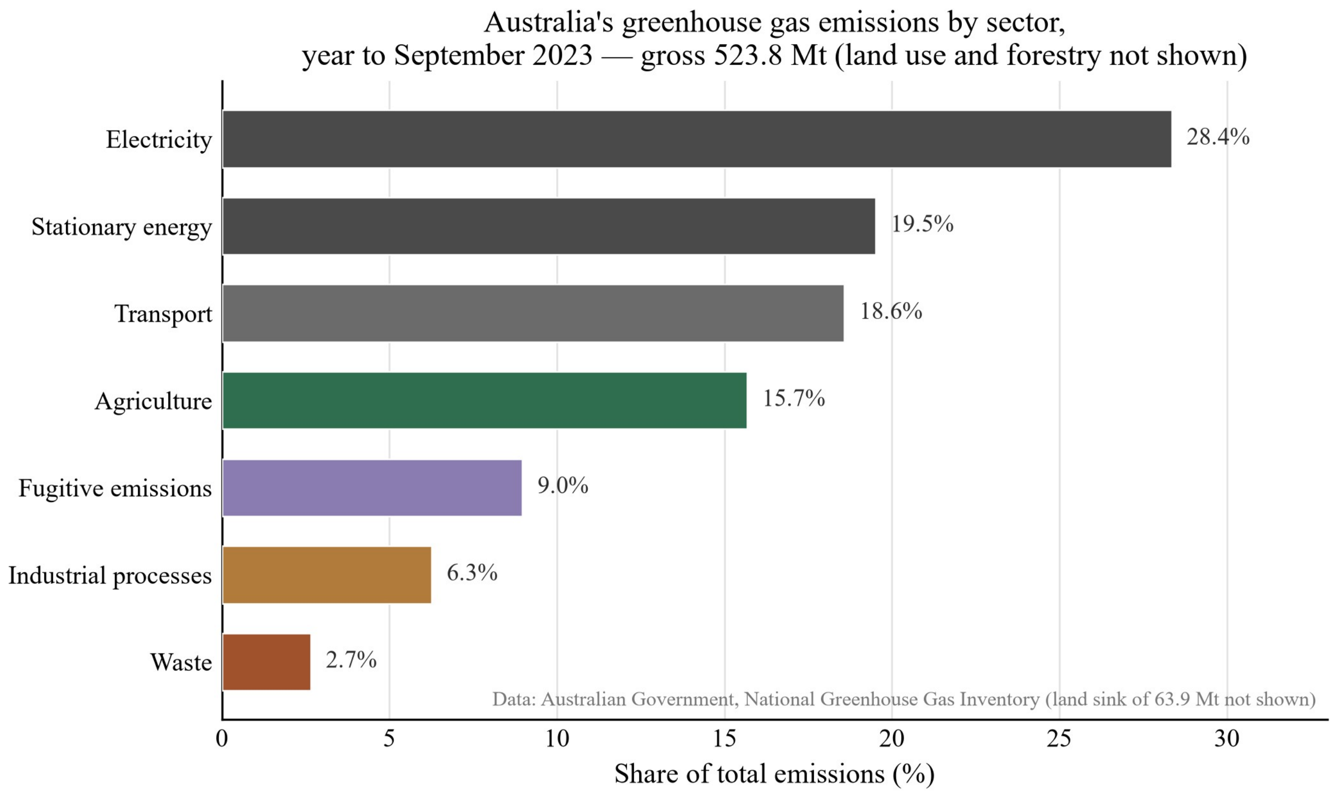
The level keeps rising for as long as the inflow (emissions) is bigger than the outflow (removal by sinks). So *"emissions fell"* and *"the CO_2 level fell"* are **different claims**. If emissions fall but are still bigger than removal, the level keeps rising — more slowly, but rising. The level only steadies when adding equals removing (**net zero** emissions), and only falls when removal is bigger than adding (net negative emissions). Keep this bath in mind whenever a report celebrates falling emissions: falling emissions slow the rise, and net zero stops it.

Where Australia's emissions come from. Australia's emissions are published each quarter in the National Greenhouse Gas Inventory. The year to September 2020 looked like this, in megatonnes of CO_2-e (Mt):



Horizontal bar chart of Australia's greenhouse gas emissions by sector for the year to September 2020 in Mt CO2-e: electricity 170.4, stationary energy 101.8, transport 89.8, agriculture 72.0, fugitive emissions 51.2, industrial processes 30.3, waste 13.3, and land use and forestry as a negative bar of 18.8 that removes CO2 from the air.

Three years later the same sectors, as shares of the gross total (523.8 Mt), looked like this:



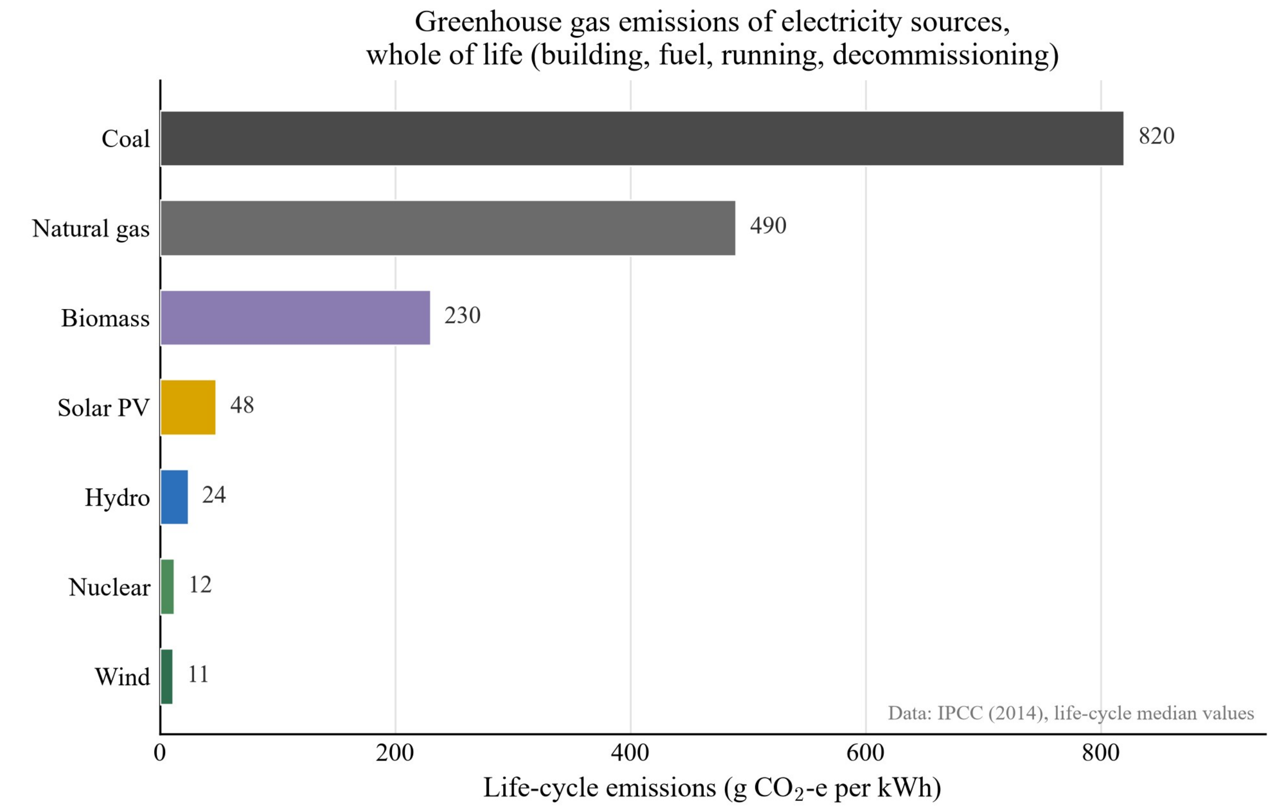
Horizontal bar chart of each sector's share of Australia's gross emissions for the year to September 2023: electricity 28.4 per cent, stationary energy 19.5 per cent, transport 18.6 per cent, agriculture 15.7 per cent, fugitive emissions 9.0 per cent, industrial processes 6.3 per cent, waste 2.7 per cent.

Department of Climate Change, Energy, the Environment and Water, "Quarterly Update of Australia's National Greenhouse Gas Inventory: September 2020", 2020. https://www.dcceew.gov.au/climate-change/publications/national-greenhouse-gas-inventory-quarterly-update-september-2020 — retrieved 2026-08-21.

