REVISION GUIDE

Energy *flows*, matter goes round

Transfers of energy and matter

Sunlight comes into an ecosystem and leaves as heat; the carbon, nitrogen and every other element are used again and again. Build a food web and pull a species out of it, follow 10,000 kJ of grass down to an owl, and plot seventy years of carbon dioxide over Hawaii to read the Earth breathing in and out.

9 chapters · a dry lab

The interactive guide, with every animation:

biologybybradford.com/guides/ib-biology-c4-2-transfers-of-energy-and-matter

Contents

01	Light in, heat out	4
02	Make it or take it	6
03	Who eats whom	8
04	Nothing goes to waste	11
05	Where the energy goes	13
06	Drawn to scale	18
07	What is left to grow	20
08	Round and round	22
09	The Earth breathing	26
	Key terms	28
	Dry lab: The Keeling curve	29
	Check yourself	30
	Answers	31

By the end you can

- [ ] Describe an ecosystem as an open system that energy and matter enter and leave, and a closed system as one only energy crosses C4.2.1
- [ ] Explain why sunlight sustains most ecosystems, and name ecosystems it does not C4.2.2
- [ ] Explain how chemical energy passes along a food chain as each consumer feeds C4.2.3
- [ ] Construct food chains and food webs, with arrows the way energy and biomass move C4.2.4
- [ ] Explain how decomposers get their energy from dead organisms, dead parts and faeces C4.2.5
- [ ] Describe autotrophs as making carbon compounds from inorganic substances with an external energy source C4.2.6
- [ ] Compare photoautotrophs, which use light, with chemoautotrophs such as iron-oxidising bacteria C4.2.7
- [ ] Describe heterotrophs as building their carbon compounds from those of other organisms C4.2.8
- [ ] Explain that autotrophs and heterotrophs both release energy by cell respiration C4.2.9
- [ ] Place organisms in trophic levels, including an organism that feeds at more than one C4.2.10
- [ ] Construct a pyramid of energy to scale from data for a real ecosystem C4.2.11
- [ ] Explain why less energy is available at each stage of a food chain C4.2.12
- [ ] Explain heat loss from respiration, in making ATP and in using it C4.2.13
- [ ] Explain why energy losses limit the number of trophic levels C4.2.14
- [ ] Describe primary production in g m^{-2} a year and compare biomes C4.2.15
- [ ] Explain why secondary production is lower than primary production C4.2.16
- [ ] Construct a carbon cycle diagram with photosynthesis, feeding and respiration C4.2.17
- [ ] Decide whether an ecosystem is a carbon sink or a carbon source C4.2.18
- [ ] Explain the release of carbon dioxide by combustion of biomass, peat, coal, oil and gas C4.2.19
- [ ] Analyse the yearly wiggle and the long rise of the Keeling curve C4.2.20
- [ ] Explain how respiration depends on photosynthesis for oxygen and photosynthesis on respiration for carbon dioxide C4.2.21
- [ ] Explain that every element living things use is recycled, with decomposers as the key C4.2.22

Tick each one when you can do it without the book.

C4.2.1 C4.2.2 ECOSYSTEMS AS OPEN SYSTEMS IN WHICH BOTH ENERGY AND MATTER CAN ENTER AND EXIT SUNLIGHT AS THE PRINCIPAL SOURCE OF ENERGY THAT SUSTAINS MOST ECOSYSTEMS

01 Light in, heat *out*

Draw a line round a wood, a pond or a stretch of seabed and call it an **ecosystem**. Two kinds of thing cross that line. Energy arrives, mostly as sunlight, and leaves as heat. Matter crosses too: rain falls in and streams carry water and dissolved minerals out, leaves blow across, gases mix with the air above, and animals walk, swim or fly in and out. A system that both energy and matter can cross is an **open system**.

Seal some soil, water, plants and small animals in a glass jar, a **mesocosm**, and you have the nearest thing to a **closed system**: light still shines in and heat still escapes through the glass, but no matter gets in or out. Whatever the organisms in the jar need, they must recycle.

For almost every ecosystem on Earth the energy starts as **sunlight**, caught by plants, algae and cyanobacteria in photosynthesis. The exceptions are places light never reaches. In a cave the animals live on what washes or falls in from the lit world outside. In the deep ocean below about 200 m there is too little light to photosynthesise: most life there feeds on a slow rain of dead matter from above, and around hydrothermal vents whole communities run on bacteria that get their energy from chemicals such as hydrogen sulfide.

KEY POINTS

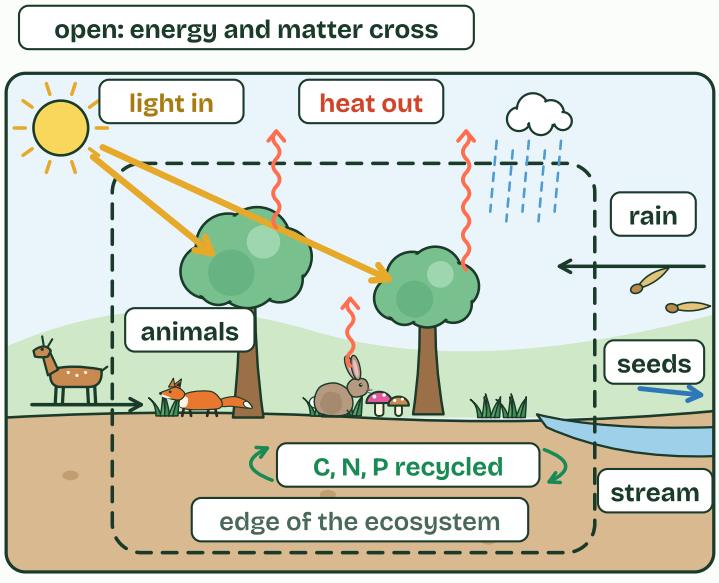
- Open system: energy and matter both cross the boundary. Most ecosystems are open.
- Closed system: only energy crosses. A sealed mesocosm comes close.
- Sunlight powers most ecosystems; caves and the deep sea are the exceptions.

KEY TERMS

ecosystem
A community of organisms together with the non-living surroundings they interact with.

open system
A system that exchanges both energy and matter with its surroundings. Almost every ecosystem is open.

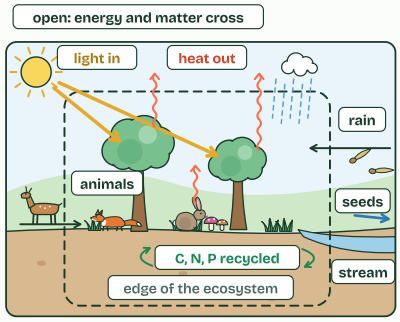
closed system
A system that exchanges energy with its surroundings but not matter.



SWITCH IT

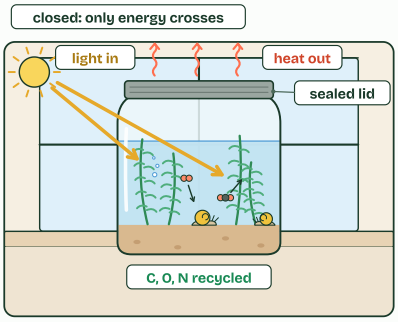
2 SETTINGS

1



A wood: open

2



A sealed jar: closed

NATURE OF SCIENCE

"Sunlight sustains ecosystems" works like a law in science: a generalisation that describes a pattern seen again and again, without explaining it. Like a law, it holds until an exception turns up. When vent communities were found on the Galápagos Rift in 1977, thriving in total darkness, the rule had to be narrowed to "most ecosystems".

PREDICT

A student seals a jar with pond water, waterweed and snails and keeps it on a sunny windowsill. What must cross the glass for the jar to keep going for years?

(A) Carbon dioxide, because the waterweed will soon use up all the carbon dioxide the jar started with

(B) Light in and heat out, because only energy has to cross: the matter inside is recycled

(C) Nothing at all, because a sealed jar holds all the energy and matter its organisms will ever need

Decide before you look. Answer on page 31.

C4.2.6 C4.2.7 C4.2.8 C4.2.9 AUTOTROPHS AS ORGANISMS THAT USE EXTERNAL ENERGY SOURCES TO SYNTHESIZE CARBON COMPOUNDS FROM SIMPLE INORGANIC SUBSTANCES USE OF LIGHT AS THE EXTERNAL ENERGY SOURCE IN PHOTOAUTOTROPHS AND OXIDATION REACTIONS AS THE ENERGY SOURCE IN CHEMOAUTOTROPHS HETEROTROPHS AS ORGANISMS THAT USE CARBON COMPOUNDS OBTAINED FROM OTHER ORGANISMS TO SYNTHESIZE THE CARBON COMPOUNDS THAT THEY REQUIRE RELEASE OF ENERGY IN BOTH AUTOTROPHS AND HETEROTROPHS BY OXIDATION OF CARBON COMPOUNDS IN CELL RESPIRATION

02 Make it or *take* it

Every organism is built of carbon compounds: carbohydrates, lipids, proteins and nucleic acids. There are two ways to get them. An **autotroph** makes them from simple inorganic substances: carbon dioxide, water, and ions such as nitrate and phosphate. Fixing carbon and building macromolecules are anabolic reactions, and they need energy, so an autotroph needs an outside energy source.

For a **photoautotroph** (plants, algae, cyanobacteria) that source is light. For a **chemoautotroph** it is an oxidation reaction: oxidising an inorganic substance releases energy. Iron-oxidising bacteria, found in iron-rich streams and mine water, oxidise iron(II) ions (Fe^{2+}) to iron(III) (Fe^{3+}), which shows as orange rust on the stones, and use the energy to fix carbon dioxide.

A **heterotroph** takes its carbon compounds from other organisms. It digests their proteins, polysaccharides and nucleic acids into small molecules, inside its gut (animals) or outside its cells (fungi and many bacteria), absorbs them and then **assimilates** them: builds them into its own proteins, its own glycogen, its own DNA.

Whichever way it got them, every organism releases energy from carbon compounds the same way: by oxidising them in **cell respiration**. A plant respires day and night, just as a fox does.