Department of Climate Change, Energy, the Environment and Water, "Quarterly Update of Australia's National Greenhouse Gas Inventory: September 2023", 2023. https://www.dcceew.gov.au/climate-change/publications/national-greenhouse-gas-inventory-quarterly-update-september-2023 — retrieved 2026-08-21.

Read the two figures together. Electricity is the largest single source in both years, and it is the sector that changed most: 170.4 Mt down to 148.5 Mt. The land use and forestry bar is the sink — it is **negative**, because growing forests and soils take more CO_2 out of the air than they release. The sink grew from −18.8 Mt to −63.9 Mt between the two years, mostly because less native forest was cleared and harvested. Counting the sink, Australia's net emissions in the year to September 2023 were 459.7 Mt, and electricity's share of that net total was 32.3%. Now look at each sector in turn, and at what mitigation means inside it.

Power generation. Burning coal or gas for electricity releases fossil carbon that was stored underground for millions of years, so a coal or gas power station adds CO_2 to the air for as long as it runs. But not all ways of generating electricity are equal. The IPCC's median totals count every emission — building the plant, making the fuel, running it and closing it down — per kilowatt-hour (kWh) delivered:

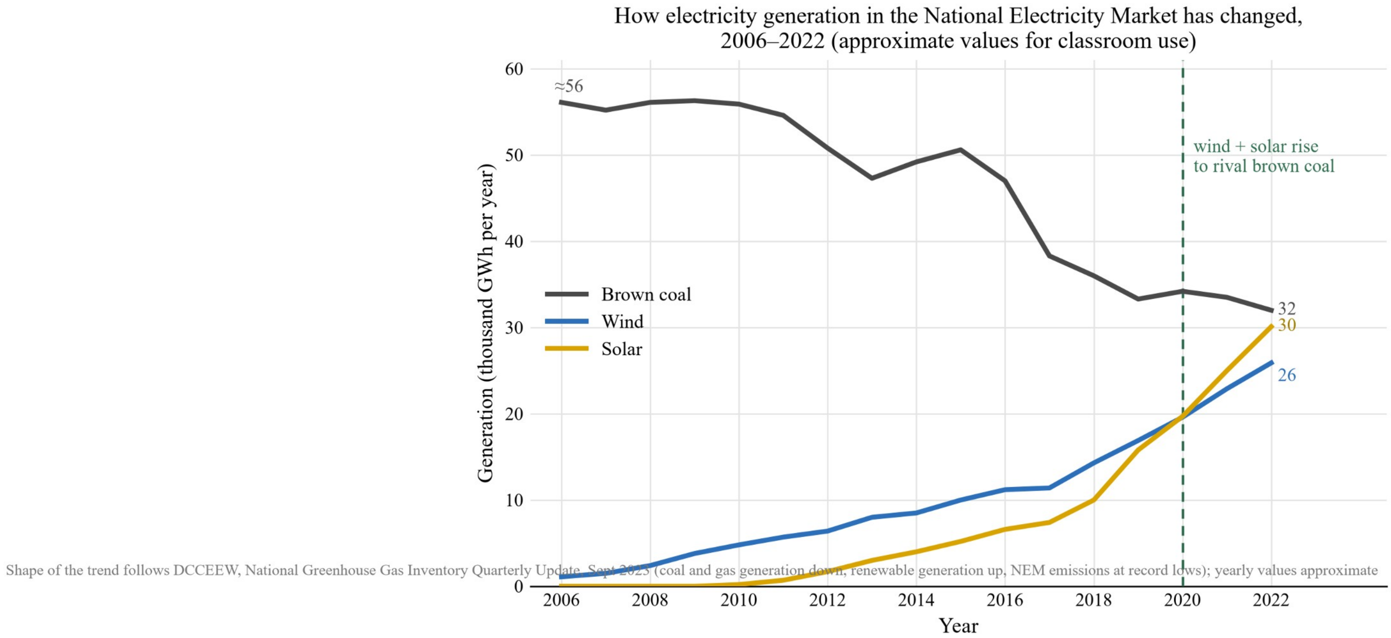


Horizontal bar chart of total emissions counting every stage, in grams of CO2-e per kWh: coal 820, natural gas 490, biomass 230, solar PV 48, hydro 24, nuclear 12, wind 11.

IPCC, "Climate Change 2014: Mitigation of Climate Change — Annex III: Technology-specific cost and performance parameters", 2014. https://www.ipcc.ch/report/ar5/wg3/ — retrieved 2026-08-21.

Coal's total (820 g CO_2-e per kWh, counting every stage) is about **75 times** wind's (11 g), and solar PV (48 g) is about one-seventeenth of coal. That ratio is the whole argument for switching fuels: the same kilowatt-hours can carry roughly a hundredth of the emissions if they come from wind instead of coal. This is also why energy efficiency (Subtopic 14C) is a mitigation tool — every kilowatt-hour not needed is a kilowatt-hour not generated.

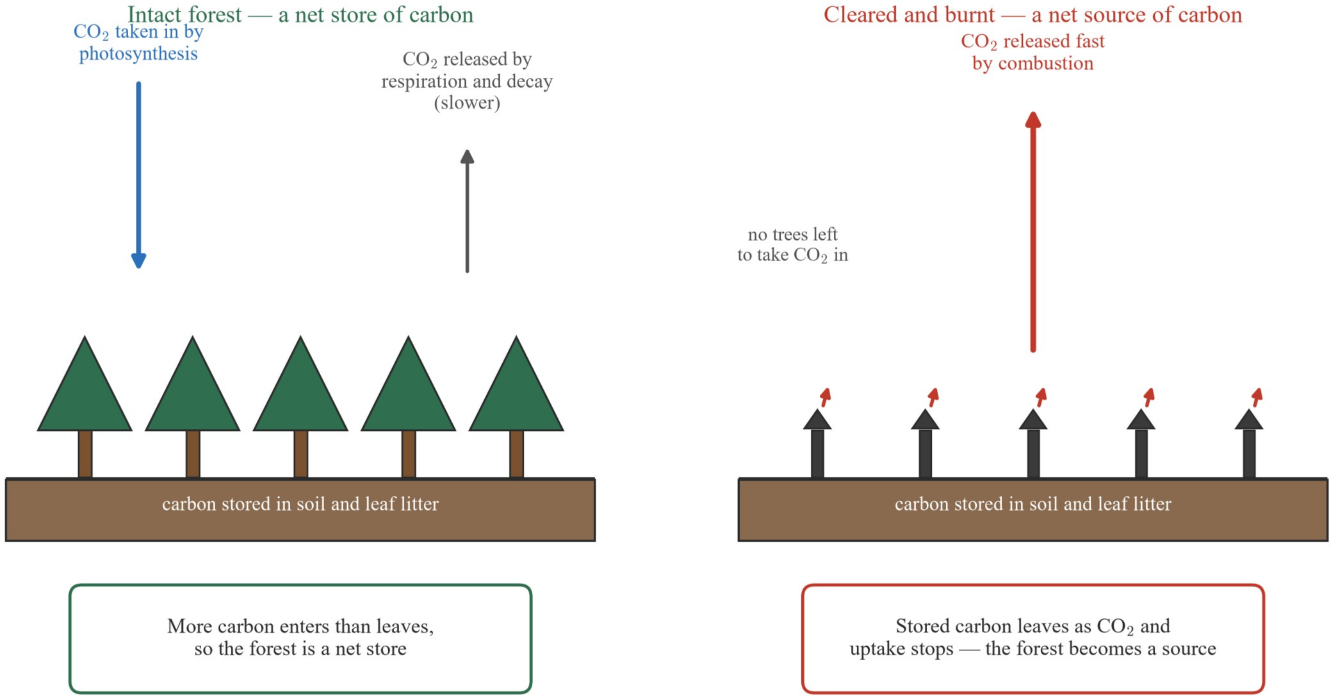
The switch is already visible in Australia's National Electricity Market (NEM), the grid that supplies most of the country's east and south, including Victoria:



Line graph, 2006 to 2022, of approximate annual generation in the National Electricity Market: brown coal falling from about 56 to 32 thousand GWh while wind rises to 26 and solar to 30, with wind and solar together rising to rival brown coal from about 2020. Values are approximate and drawn to the documented trend.

The inventory's own words for the year to September 2023 match the picture: electricity-sector emissions fell 4.9% that year, "reflecting decreases in gas and coal generation of 28.1% and 4.1% respectively and an increase of 15.4% in renewable generation in the National Electricity Market"; over the same year NEM emissions fell 5.3% to "the lowest levels on record", helped by low electricity demand in South Australia, New South Wales and Victoria "due to increasing levels of rooftop solar generation". Over the longer term, electricity-sector emissions are down 29.8% (63.2 Mt) from the peak recorded in the year to June 2009. Victoria fits this story: much of its electricity has long come from Latrobe Valley brown coal, and the rise of wind, solar and rooftop solar in the state is exactly the transition the figure sketches. The mitigation tools in power generation are therefore: generate with wind, solar and hydro instead of coal and gas; waste less electricity through efficiency; and move other fuels onto the cleaner grid (for example, electric vehicles and heat pumps instead of petrol engines and gas burners).

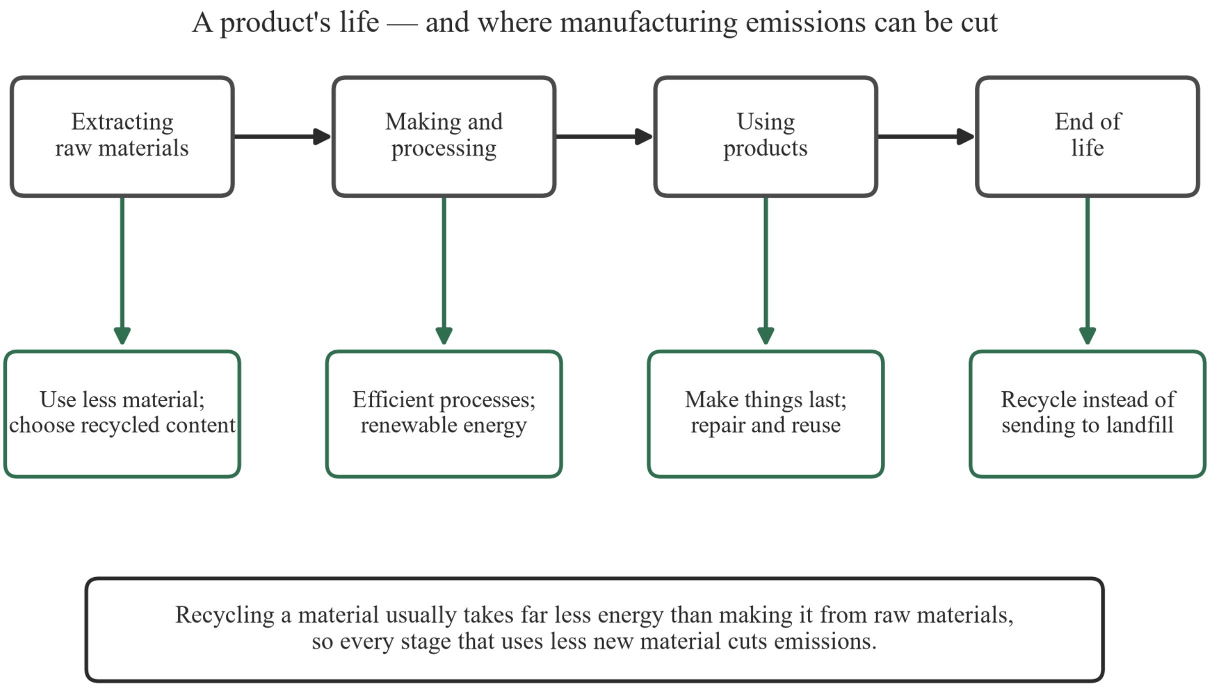
Deforestation and land use. A forest is a carbon store: photosynthesis takes CO_2 in and locks the carbon into wood, leaves and soil. Clear the forest and burn the timber, and the store is emptied back into the air while the taking-in stops:



Two-panel sketch comparing an intact forest, which takes in CO2 by photosynthesis and stores carbon in soil and leaf litter, with a cleared and burnt forest, which releases stored CO2 fast by combustion and has no trees left to take CO2 in.

Deforestation is therefore a double hit on the bath — it opens a new tap (combustion and decay of the cleared trees) and removes part of the drain (the uptake a living forest provides). The reverse is mitigation: protecting existing forest keeps the store locked up; replanting and regrowth rebuild it. Australia's numbers show how much the land sector matters. In the year to September 2020 the land sink was −18.8 Mt; by the year to September 2023 it was −63.9 Mt, and the inventory attributes the change mainly to reduced land clearing and native forest harvesting, together with plantations and carbon stored in soils. The lesson for mitigation is direct: what happens to forests is not a sideshow to the energy story, it is part of the same balance sheet.

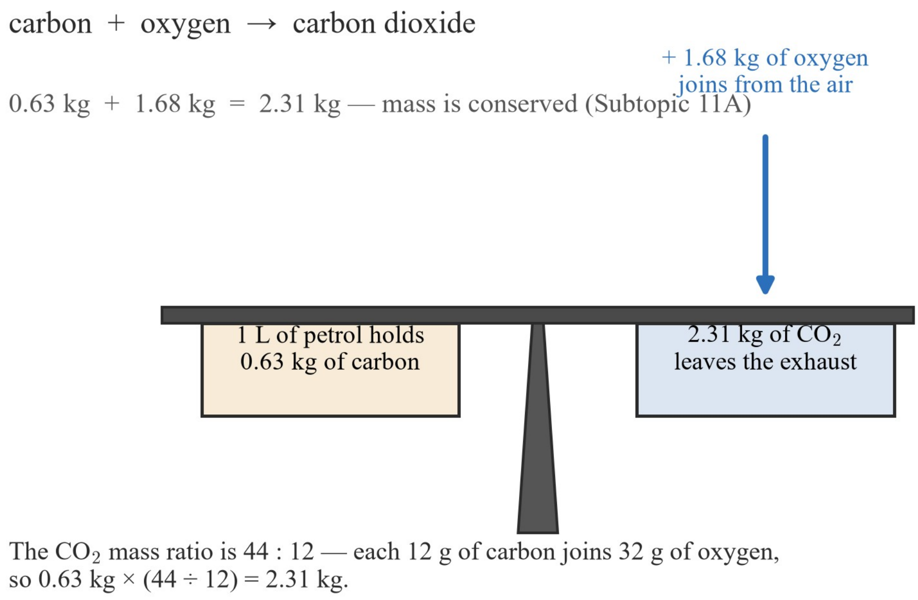
Manufacturing. Making things costs emissions twice over: the energy used in factories (which appears in the electricity and stationary-energy bars), and the chemical processes themselves (the industrial-processes bar — 6.3% of Australia's gross emissions). Materials such as steel, cement and aluminium are among the most energy-hungry products there are. Mitigation can act at every stage of a product's life:



Flow diagram of a product's life: extracting raw materials, making and processing, using products, and end of life; under each stage a green mitigation box — use less material and choose recycled content; efficient processes on renewable energy; make things last, repair and reuse; recycle instead of sending to landfill — and a note that recycling a material usually takes far less energy than making it from raw materials.