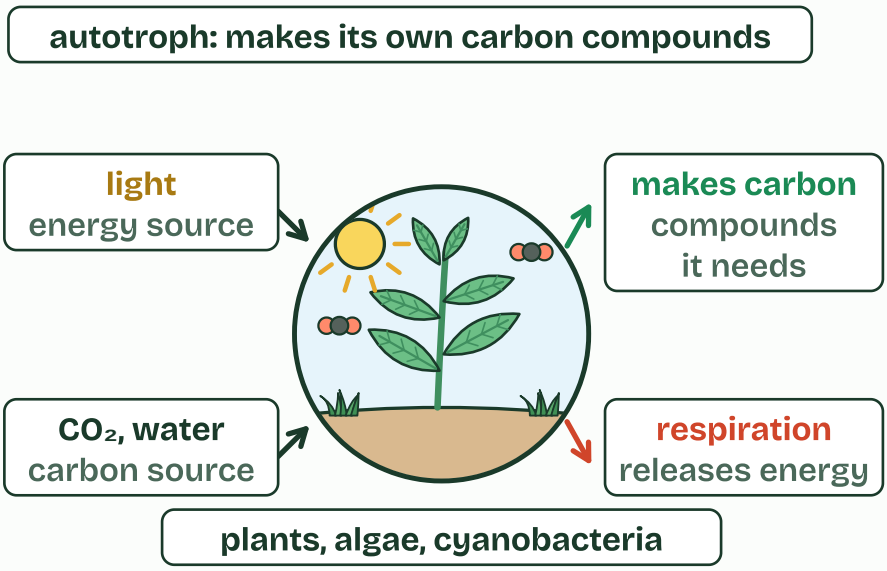
KEY POINTS

- Autotroph: inorganic carbon plus outside energy. Photo- uses light; chemo- uses oxidation of inorganic chemicals.
- Heterotroph: carbon compounds from other organisms, digested and then assimilated.
- Both respire to release energy.

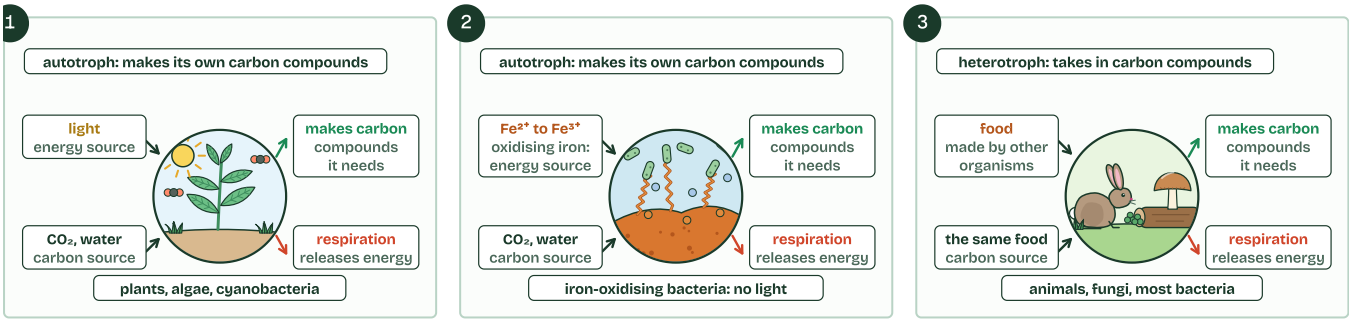
KEY TERMS

autotroph
An organism that makes its own carbon compounds from simple inorganic substances, such as carbon dioxide, using an external energy source.

heterotroph
An organism that gets its carbon compounds from other organisms, living or dead, and uses them to make the carbon compounds it needs.



SWITCH IT 3 SETTINGS



Photoautotroph Chemoautotroph Heterotroph

WATCH OUT

Plants do not "photosynthesise instead of respiring". They do both: photosynthesis makes the carbon compounds, and respiration releases energy from them, in every living cell, day and night.

PREDICT

Iron-oxidising bacteria live in a mine shaft with no light. What is the source of the carbon in their proteins?

(A) Iron ions, which the bacteria oxidise and then build into the amino acids of their proteins

(B) Carbon dioxide, which the bacteria fix using energy released by oxidising iron ions

(C) Dead organisms washed into the mine, whose proteins the bacteria digest and then absorb

Decide before you look. Answer on page 31.

C4.2.3 C4.2.4 C4.2.10 FLOW OF CHEMICAL ENERGY THROUGH FOOD CHAINS CONSTRUCTION OF FOOD CHAINS AND FOOD WEBS TO REPRESENT FEEDING RELATIONSHIPS IN A COMMUNITY CLASSIFICATION OF ORGANISMS INTO TROPHIC LEVELS

03 Who eats *whom*

When a caterpillar eats an oak leaf, the carbon compounds of the leaf become the caterpillar's food, and the chemical energy in them passes with them. A **food chain** shows that passing along: oak tree, caterpillar, blue tit, sparrowhawk. Each arrow means "is eaten by", so it points the way the energy and the biomass go: from the food to the feeder, never the other way.

Each place in a chain is a **trophic level**. The **producer** is first, then the **primary consumer** that eats it, the **secondary consumer** that eats that, and the **tertiary consumer**.

Real animals rarely eat one thing, so chains link up into a **food web**. In a web an animal can sit on more than one level. A wood mouse eating acorns is a primary consumer; the same mouse eating a caterpillar is a secondary consumer. Name the level for each chain, not once for the animal.

KEY POINTS

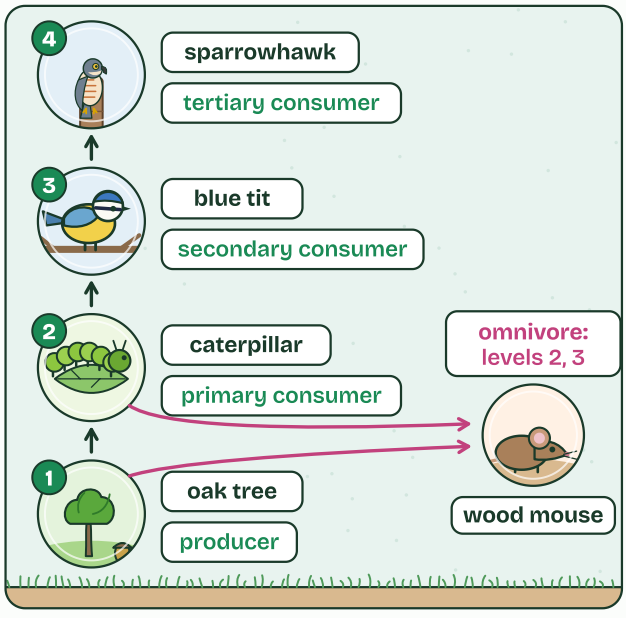
- Arrows: from the eaten to the eater, the way energy flows.
- Producer, primary, secondary, tertiary consumer.
- An omnivore can be on two or more levels at once.

KEY TERMS

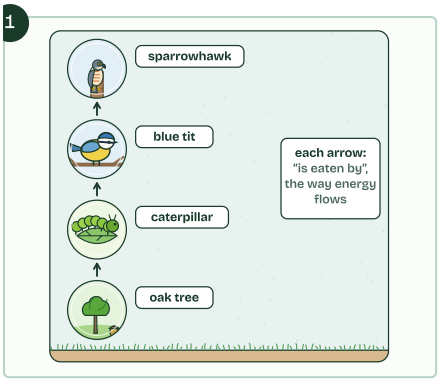
food chain
A sequence of organisms, each of which feeds on the one before it, showing how chemical energy passes from one to the next.

trophic level
The position an organism occupies in a food chain: producer, primary consumer, secondary consumer and so on.

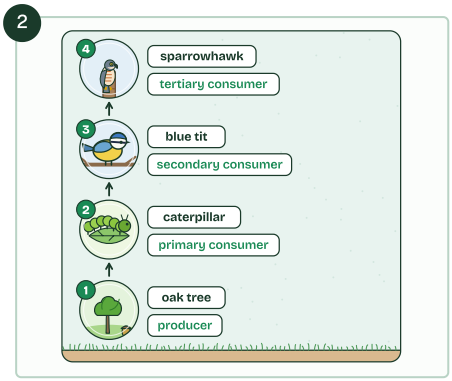
food web
A diagram of all the feeding relationships in a community, made of many interlinked food chains.



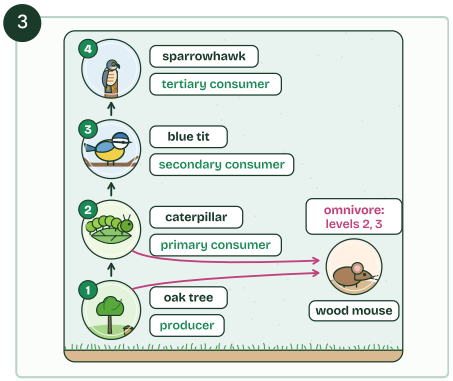
STEP BY STEP 3 STEPS



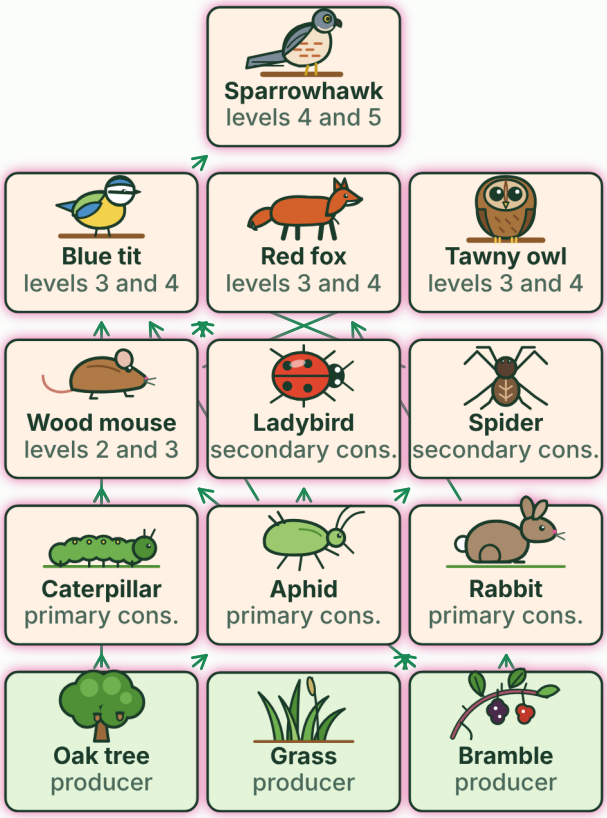
A food chain: each arrow means **is eaten by**.