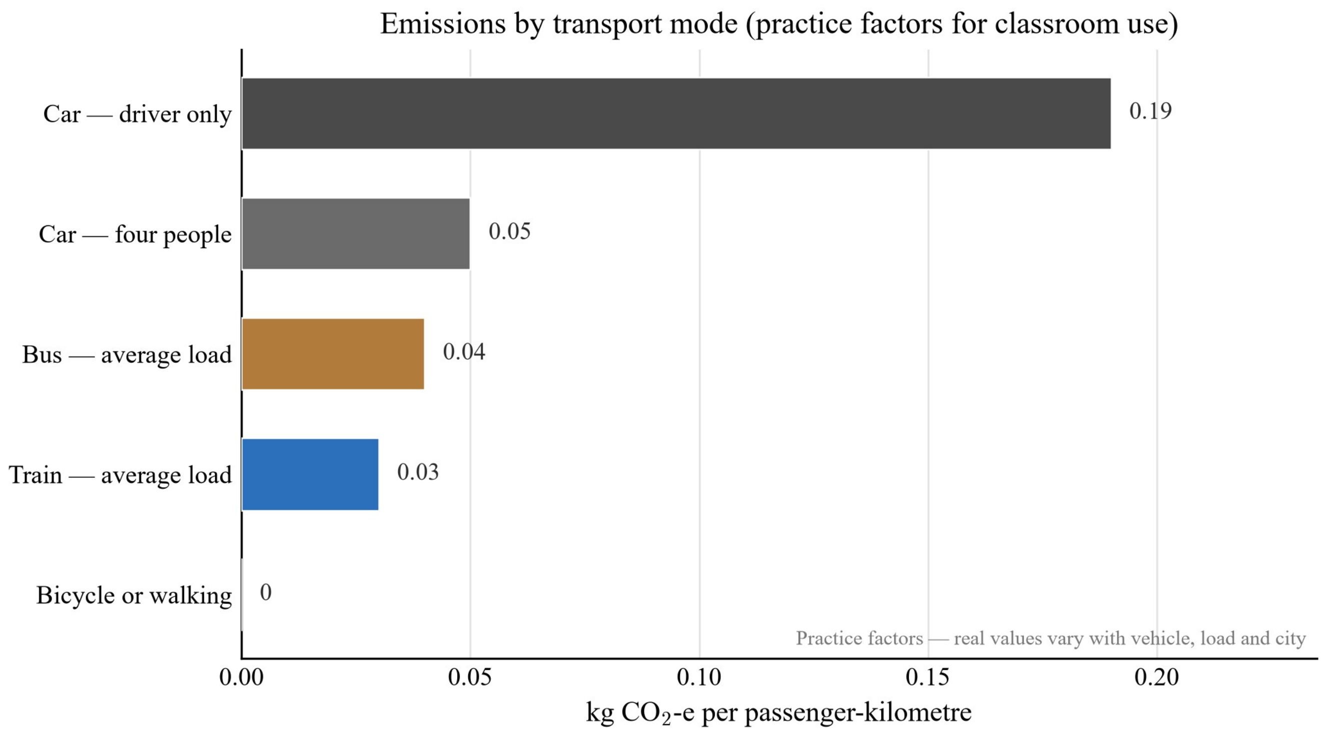
The bottom line of that figure is the strongest single fact in manufacturing mitigation: making a metal from recycled scrap usually takes a small fraction of the energy of making it from ore, so every stage that substitutes recycled material for new material cuts emissions. So do efficient factories run on renewable electricity, products designed to last and be repaired, and recycling at end of life. This is also where "resource consumption" — the last activity the content description names — belongs: buying less, wasting less and reusing more are mitigation, because every product not made is a product whose factory emissions never happen.

Transport. Petrol and diesel engines release the carbon in the fuel as CO_2, and the mass involved surprises most people. One litre of petrol weighs about three quarters of a kilogram, yet burning it produces about 2.3 kg of CO_2. The extra mass is not created — it comes from the air:



Balance sketch showing 1 litre of petrol holding 0.63 kg of carbon joining 1.68 kg of oxygen from the air to give 2.31 kg of CO2 at the exhaust, with the note that the CO2 mass ratio is 44 to 12 because each 12 g of carbon joins 32 g of oxygen.

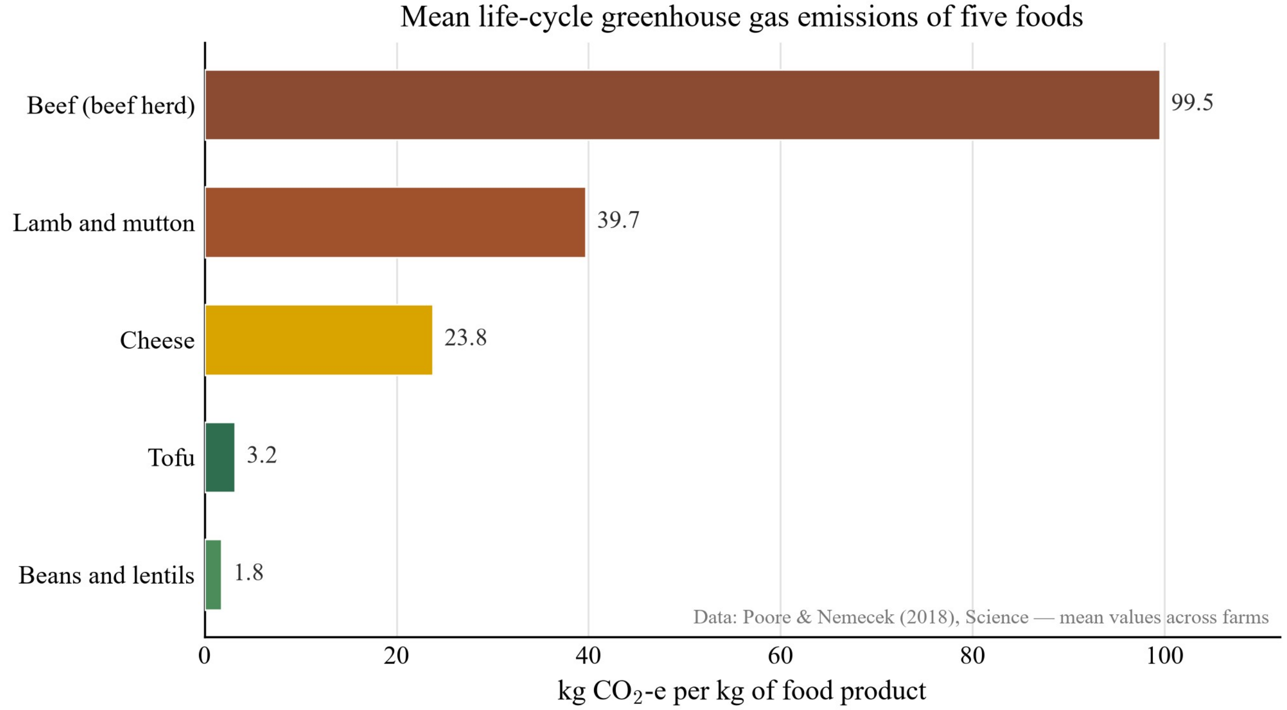
Each carbon atom (mass 12) picks up two oxygen atoms (mass 32) to become a CO_2 molecule (mass 44), so every 1 kg of carbon leaves the exhaust as 44 ÷ 12 ≈ 3.7 kg of CO_2. Mass is conserved (Subtopic 11A); the fuel simply collects oxygen from the air on its way out. The mitigation question in transport is then: how much driving, and by what mode? Practice factors for classroom use look like this:



Horizontal bar chart of practice emission factors in kg CO2-e per passenger-kilometre: car with driver only 0.19, car with four people 0.05, bus at average load 0.04, train at average load 0.03, bicycle or walking 0.

Real values vary with the vehicle, the load and the city, but the pattern is always the same, and it gives four mitigation levers: **share the car** (four people in one car cut the per-person factor to about a quarter), **shift to buses and trains**, **walk or ride for short trips** (zero tailpipe emissions), and **choose efficient or electric vehicles** — remembering that an electric vehicle's emissions then depend on how the electricity is generated, which is the power-generation story above.

Food production and consumption. Food carries very different emissions depending on what it is. Cattle and sheep are ruminants — animals whose stomachs produce methane (CH_4) as they digest grass — and methane traps far more energy per kilogram than CO_2 while it is in the air, so ruminant meat sits at the top of any food emissions chart. Mean values counting every stage from farm to shop, per kilogram of product, from the largest study of its kind look like this:

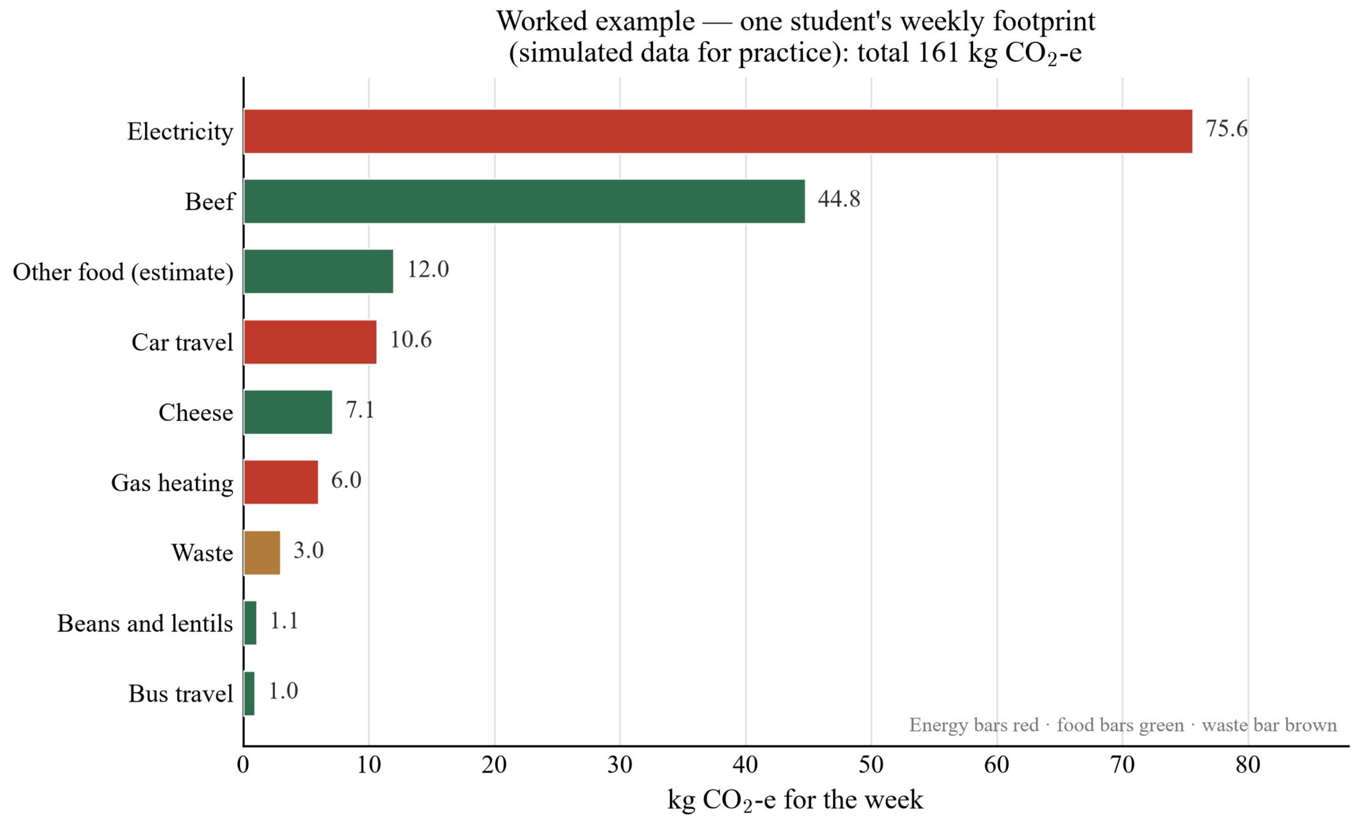


Horizontal bar chart of mean greenhouse gas emissions counting every stage, in kg CO2-e per kg of food product: beef 99.5, lamb and mutton 39.7, cheese 23.8, tofu 3.2, beans and lentils 1.8.

J. Poore and T. Nemecek, "Reducing food's environmental impacts through producers and consumers", Science, vol. 360, 2018; data via Our World in Data, "Environmental impacts of food production". https://ourworldindata.org/environmental-impacts-of-food — retrieved 2026-08-21.

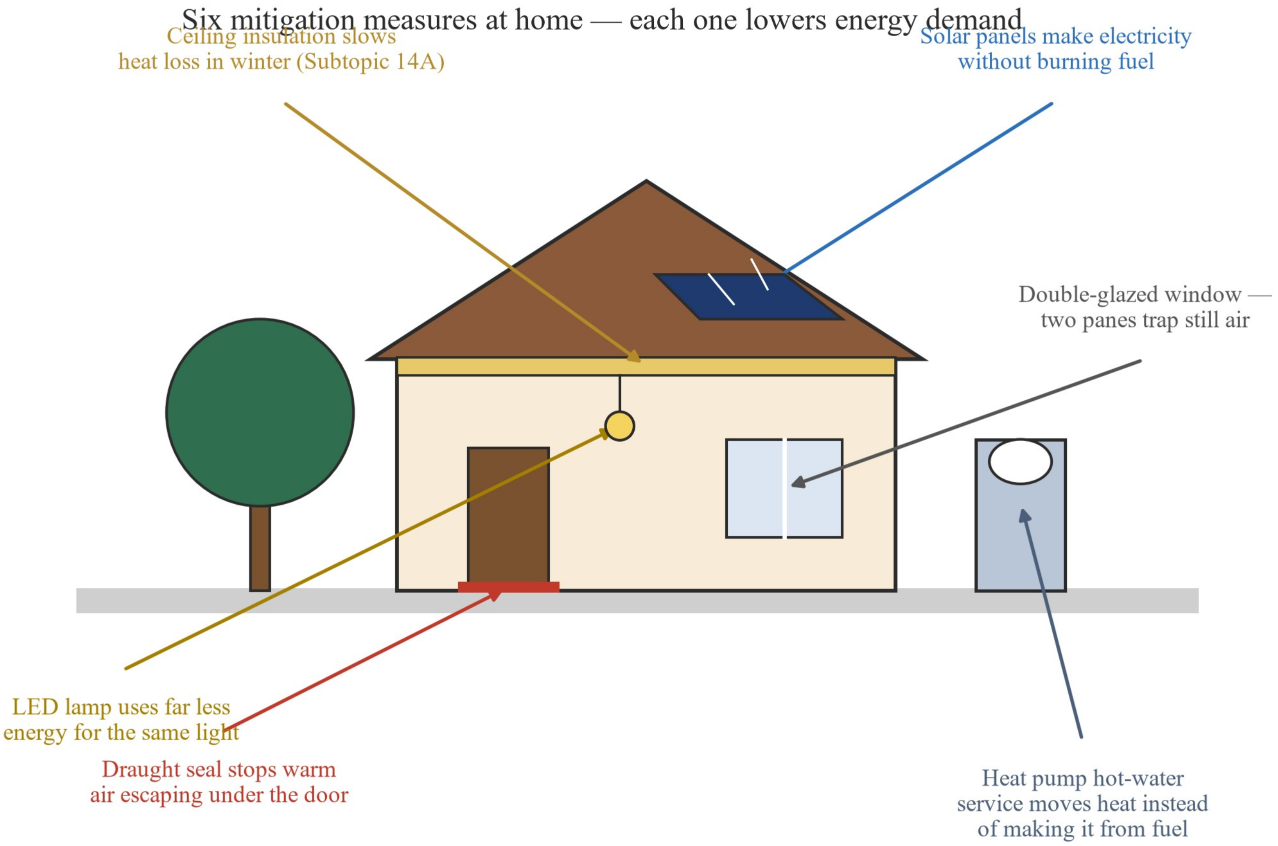
Beef's mean of about 99.5 kg CO_2-e per kg is more than 50 times the 1.8 kg for beans and lentils that supply similar protein. Food mitigation therefore works on three fronts: **what is eaten** (more plant protein, less of the highest-emission animal foods), **what is wasted** (food rotting in landfill releases methane, and every wasted kilogram also wasted the emissions of producing it), and **how farms operate** (better feed, fertiliser and land management cut methane and nitrous oxide). None of this requires every meal to change; like the bath, it is the total flow that matters.

The carbon footprint — adding the flows up. An individual's **carbon footprint** is the total mass of greenhouse gases, as CO_2-e, released by their activities over a period — the flows from power, travel, food and waste added together. Footprints are built by multiplying an **activity** (kWh used, km travelled, kg eaten) by an **emission factor** (kg CO_2-e per unit of activity), exactly as in the worked example below:



Horizontal bar chart of one student's simulated weekly footprint totalling about 161 kg CO2-e: electricity 75.6, beef 44.8, other food 12.0, car travel 10.6, cheese 7.1, gas heating 6.0, waste 3.0, beans and lentils 1.1, bus travel 1.0; energy bars red, food bars green, waste bar brown.

Two patterns in that footprint are typical and useful. First, the biggest bars are usually **energy and ruminant food** — so that is where one change moves the total most. Second, small factors multiplied by large activities still matter: the bus factor is tiny, but 24 km of bus travel still shows up. At home, the same logic gives the familiar set of measures, each of which lowers the energy flowing in:



Cutaway sketch of a house with six labelled mitigation measures: solar panels on the roof, ceiling insulation, a draught seal under the door, a double-glazed window, an LED lamp, and a heat-pump hot-water service outside, plus a shading tree.

Insulation, draught seals and double glazing slow heat loss in winter (Subtopic 14A), so less fuel is burned to keep the house warm; LEDs and heat pumps get the same service from less energy; rooftop solar supplies energy without burning fuel at all.

Comparing fairly: percentage change and per person. Two tools from `VC2M9M05` do most of the work when trends and footprints are compared.