Each step is a **trophic level**.



A **wood mouse** eats acorns and caterpillars: two levels at once.



The food web of an oak wood in England, sorted into trophic levels with producers at the bottom. Each arrow runs from a food to the organism that eats it, the way the energy flows. An omnivore sits on two levels.

WATCH OUT

The commonest slip in an exam food web is an arrow pointing from the fox to the rabbit ("the fox eats the rabbit"). The arrow shows where the energy goes, so it points at the fox.

PREDICT

Build the woodland web below, then switch to Remove a species. Before you run it, predict: the sparrowhawk eats only blue tits. If the sparrowhawks are removed, what happens?

(A) Every population in the web rises, because there is no longer a top predator eating any of the animals

(B) The blue tits rise a lot, but the caterpillars fall only a little, because blue tits share their feeding among four kinds of prey

(C) Nothing changes, because the sparrowhawk is at the top of the web and nothing in the web depends on it

Decide before you look. Answer on page 31.

C4.2.5 SUPPLY OF ENERGY TO DECOMPOSERS AS CARBON COMPOUNDS IN ORGANIC MATTER COMING FROM DEAD ORGANISMS

04 Nothing goes to *waste*

Much of what a wood makes is never eaten alive. Leaves fall, branches die, animals die whole, and every animal produces faeces. All of it is still made of carbon compounds, so it still holds chemical energy: a whole food supply for the **decomposers**.

There are two kinds. **Detritivores** such as earthworms, woodlice and millipedes eat dead matter, digest it inside their guts and leave it in smaller pieces. **Saprotrophs**, most fungi and many bacteria, secrete enzymes onto the dead matter and absorb the small molecules the enzymes release: their digestion happens outside their cells.

Decomposers respire the carbon compounds they take in, releasing carbon dioxide and heat, and they leave behind mineral ions such as nitrate and phosphate that plants can take up again. They are not usually drawn on a food chain, but energy from every level reaches them.

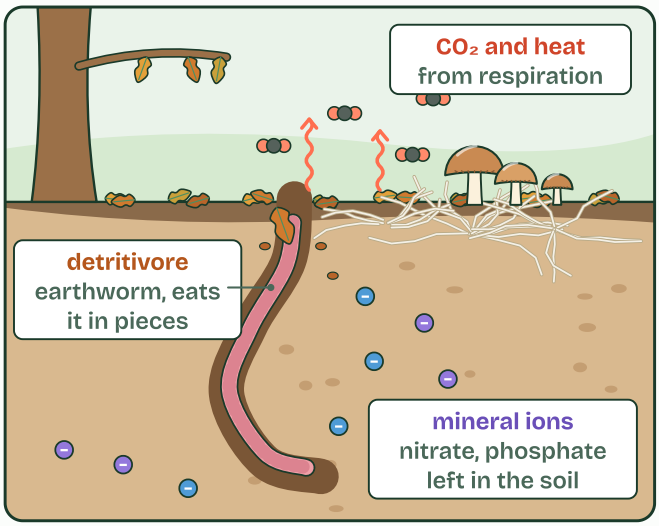
KEY POINTS

- Dead organisms, dead parts and faeces carry energy as carbon compounds.
- Detritivores digest inside; saprotrophs digest outside their cells.
- Decomposers release carbon dioxide, heat and mineral ions.

KEY TERMS

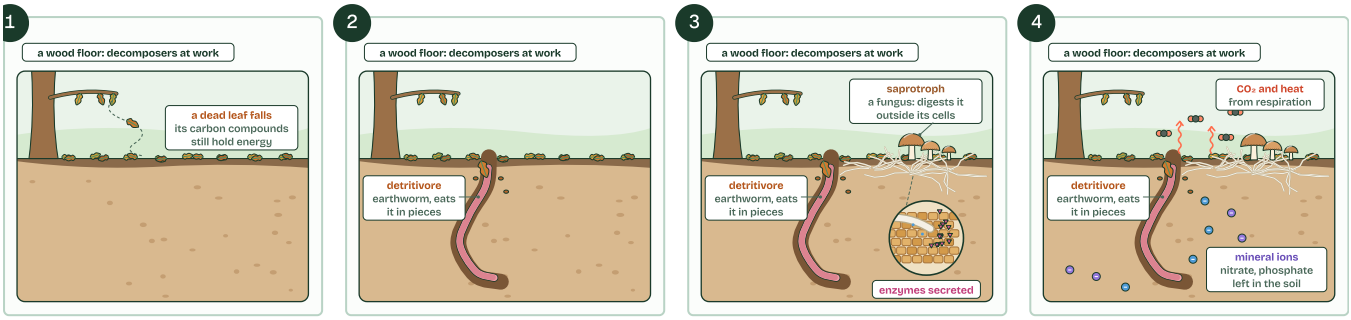
decomposers
Organisms that feed on dead organic matter and break it down: saprotrophs and detritivores.

a wood floor: decomposers at work



STEP BY STEP

4 STEPS



A dead leaf falls: its carbon compounds still hold energy.

An earthworm, a **detritivore**, eats it in pieces.

A fungus, a **saprotroph**, secretes enzymes and digests it outside its cells.

Respiration releases **carbon dioxide** and **heat**; **mineral ions** are left in the soil.

PREDICT

A sheep eats grass, but much of the grass comes out again as faeces. Where does the energy in the faeces go next?

(A) Back to the grass, which absorbs the carbon compounds in the faeces through its roots as food

(B) To dung beetles, fungi and bacteria, which feed on the faeces and release the energy in respiration

(C) Nowhere, because energy in faeces has been used up by the sheep already and none is left in them

Decide before you look. Answer on page 31.

C4.2.12 C4.2.13 C4.2.14 REDUCTIONS IN ENERGY AVAILABILITY AT EACH SUCCESSIVE STAGE IN FOOD CHAINS DUE TO LARGE ENERGY LOSSES BETWEEN TROPHIC LEVELS HEAT LOSS TO THE ENVIRONMENT IN BOTH AUTOTROPHS AND HETEROTROPHS DUE TO CONVERSION OF CHEMICAL ENERGY TO HEAT IN CELL RESPIRATION RESTRICTIONS ON THE NUMBER OF TROPHIC LEVELS IN ECOSYSTEMS DUE TO ENERGY LOSSES

05 Where the energy *goes*

Of the chemical energy in one trophic level, only a small share, often about a tenth, ends up in the next. The rest is lost from the chain in three ways:

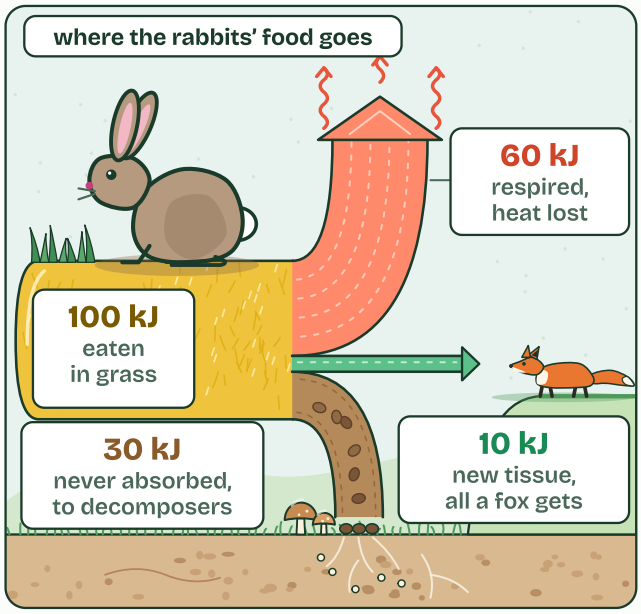
Not eaten: roots, bark, bones and whole organisms that die uneaten go to the decomposers.
Not absorbed: food that passes through the gut undigested leaves as faeces, also to the decomposers.
Respired: most of what is absorbed is respired to keep the organism alive, and leaves as heat.

No energy transfer is 100% efficient. Some energy becomes heat when ATP is made in respiration, and more when the ATP is used: for muscle contraction, for active transport, for building proteins. This happens in plants as well as animals, and heat cannot be turned back into chemical energy by any organism, so it is lost to the ecosystem.

So each level has far less energy than the one below. There are fewer organisms at each step, or smaller ones, so less biomass. A gram of fox holds about as much energy as a gram of rabbit: the energy per gram does not fall, there is just much less of it. After four or five steps too little is left to support a population of another level. That is why food chains rarely have more than five levels.

KEY POINTS

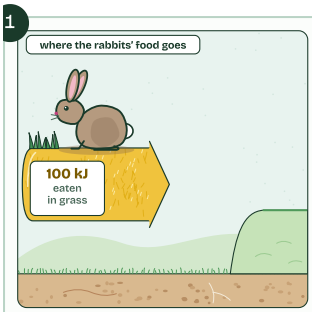
- Losses: parts not eaten, food not absorbed (faeces), heat from respiration.
- Heat is released when ATP is made and when it is used.
- Less energy each step, so less biomass, so few levels.



STEP BY STEP

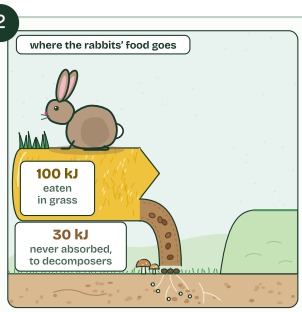
4 STEPS

1



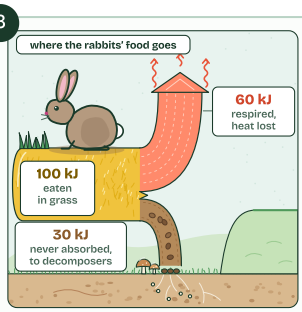
Rabbits eat grass holding **100 kJ** of chemical energy. Follow it.