Percentage change measures a trend against its starting value:

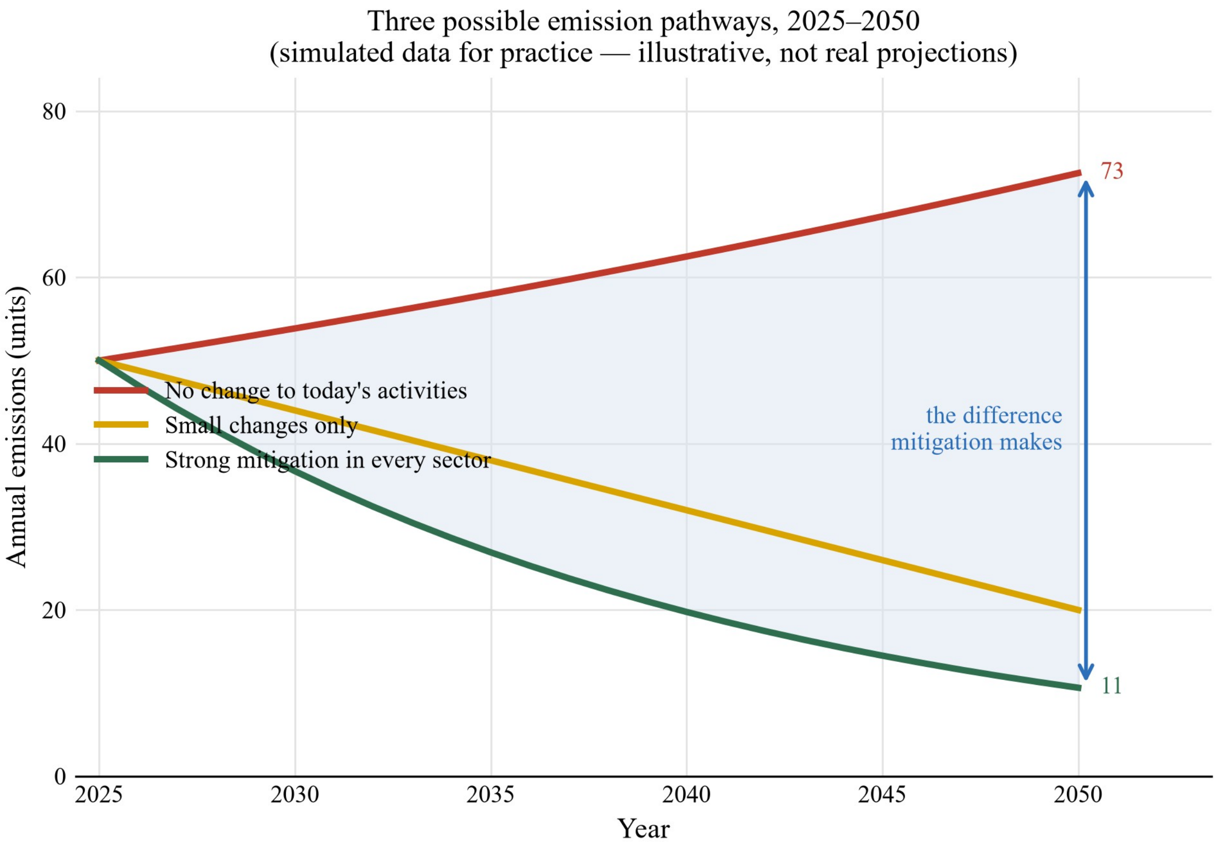
$$\text{percentage change} = \frac{\text{new value} - \text{starting value}}{\text{starting value}} \times 100$$

A fall of 20 Mt matters more when the starting value is 100 Mt (−20%) than when it is 1 000 Mt (−2%). *Per-capita normalisation* divides a total by the number of people it belongs to, because 500 Mt from 25 million people is a very different story from 500 Mt from 100 million people:

$$\text{emissions per person} = \frac{\text{total emissions}}{\text{population}}$$

Since 1 Mt = 1 000 000 t, a total in Mt divided by a population in millions gives tonnes per person directly. Both tools appear in the worked examples and questions below, and both are what “describe trends in patterns of global climate change” means in practice: a trend is not just a direction, it is a size compared with a starting point, and a fair comparison between places is per person, not per country.

Three pathways — mitigation changes the slope. Putting the sectors together, the choice this generation faces can be drawn as pathways of annual emissions:

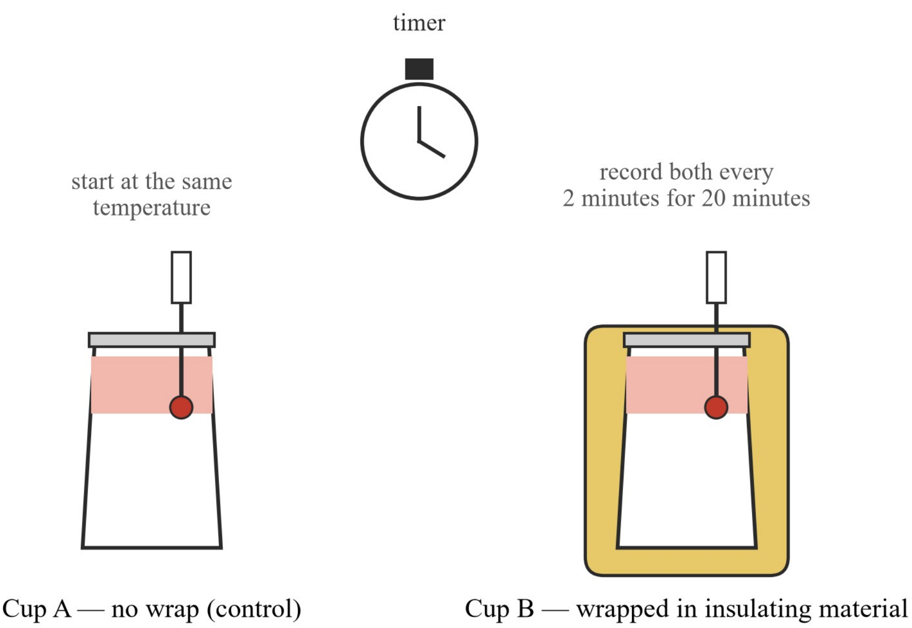


Line graph of three simulated emission pathways from 2025 to 2050: no change to today's activities rising to about 73 units, small changes only falling to 20 units, and strong mitigation in every sector falling to about 11 units, with the shaded gap labelled the difference mitigation makes. Simulated data for practice.

The shaded gap is the point of the whole subtopic: every measure above — cleaner electricity, protected and replanted forest, recycled materials, shared and active transport, lower-emission food and less waste — widens that gap. And remember the bath: even the strongest pathway still adds some emissions in 2050, so the level only steadies once what is added is matched by what is removed. That is why mitigation includes growing the sinks, not just cutting the sources.

Activities

Activity 1 — Modelling home insulation (links to 3A and 4A). Set up the two cups shown below, each with the same volume of warm (not boiling) water, the same lid and the same starting temperature; wrap one cup in an insulating material and leave the other bare as the control. Record both temperatures every 2 minutes for 20 minutes.



The wrapped cup models an insulated house; the bare cup models an uninsulated one.

Sketch of the apparatus: two cups of warm water, each with a lid and a thermometer, one bare as the control and one wrapped in insulating material, with a timer; the wrapped cup models an insulated house and the bare cup an uninsulated one.

Plot both cooling curves on one set of axes (time on the horizontal axis, temperature on the vertical). Identify the independent variable (the wrap), the dependent variable (the temperature fall) and two control variables you kept the same. Which cup models the insulated house? Explain, in one or two sentences, why a house that loses heat more slowly needs less energy to keep warm, and how that connects an insulation batt to the electricity bar of a carbon footprint. Take care with warm water and wipe up spills at once.

Activity 2 — A week in your own footprint (links to 4B and E06). Using the practice factors below, estimate one week of your own footprint. Keep a simple log for seven days: kWh of electricity your share of the house used (your meter reading or an estimate), km travelled by car, bus and train, MJ of gas heating, and kg of beef, cheese and beans or lentils eaten.

Activity	Practice factor
Electricity	0.90 kg CO_2-e per kWh
Reticulated gas	0.05 kg CO_2-e per MJ
Car, driver only	0.19 kg CO_2-e per km
Bus	0.04 kg CO_2-e per km
Train	0.03 kg CO_2-e per km
Beef	99.5 kg CO_2-e per kg
Cheese	23.8 kg CO_2-e per kg
Beans and lentils	1.8 kg CO_2-e per kg

(Practice factors for classroom use — energy and travel factors are approximate Australian values, food factors are the Poore & Nemecek means shown in the food figure.)

Multiply each activity by its factor, list the bars from largest to smallest, and total them. Then propose **two** strategies that would cut your largest bars, and for each one estimate the new total. Compare your two strategies: which single change moved the total most, and why?

Worked examples

Emission factors used in these examples are the practice factors of Activity 2; inventory values are the official figures quoted in the Theory.