2



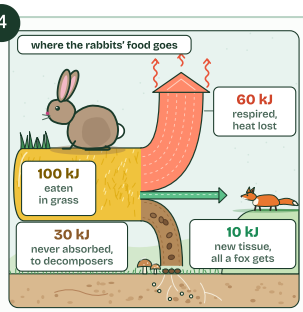
About **30 kJ** is never absorbed: it leaves in **faeces**, food for decomposers.

3



About **60 kJ** is used in **respiration** and released as **heat**, lost from the ecosystem.

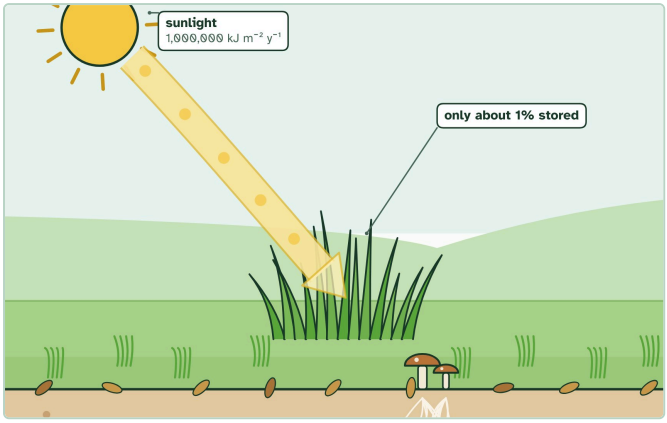
4



Only about **10 kJ** ends up in new rabbit tissue: all a fox can get.

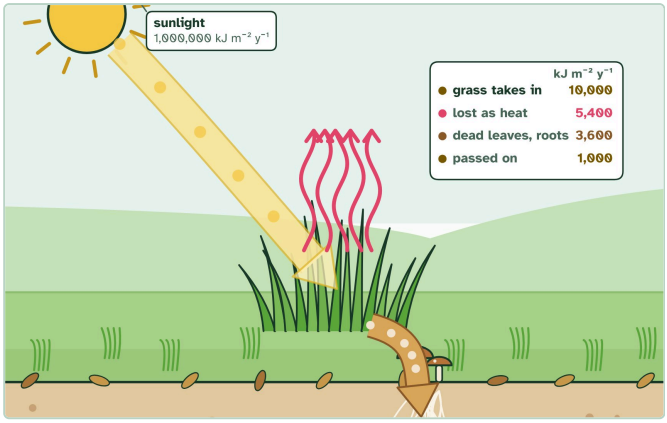
ANIMATION · WATCH IT HAPPEN: ENERGY DOWN A FOOD CHAIN
10 MOMENTS

1 PRODUCER



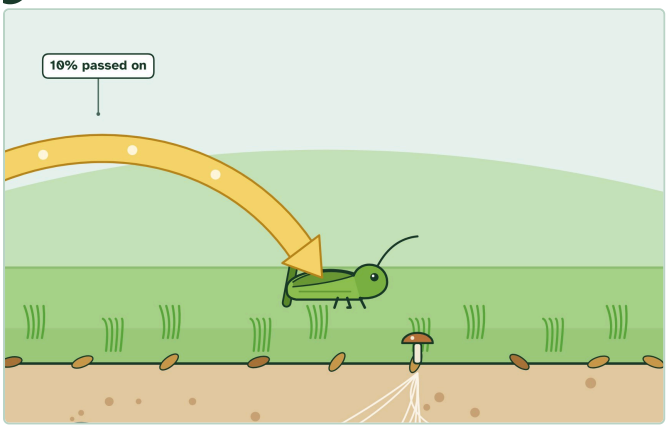
About 1,000,000 kJ of sunlight falls on each square metre a year. **Photosynthesis** stores about 1% in the grass: **10,000 kJ m⁻² y⁻¹**.

2 GRASS LOSES



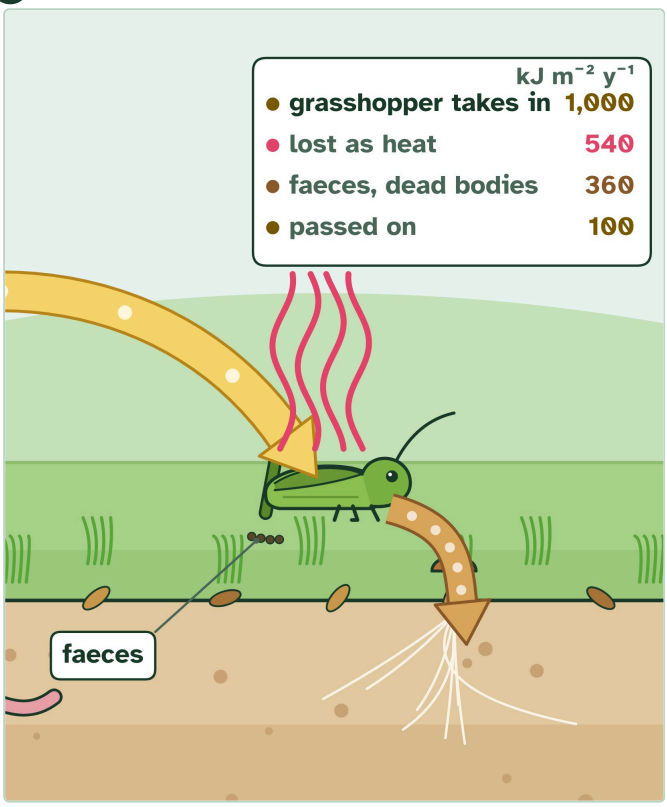
The grass **respires** to stay alive, so much of its energy rises away as **heat**. Dead leaves and roots go to the **decomposers** in the soil.

3 LEVEL 2



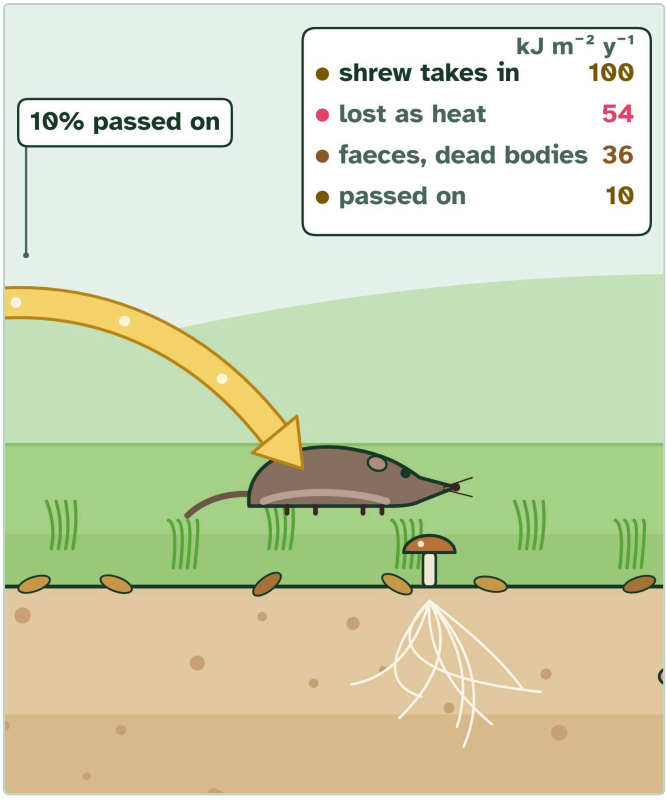
Only the grass that grasshoppers eat and build into their bodies flows on: about **10%**, so they hold **1,000 kJ m⁻² y⁻¹**.

4 GRASSHOPPER LOSES



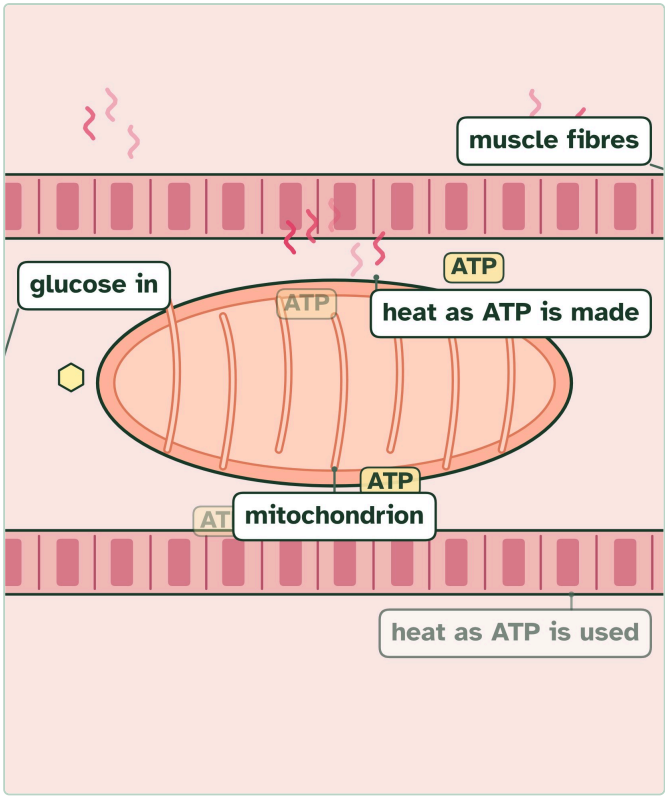
Grasshoppers lose most of theirs too: **heat** from their respiration, and **faeces** and dead bodies to the decomposers.