Example 1 — scaffolded

The electricity sector released 170.36 Mt CO_2-e in the year to September 2020 and 148.5 Mt in the year to September 2023. Calculate the percentage change in electricity-sector emissions over this period, and state what the sign tells you.

Working	Comment
change = 148.5 − 170.36 = −21.86 Mt	New value minus starting value; the negative sign means a fall.
percentage change = (−21.86 ÷ 170.36) × 100	Percentage change is always measured against the *starting* value (VC2M9M05).
= −12.8% (3 s.f.)	A fall of about 13% in three years.

Electricity-sector emissions fell by about **12.8%** between the two inventory years — the fastest-falling sector in the inventory, and the reason electricity's share of the total shrank between the two sector figures.

Example 2 — scaffolded

One student logs a week of activity: 84 kWh of electricity, 120 MJ of gas heating, 56 km of car travel as the only passenger, 24 km of bus travel, 0.45 kg of beef, 0.30 kg of cheese, 0.60 kg of beans and lentils, 12.0 kg CO_2-e of other food (estimate) and 3.0 kg CO_2-e of waste. Build the weekly footprint.

Working	Comment
Electricity: 84 × 0.90 = 75.6 kg	Activity × emission factor, one product at a time.
Gas: 120 × 0.05 = 6.0 kg	Same method, different factor.
Car: 56 × 0.19 = 10.6 kg	The driver-only factor applies.
Bus: 24 × 0.04 = 1.0 kg	Rounded from 0.96 kg.
Beef: 0.45 × 99.5 = 44.8 kg	Half a kilogram of beef carries a very large factor.
Cheese: 0.30 × 23.8 = 7.1 kg	
Beans and lentils: 0.60 × 1.8 = 1.1 kg	
Other food 12.0 kg + waste 3.0 kg	Given as estimates.
Total = 75.6 + 6.0 + 10.6 + 1.0 + 44.8 + 7.1 + 1.1 + 12.0 + 3.0 = 161.2 kg	Add every bar; this is the footprint figure's total, ≈161 kg CO_2-e.

The weekly footprint is about **161 kg CO_2-e** — roughly 8.4 t per year if every week looked the same. As in the footprint figure, the two largest bars are electricity and beef, so those are the bars where one change would matter most.

Example 3 — unscaffolded

A student makes one 15 km trip. Compare the trip's emissions for three choices: driving alone, taking a bus at average load, and a car shared by four people. How much CO_2-e does the bus save compared with driving alone?

Driving alone: 15 × 0.19 = **2.85 kg CO_2-e**.

Bus: 15 × 0.04 = **0.60 kg CO_2-e**.

Car shared four ways: 15 × 0.05 = **0.75 kg CO_2-e**.

The bus saves 2.85 − 0.60 = **2.25 kg CO_2-e** per trip compared with driving alone — and the shared car, at 0.75 kg, is nearly as good as the bus on this trip, which is the sharing lever in the transport figure. Done five days a week, the bus choice saves about 11 kg CO_2-e a week.

Example 4 — unscaffolded

Two countries (simulated data for practice). Country A emits 480 Mt CO_2-e in a year and has 24 million people. Country B emits 900 Mt CO_2-e and has 60 million people. Which country's *average person* is responsible for more emissions, and by how much?

Because 1 Mt = 1 000 000 t, dividing Mt by millions of people gives tonnes per person:

Country A: 480 ÷ 24 = **20 t per person**.

Country B: 900 ÷ 60 = **15 t per person**.

Country B's **total** is nearly double Country A's, but its average person is responsible for less: 20 t versus 15 t, a difference of **5 t per person**. Totals tell you about a country's share of the global flow; per-person values tell you about the pattern of life that produces it. Both are needed to describe trends fairly, and the same normalisation is how Australia's ≈17–18 t per person is compared with other countries' patterns of life.

Practice questions

Scaffolded questions

Question 1 (2 marks) Look at the cause-chain figure. (a) Name the two greenhouse gases shown in the greenhouse-gas box besides CO_2. (b) State where the dashed mitigation line cuts the chain.

Question 2 (3 marks) Look at the bath figure. A news headline reads "Emissions fell again this year". Using the ideas of a rate and a level, explain why this headline does **not** mean the amount of CO_2 in the atmosphere fell.

Question 3 (3 marks) Look at the 2020 sector figure (Mt). (a) Name the largest source sector and give its value. (b) Name the sink sector and give its value, and say in one sentence what a negative bar means.

Question 4 (4 marks) Look at the electricity intensity figure. (a) Which source has the highest emissions per kWh when every stage is counted, and what is its value? (b) Show, as a ratio, how many times larger coal's emissions are than wind's. (c) In one sentence, say what this ratio means for choosing how to generate electricity.

Question 5 (3 marks) Using the food figure's mean values, calculate the emissions of 0.50 kg of cheese and of 0.50 kg of tofu, and find the difference between them.

Question 6 (3 marks) Look at the petrol-mass figure. One litre of petrol holds 0.63 kg of carbon, yet burning it releases 2.31 kg of CO_2. (a) Explain where the extra mass comes from. (b) Show the 44 : 12 ratio as a multiplication that turns 0.63 kg of carbon into 2.31 kg of CO_2.

Unscaffolded questions

Question 7 (3 marks) Stationary energy (excluding electricity) released 101.83 Mt CO_2-e in the year to September 2020 and 102.2 Mt in the year to September 2023. Calculate the percentage change, and compare it with the electricity sector's −12.8% from Example 1.

Question 8 (3 marks) Transport released 89.83 Mt CO_2-e in the year to September 2020 and 97.3 Mt in the year to September 2023. Calculate the percentage change, and state whether transport was moving with or against the mitigation direction over these years.

Question 9 (3 marks) Australia's net emissions in the year to September 2023 were 459.7 Mt. Taking the population as 26 million, calculate the emissions per person in tonnes, and explain in one sentence why this per-person value is more useful than the total when comparing countries' patterns of life.

Question 10 (4 marks) In the year to September 2020, agriculture released 72.04 Mt out of a gross total of 528.9 Mt; in the year to September 2023 it released 82.1 Mt out of a gross total of 523.8 Mt. (a) Show that agriculture's share of the gross total rose from about 13.6% to about 15.7%. (b) Agriculture's emissions rose by only about 10 Mt, yet its share rose by more than two percentage points. Explain why, naming which other sector's fall made this happen.

Question 11 (4 marks) A student travels 10 km to school and 10 km home, five days a week (100 km per week). (a) Calculate the weekly emissions if every kilometre is driven, as the only passenger. (b) Calculate the weekly emissions if every kilometre is by train. (c) Find the weekly saving from switching, and the saving over a 40-week school year.

Question 12 (4 marks) In Example 2's footprint (total 161.2 kg CO_2-e per week), the student replaces half of the beef (0.225 kg) with the same mass of beans and lentils. (a) Calculate the new weekly total. (b) Calculate the weekly saving and express it as a percentage of the original total.

Question 13 (3 marks) The inventory reports that NEM emissions in the year to September 2023 were the lowest on record. Give **two** distinct reasons from the inventory's own account (quoted in the Theory) for that record low.

Question 14 (4 marks) In Activity 1, the wrapped cup is the model of an insulated house. (a) Explain why the wrapped cup's water cools more slowly. (b) Name two control variables that must be the same in both cups for the comparison to be fair. (c) Connect the model to mitigation in two sentences: why does a better-insulated house lead to lower greenhouse gas emissions?

Question 15 (3 marks) In the pathways figure, the strong-mitigation pathway still releases about 11 units of emissions per year in 2050. Using the bath figure, explain whether the CO_2 level in the air is falling on that pathway, and state the condition under which the level would stop rising.

Question 16 (4 marks) Look at the manufacturing figure. (a) Choose two stages of the product's life and, for each, give the mitigation measure shown and one sentence on why it cuts emissions. (b) Explain in one sentence why recycling a metal usually cuts emissions compared with making it from ore.