5 LEVEL 3



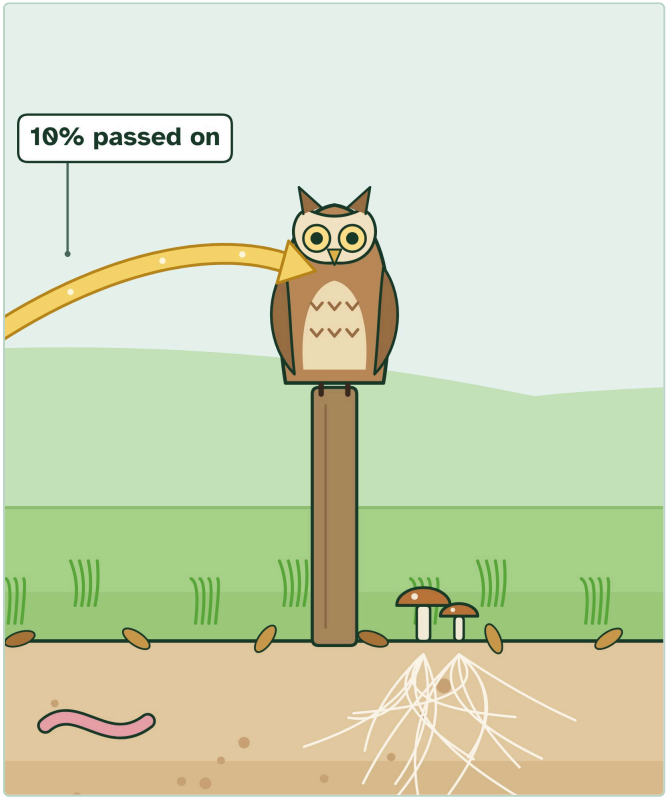
The **shrews** get 10%: **100 kJ m⁻² y⁻¹**. A shrew respires fast to stay warm, so even more goes as heat.

6 INSIDE A CELL



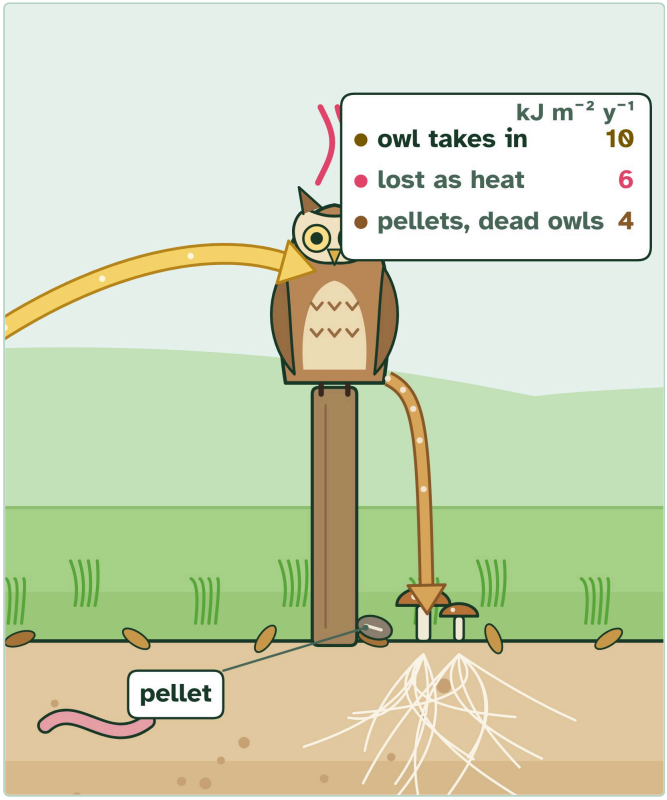
Why so much heat? In a shrew's muscle cell, **respiration** makes ATP and releases heat, and using the **ATP** to contract releases more.

7 LEVEL 4



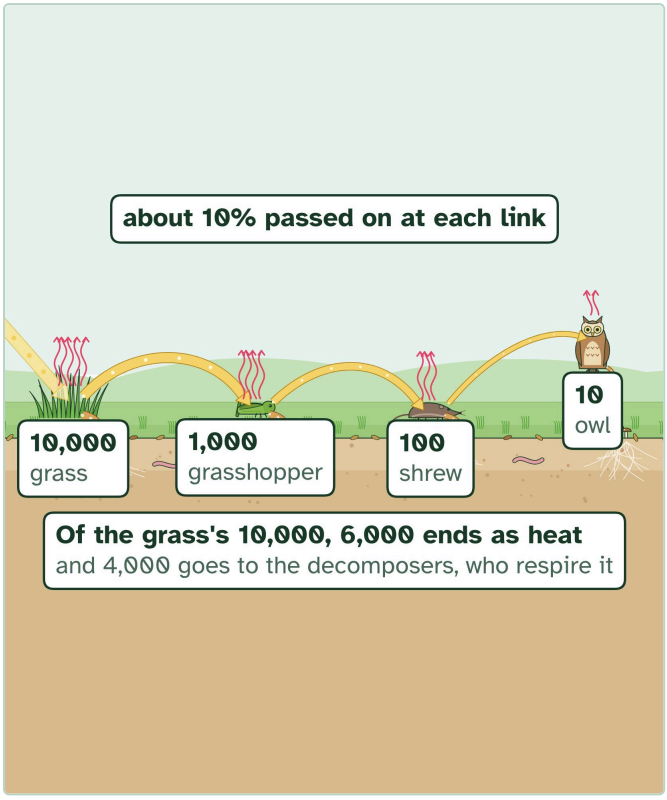
The **owls** get **10 kJ m⁻² y⁻¹**, a thousandth of the grass. Heat cannot become chemical energy again, so it is lost for good.

8 OWL PELLET



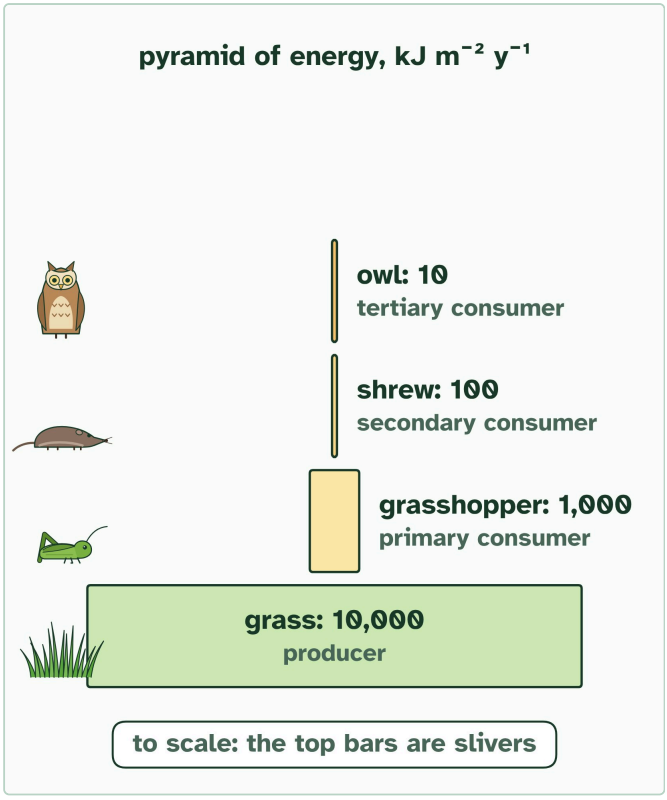
An owl coughs up a **pellet** of fur and bones it could not digest: more chemical energy for the decomposers, and more heat from the owl.

9 THE WHOLE CHAIN



The whole chain: at every link most energy is lost. The ribbons are drawn on a log scale, or the owl's would be too thin to see.

10 PYRAMID



Stacked to scale, the stores make a **pyramid of energy**. Above the owl there is too little left for another level.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-c4-2-transfers-of-energy-and-matter#losses

WATCH OUT

Energy is not "used up" or "destroyed" along a food chain. It is converted to heat and leaves the ecosystem; the total is conserved.

PREDICT

Turn the film's efficiency down from 10% to 5%. What happens to the owl?

(A) It gets half as much energy, because only the last step from the shrew to the owl passes on less

(B) It gets an eighth as much energy, because each of the three steps from the grass passes on half as much

(C) It gets the same, because owls hunt harder and so can take as much energy as they need from shrews

Decide before you look. Answer on page 31.

06 Drawn to *scale*

C4.2.11 CONSTRUCTION OF ENERGY PYRAMIDS

A **pyramid of energy** stacks the trophic levels from the producers up, each bar as wide as the energy passing through that level. The units are energy per area per time, usually kJ m^{-2} a year (kJ m^{-2} y^{-1}).

The data in the figure are from Howard Odum's study of Silver Springs, a clear spring-fed river in Florida, in the 1950s, one of the first ecosystems measured from top to bottom. Draw the bars to scale and the shape tells the story: the producers' bar is enormous, the herbivores' a sixth of it, and the top carnivores' a thin line.

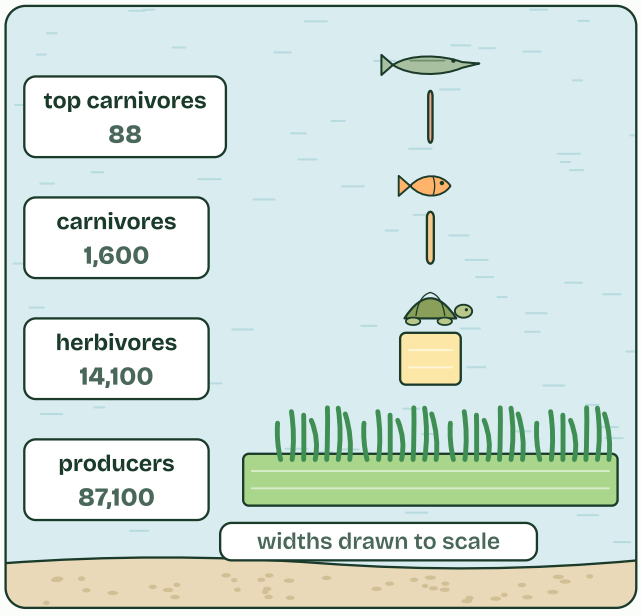
To build one, pick a scale that fits the biggest bar (here 87,100 kJ to 340 units), divide the others by the same factor, and centre each bar on the one below. Label each bar with its level and its value. Working out each level as a percentage of the one below gives its **efficiency** of transfer.

KEY POINTS

- One bar a level, producers at the bottom, width in proportion to energy.
- Units: kJ m^{-2} a year.
- Efficiency = energy at a level ÷ energy at the level below × 100.

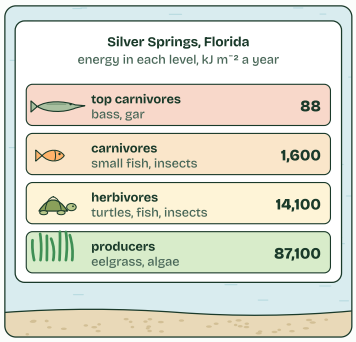
KEY TERMS

pyramid of energy
A bar chart, one bar a trophic level stacked from the producers up, with each bar's width proportional to the energy that level takes in per unit area per year.



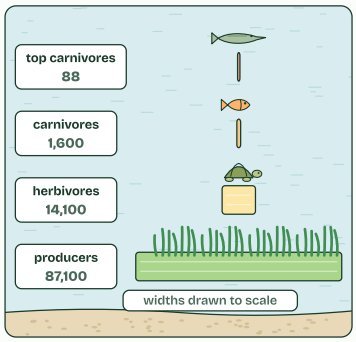
STEP BY STEP 2 STEPS

1



The data: energy at each level, kJ m^{-2} a year.

2



The same data as a **pyramid of energy**, to scale.

PREDICT

A pyramid of numbers for an oak wood can be upside down: one tree feeds thousands of caterpillars. Can a pyramid of energy ever be upside down?

(A) Yes, when one large producer such as an oak tree feeds a great many small consumers in the level above

(B) No, because each level can only pass on part of the energy it took in, so every bar is narrower than the one below

(C) Yes, in a winter when the producers stop growing but the consumers go on feeding on what is left

Decide before you look. Answer on page 31.

C4.2.15 C4.2.16 PRIMARY PRODUCTION AS ACCUMULATION OF CARBON COMPOUNDS IN BIOMASS BY AUTOTROPHS SECONDARY PRODUCTION AS ACCUMULATION OF CARBON COMPOUNDS IN BIOMASS BY HETEROTROPHS

07 What is left to *grow*

Primary production is the building up of carbon compounds in biomass by autotrophs. All the carbon a plant fixes by photosynthesis is its **gross** primary production. It respires some of that straight away to stay alive, and what is left is its **net** primary production: new leaves, wood, roots, seeds. Net production is what herbivores and decomposers can use. It is measured as mass per area per time, usually g m^{-2} a year.

Biomes differ hugely. A tropical rainforest, warm, wet and lit all year, makes over 2,000 g m^{-2} a year; a hot desert, short of water, under 100. The open ocean makes little per square metre, but there is so much of it that it adds up to nearly half of all the world's production.

Secondary production is the same thing for heterotrophs: biomass they build as they grow and reproduce. It is always lower than primary production, because heterotrophs can only build from what autotrophs made, and they turn much of what they eat into carbon dioxide and water in respiration.

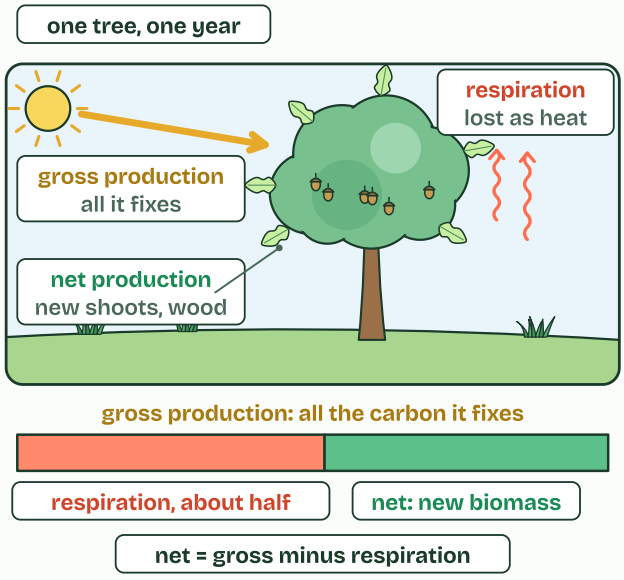
KEY POINTS

- Net production = gross production − respiration.
- Units: g m^{-2} a year. Rainforests highest, deserts and tundra lowest.
- Secondary production is lower than primary production.

KEY TERMS

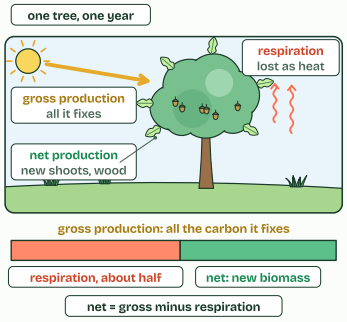
primary production
The accumulation of carbon compounds in biomass by autotrophs, measured as mass of carbon (or dry mass) per unit area per unit time, usually g m^{-2} a year.

secondary production
The accumulation of carbon compounds in biomass by heterotrophs, as they grow and reproduce.



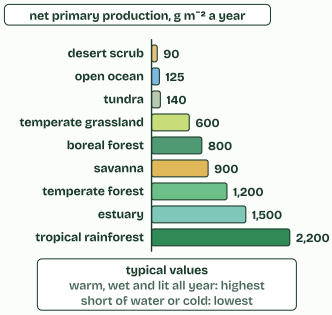
SWITCH IT
2 SETTINGS

1



One tree

2



Biomes compared

PREDICT

Why does a tropical rainforest have a much higher net primary production than the tundra?

(A) Rainforest plants respire less than tundra plants do, so more of what they fix is left over to grow with

(B) The tundra has far fewer herbivores, so less of its biomass is eaten and less new growth is needed there

(C) It is warm, wet and lit all year, so photosynthesis goes on fast all year, while the tundra is cold and dark for months

Decide before you look. Answer on page 31.

C4.2.17 C4.2.18 C4.2.19 CONSTRUCTING CARBON CYCLE DIAGRAMS ECOSYSTEMS AS CARBON SINKS AND CARBON SOURCES RELEASE OF CARBON DIOXIDE INTO THE ATMOSPHERE DURING COMBUSTION OF BIOMASS, PEAT, COAL, OIL AND NATURAL GAS

08 Round and *round*

Energy flows through an ecosystem once; carbon goes round. **Photosynthesis** takes carbon dioxide from the air (or from water) and fixes it into carbon compounds. **Feeding** passes those compounds to consumers, and death and egestion pass them to decomposers. **Respiration**, by producers, consumers and decomposers alike, turns them back into carbon dioxide. A carbon cycle diagram shows those stores and the processes that move carbon between them, each arrow labelled.

If an ecosystem fixes more carbon by photosynthesis than it releases by respiration, it takes carbon dioxide out of the air: it is a **carbon sink**. A growing forest is a sink, and so is a peat bog, where waterlogged, acidic soil slows decomposition so much that dead moss piles up for thousands of years. If respiration wins, it is a **carbon source**: a drained bog, or a forest after a fire.

Old sinks can be burned. **Combustion** of wood and other biomass, peat, coal, oil and natural gas oxidises their carbon to carbon dioxide. These stores formed at very different times: wood in years, peat over thousands of years, coal mostly around 300 million years ago from swamp forests, and oil and gas from marine plankton over tens to hundreds of millions of years. Lightning has always set some forests and peat alight, but humans now burn fossil fuels and biomass far faster than any natural process.

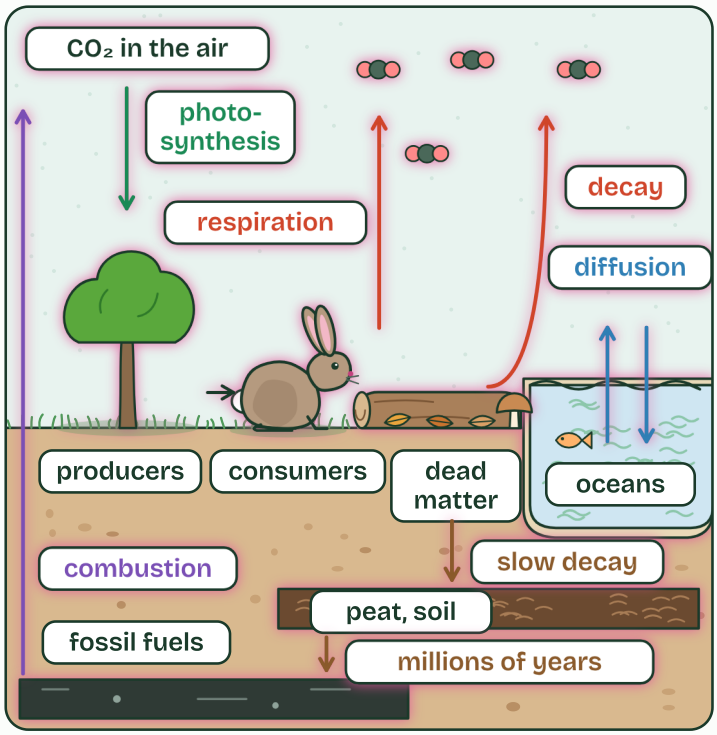
KEY POINTS

- Photosynthesis removes CO_2; respiration and combustion return it.
- Sink: photosynthesis > respiration. Source: respiration > photosynthesis.
- Biomass, peat, coal, oil and gas: sinks of different ages, released by burning.

KEY TERMS

carbon sink
An ecosystem or store that takes in more carbon than it releases, so there is a net uptake of carbon dioxide.

carbon source
An ecosystem or store that releases more carbon than it takes in, so there is a net release of carbon dioxide.



The oceans: carbon dioxide dissolves in sea water (as hydrogencarbonate ions). The oceans hold about fifty times as much carbon as the air.

Coal, oil and natural gas: carbon from organisms that lived millions of years ago, buried and changed by heat and pressure.

Producers (plants, algae): carbon fixed from carbon dioxide by photosynthesis into carbon compounds.