Answers

Question 1 (a) CH_4 (methane) and N_2O (nitrous oxide); (b) at the sources — it crosses every flow from the six activities into the greenhouse-gas box. **Question 2** Emissions are the rate in; the level falls only when the rate in is smaller than the rate out — see solution. **Question 3** (a) electricity, 170.4 Mt; (b) land use and forestry, −18.8 Mt; the negative bar means the land took more CO_2 out of the air than it added. **Question 4** (a) coal, 820 g CO_2-e per kWh; (b) 820 ÷ 11 ≈ 75; (c) see solution. **Question 5** cheese 11.9 kg; tofu 1.6 kg; difference 10.3 kg. **Question 6** (a) oxygen from the air joins the carbon; (b) 0.63 × (44 ÷ 12) = 2.31. **Question 7** +0.4% (a rise), against electricity's −12.8% (a fall). **Question 8** +8.3%; against the mitigation direction (emissions grew). **Question 9** 17.7 t per person; see solution. **Question 10** (a) 13.6% and 15.7%; (b) electricity's fall shrank the total. **Question 11** (a) 19 kg; (b) 3.0 kg; (c) 16 kg per week; 640 kg per 40-week year. **Question 12** (a) ≈139 kg; (b) ≈22 kg, about 14%. **Question 13** coal and gas generation down (−4.1%, −28.1%) with renewable generation up (+15.4%); low demand in SA, NSW and Victoria from rooftop solar. **Question 14** (a) the wrap slows heat loss to the surroundings; (b) any two of: same volume, same starting temperature, same cup and lid, same room; (c) see solution. **Question 15** No — 11 units are still added each year, so the level still rises (more slowly); it stops rising only at net zero, when adding equals removing. **Question 16** (a) any two stages with their measures; (b) recycling uses far less energy than extracting and refining from ore.

Fully-worked solutions

Question 1 (a) The box reads "CO_2, CH_4, N_2O", so besides CO_2 the two gases are **methane (CH_4)** and **nitrous oxide (N_2O)**. *(1 mark)* (b) The dashed mitigation line crosses all six arrows **at the sources** — between the activity boxes and the greenhouse-gas box — meaning mitigation acts by shrinking the flows each activity sends into the air (and, for forests, by enlarging the sink). *(1 mark)*

Question 2 Emissions are the *rate* at which CO_2 is added (the tap), while the CO_2 in the atmosphere is the *level* (the water in the bath). The level falls only when the inflow is smaller than the outflow to sinks. "Emissions fell" means the tap was turned down; if the inflow is still bigger than the outflow, the level keeps rising — more slowly, but rising. So the headline reports a smaller rate, not a falling level. *(3 marks: rate/level identified, 1; level falls only when inflow < outflow, 1; applied to the headline, 1)*

Question 3 (a) The largest source sector is **electricity at 170.4 Mt CO_2-e**. *(1 mark)* (b) The sink sector is **land use and forestry at −18.8 Mt**. A negative bar means that sector **removed more CO_2 from the air than it released** — the land was a net store of carbon that year. *(2 marks: value, 1; meaning of negative bar, 1)*

Question 4 (a) **Coal, 820 g CO_2-e per kWh.** *(1 mark)* (b) 820 ÷ 11 ≈ **75** — coal's total is about 75 times wind's. *(2 marks: correct ratio, 1; value ≈75, 1)* (c) The same electricity can be generated with roughly a hundredth of the emissions (counting every stage) by choosing wind over coal, so switching generation from coal to wind, solar and hydro is one of the largest mitigation levers available. *(1 mark)*

Question 5 Cheese: 0.50 × 23.8 = **11.9 kg CO_2-e**. Tofu: 0.50 × 3.2 = **1.6 kg CO_2-e**. Difference: 11.9 − 1.6 = **10.3 kg CO_2-e** — the same half-kilogram of protein food carries about 10 kg more emissions as cheese than as tofu. *(3 marks: each value, 1; difference, 1)*

Question 6 (a) The extra mass comes from **oxygen in the air**. Burning joins each carbon atom (mass 12) to two oxygen atoms (mass 32); the carbon was in the fuel, but most of the mass of the CO_2 that leaves the exhaust was collected from the air during combustion. Mass is conserved — nothing is created. *(2 marks)* (b) 0.63 × (44 ÷ 12) = 0.63 × 3.67 ≈ **2.31 kg CO_2**. *(1 mark)*

Question 7 change = 102.2 − 101.83 = +0.37 Mt. Percentage change = (0.37 ÷ 101.83) × 100 ≈ **+0.4%**. Stationary energy was essentially flat (a tiny rise), while electricity fell by 12.8% — the two energy sectors moved in opposite directions over these years. *(3 marks: change, 1; percentage, 1; comparison, 1)*

Question 8 change = 97.3 − 89.83 = +7.47 Mt. Percentage change = (7.47 ÷ 89.83) × 100 ≈ **+8.3%**. Transport emissions **grew**, so transport was moving **against** the mitigation direction over these years — the inventory's +4.5% for the single year to September 2023 reflects the same trend, as travel returned after the pandemic years. *(3 marks: change, 1; percentage, 1; direction, 1)*

Question 9 459.7 Mt ÷ 26 million people: since 1 Mt = 1 000 000 t, this is 459.7 ÷ 26 ≈ **17.7 t per person**. The total mostly reflects how many people a country has as well as how they live; the per-person value strips out population size, so it compares patterns of life — energy mix, transport, diet — which is what mitigation actually acts on. *(3 marks: value, 2; explanation, 1)*

Question 10 (a) 2020: (72.04 ÷ 528.9) × 100 ≈ **13.6%**. 2023: (82.1 ÷ 523.8) × 100 ≈ **15.7%**. *(2 marks)* (b) A share is a fraction of a total. Agriculture's own emissions rose, but the gross total *shrank* slightly (528.9 → 523.8 Mt) because **electricity fell by about 22 Mt**, so agriculture's slice of a slightly smaller pie grew faster than its own 10 Mt rise alone would suggest. A sector's share can rise even when the sector is changing only a little, if other sectors fall. *(2 marks)*

Question 11 (a) 100 km × 0.19 = **19 kg CO_2-e** per week. *(1 mark)* (b) 100 km × 0.03 = **3.0 kg CO_2-e** per week. *(1 mark)* (c) Saving = 19 − 3.0 = **16 kg per week**; over 40 weeks, 16 × 40 = **640 kg CO_2-e** — more than the whole weekly footprint of Example 2, saved by one mode switch. *(2 marks)*

Question 12 (a) Original beef bar: 0.45 × 99.5 = 44.775 kg. New beef: 0.225 × 99.5 = 22.39 kg. Added beans and lentils: 0.225 × 1.8 = 0.41 kg. New total = 161.2 − 44.775 + 22.39 + 0.41 ≈ **139 kg CO_2-e**. *(2 marks)* (b) Saving = 161.2 − 139.2 = 22.0 kg. As a percentage of the original: (22.0 ÷ 161.2) × 100 ≈ **14%**. Halving one food item cuts the whole weekly footprint by about a seventh — the food lever is that powerful because beef's factor is so large. *(2 marks)*

Question 13 Any two of: (1) coal generation fell 4.1% and gas generation fell 28.1% while renewable generation rose 15.4% in the NEM — the mix shifted towards low-emission sources; (2) electricity demand was low in South Australia, New South Wales and Victoria because rooftop solar kept rising, so less grid electricity (and less coal and gas burning) was needed. *(3 marks: one reason, 2; second reason, 1)*

Question 14 (a) The insulating wrap slows the transfer of thermal energy from the warm water to the cooler surroundings, so the wrapped cup's temperature falls more slowly. *(1 mark)* (b) Any two of: the same volume of water, the same starting temperature, the same cup and lid, the same room (same surrounding temperature), readings at the same times. *(1 mark)* (c) A house that loses heat more slowly needs less heating to stay warm, so less gas is burned (or less electricity drawn) for the same comfort; with today's energy mix that means less CO_2 released — the insulation batt is a mitigation measure because it shrinks the energy flow in the footprint. *(2 marks)*

Question 15 No, the level is **not** falling. The pathway still adds about 11 units per year in 2050, and the bath's level falls only when the inflow is smaller than the outflow; with 11 units still flowing in, the level keeps rising, just more slowly than on the other pathways. The level would stop rising at **net zero** — when emissions (adding) equal removal by sinks (removing) — and would fall only if removal exceeded adding. *(3 marks: level still rising, 1; reason via inflow/outflow, 1; net zero condition, 1)*

Question 16 (a) Any two, for example: *Extracting raw materials* — use less material and choose recycled content, which cuts the emissions of extracting and refining new ore; *Making and processing* — run efficient processes on renewable energy, which cuts the factory's fuel and electricity emissions; *Using products* — make things last and repair them, so fewer replacements are manufactured; *End of life* — recycle instead of landfill, so the material re-enters making instead of being dug up again. *(2 marks: one per stage-measure pair with a reason)* (b) The metal already exists in scrap, so recycling skips the most energy-hungry steps (mining, refining and first smelting); less energy means less fuel burned and lower emissions. *(2 marks)*