The atmosphere: about 870 billion tonnes of carbon as carbon dioxide, about 0.04% of the air. It is the store the other arrows draw from and return to.

Respiration, by producers, consumers and decomposers: carbon compounds are oxidised and carbon dioxide is released to the air.

Decomposition: saprotrophs respire the carbon compounds in dead matter, releasing carbon dioxide.

Over millions of years, buried peat and dead organisms are changed by heat and pressure into coal, oil and gas.

Diffusion: carbon dioxide dissolves into the oceans and comes out again; more dissolves when there is more in the air.

Soil carbon and peat: where it is waterlogged and acidic, decomposition is too slow and dead plants build up as peat, a carbon sink.

Dead organisms, leaf litter and faeces: carbon compounds that decomposers feed on.

Consumers: carbon taken in as food, by feeding on producers or other consumers.

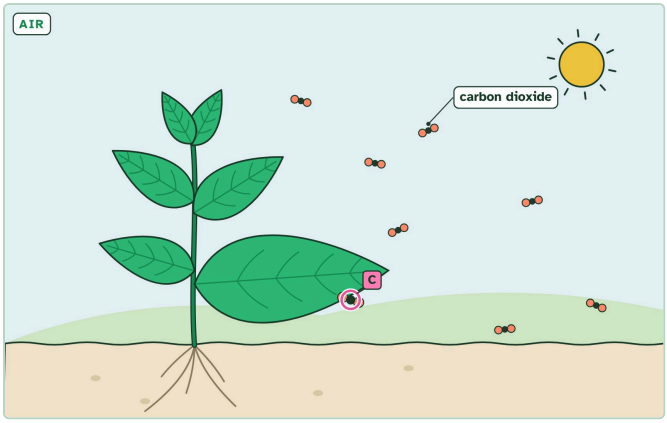
Photosynthesis: producers take in carbon dioxide and fix it into carbon compounds. It removes carbon dioxide from the air.

Feeding: carbon compounds pass from producers to consumers, and from consumers to consumers.

Where decomposition is slow (waterlogged, acidic, cold), dead matter builds up as peat and soil carbon instead of being respired.

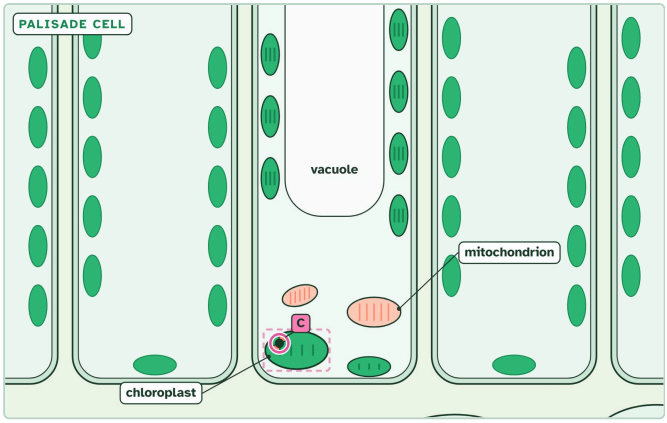
Combustion: burning fossil fuels, peat or biomass (wood, forests) oxidises their carbon compounds and releases carbon dioxide, faster than photosynthesis takes it back.

1 AIR



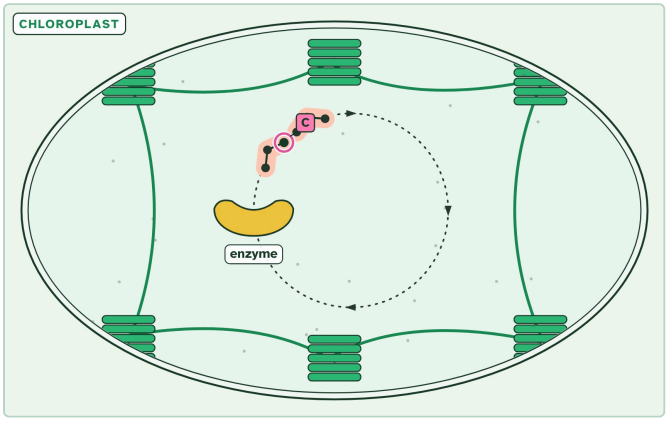
One **carbon atom**, in a molecule of **carbon dioxide** in the air.

2 CHLOROPLAST



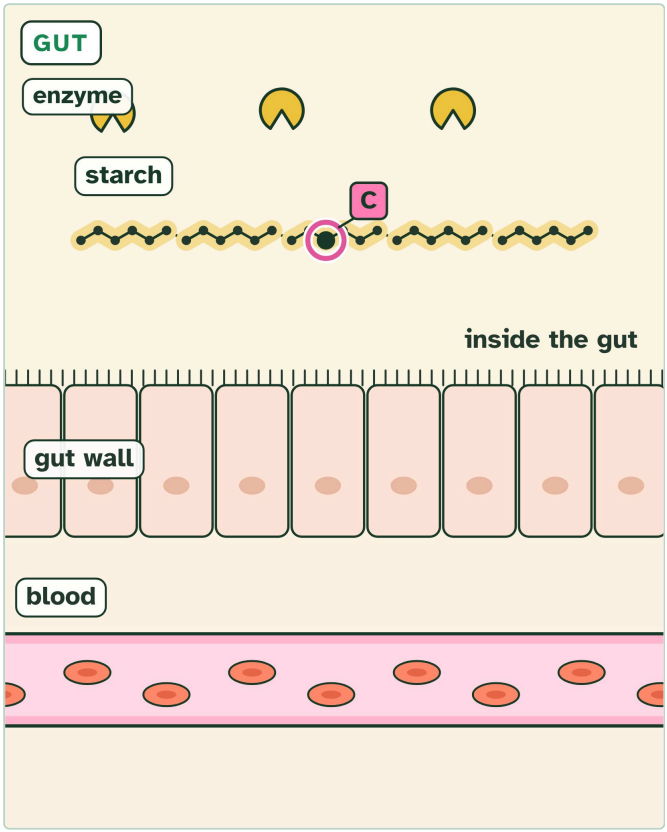
It **diffuses** in through a stoma and into a chloroplast.

3 CHLOROPLAST



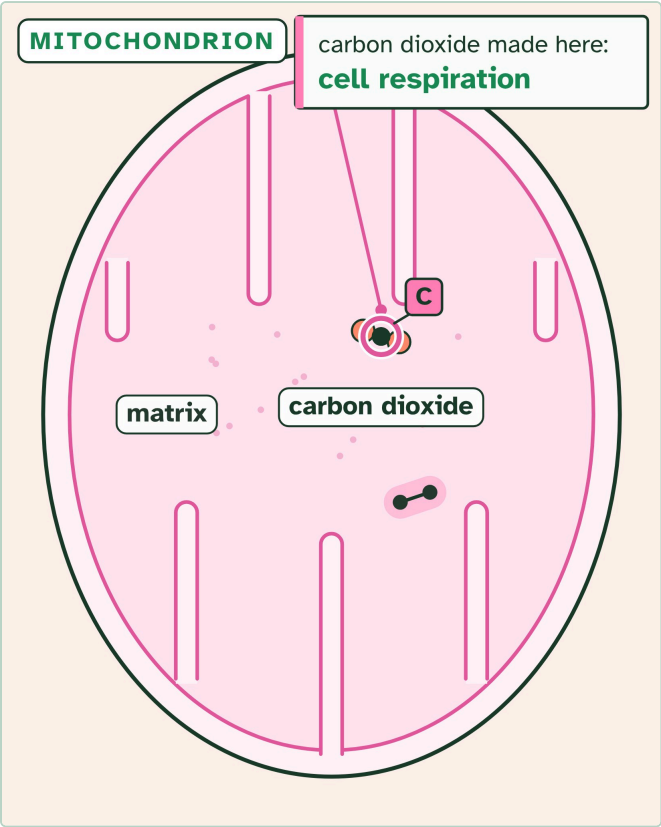
In the chloroplast it is **fixed**: joined to a compound already there.

4 GUT



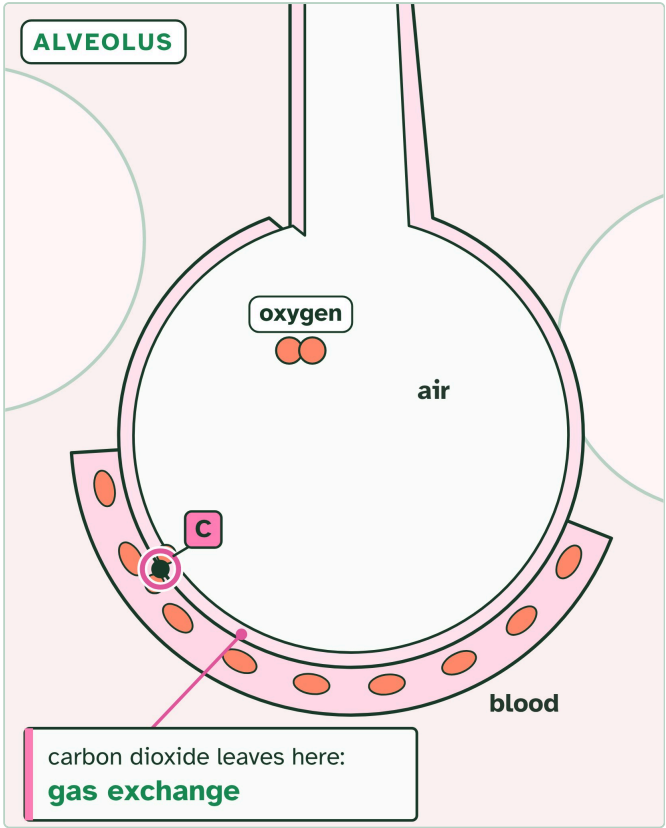
A rabbit eats the leaf. **Digestion** breaks the starch back into glucose, which passes into its blood.

5 MITOCHONDRION



The carbon dioxide is **made in the mitochondrion**: this is cell respiration.

6 BLOOD



It leaves the body in the lungs: that is **gas exchange**, not respiration.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-c4-2-transfers-of-energy-and-matter#carbon

PREDICT

A peat bog is drained for farming. Air gets into the peat. What happens to the bog's carbon?

(A) It stays locked in, because peat is made of dead plants that decomposers are unable to digest

(B) Decomposers can now respire it, so the bog turns from a carbon sink into a carbon source

(C) It increases, because crops planted on the drained bog fix more carbon than the moss did

Decide before you look. Answer on page 32.

C4.2.20 C4.2.21 C4.2.22 ANALYSIS OF THE KEELING CURVE IN TERMS OF PHOTOSYNTHESIS, RESPIRATION AND COMBUSTION DEPENDENCE OF AEROBIC RESPIRATION ON ATMOSPHERIC OXYGEN PRODUCED BY PHOTOSYNTHESIS, AND OF PHOTOSYNTHESIS ON ATMOSPHERIC CARBON DIOXIDE PRODUCED BY RESPIRATION RECYCLING OF ALL CHEMICAL ELEMENTS REQUIRED BY LIVING ORGANISMS IN ECOSYSTEMS

09 The Earth *breathing*

In 1958 Charles David Keeling began measuring carbon dioxide in the air on Mauna Loa, a volcano in Hawaii, far from any city or forest. The record has run every month since, and its graph is the **Keeling curve**. It shows two patterns.

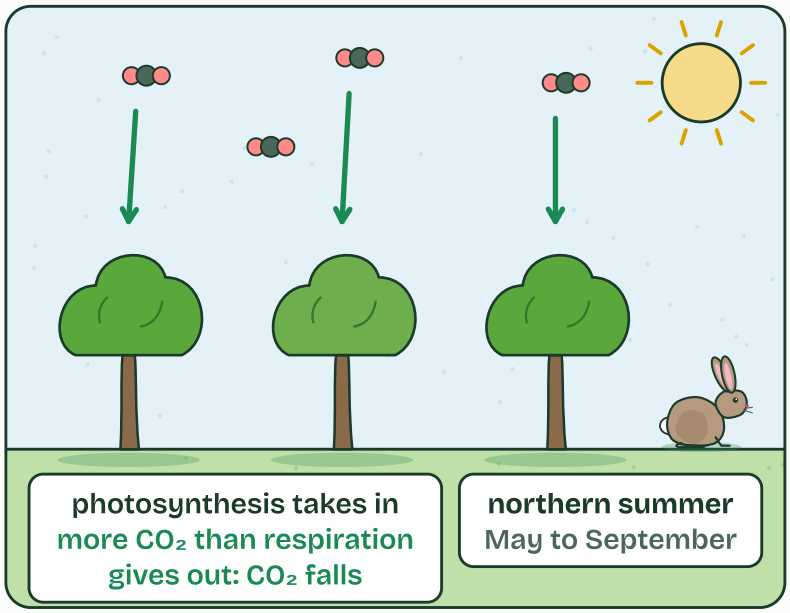
The yearly wiggle. Each year the concentration peaks in about May and falls to a low in about September or October. Most of the land and its forests are in the northern hemisphere. In the northern summer, photosynthesis there takes up more carbon dioxide than respiration and decay release, so the level falls. In the winter photosynthesis almost stops, while respiration, decay and burning go on, so it rises again.

The long rise. Every year ends higher than the one before: from about 315 ppm in 1958 to over 420 ppm now, and the rise is getting faster. The main cause is combustion of fossil fuels, with forests cleared and burned, releasing carbon faster than photosynthesis and the oceans take it back.

Behind the wiggle is a huge two-way trade. Every aerobic organism depends on the oxygen that photosynthesis puts into the air, and photosynthesis depends on the carbon dioxide that respiration puts back. Each year about a hundred billion tonnes of carbon go each way on land alone. Carbon is not special: every element living things use, nitrogen, phosphorus, sulfur, the lot, is recycled, and decomposers are what return them to the soil and water for producers to use again.

KEY POINTS

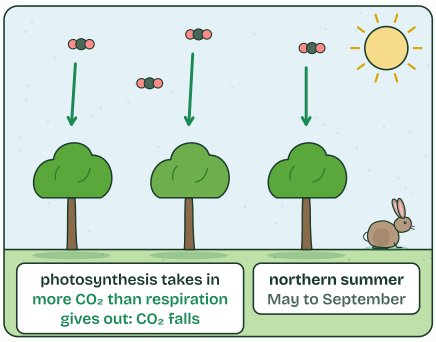
- Wiggle: northern summer photosynthesis lowers CO_2; winter respiration raises it.
- Rise: combustion of fossil fuels and deforestation.
- Photosynthesis and respiration supply each other; all elements are recycled.



SWITCH IT

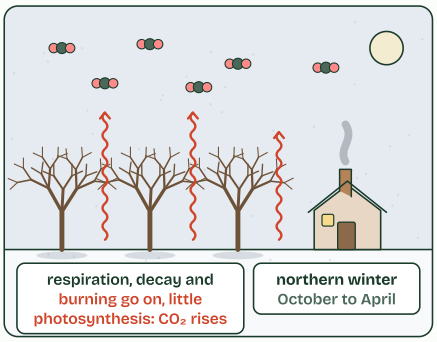
2 SETTINGS

1



Northern summer

2



Northern winter

WATCH OUT

The wiggle is not caused by people burning more fuel to keep warm in winter. Combustion adds to the long rise; the wiggle is the northern forests photosynthesising in summer and not in winter.

PREDICT

A station in New Zealand, in the southern hemisphere, also measures carbon dioxide. What would you expect its wiggle to look like?

(A) The same as Mauna Loa's but bigger, because there is more ocean in the south and the oceans take up carbon dioxide each summer

(B) Much smaller, because there is far less land and forest in the southern hemisphere to drive a seasonal swing

(C) There would be no long rise there, because almost all of the fossil fuel is burned in the northern hemisphere

Decide before you look. Answer on page 32.

Key terms

Every term this guide defines, A to Z, with the chapter it is in. Cover the right-hand side and test yourself.

autotroph 02
An organism that makes its own carbon compounds from simple inorganic substances, such as carbon dioxide, using an external energy source.

carbon sink 08
An ecosystem or store that takes in more carbon than it releases, so there is a net uptake of carbon dioxide.

carbon source 08
An ecosystem or store that releases more carbon than it takes in, so there is a net release of carbon dioxide.

closed system 01
A system that exchanges energy with its surroundings but not matter.

decomposers 04
Organisms that feed on dead organic matter and break it down: saprotrophs and detritivores.

ecosystem 01
A community of organisms together with the non-living surroundings they interact with.

food chain 03
A sequence of organisms, each of which feeds on the one before it, showing how chemical energy passes from one to the next.

food web 03
A diagram of all the feeding relationships in a community, made of many interlinked food chains.

heterotroph 02
An organism that gets its carbon compounds from other organisms, living or dead, and uses them to make the carbon compounds it needs.

open system 01
A system that exchanges both energy and matter with its surroundings. Almost every ecosystem is open.

primary production 07
The accumulation of carbon compounds in biomass by autotrophs, measured as mass of carbon (or dry mass) per unit area per unit time, usually g m^{-2} a year.

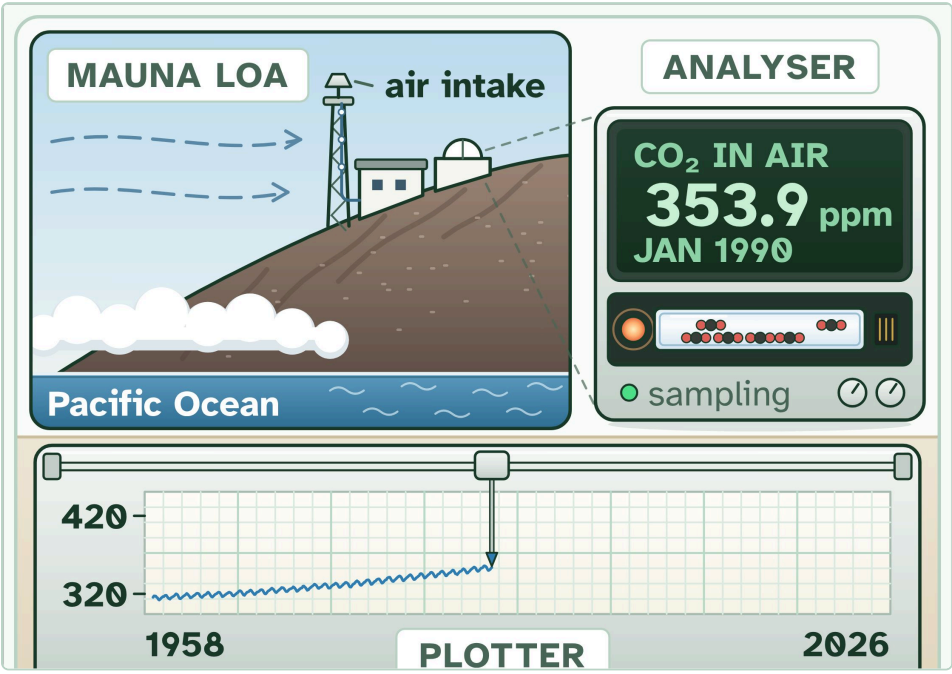
pyramid of energy 06
A bar chart, one bar a trophic level stacked from the producers up, with each bar's width proportional to the energy that level takes in per unit area per year.

secondary production 07
The accumulation of carbon compounds in biomass by heterotrophs, as they grow and reproduce.

trophic level 03
The position an organism occupies in a food chain: producer, primary consumer, secondary consumer and so on.

Dry lab: *The Keeling curve*

Plot every monthly mean of carbon dioxide in the air at Mauna Loa, Hawaii, from 1958 to now. Read the yearly wiggle, then measure how fast the long rise is climbing, decade by decade.



Run it online: change the variables, run the trials, and the table and graph fill in as you go. `biologybybradford.com/guides/ib-biology-c4-2-transfers-of-energy-and-matter#lab`

Your question

Why does the carbon dioxide in the air go up and down every year, and why does each year end higher than the last? Predict first: in which month of the year is it highest at Mauna Loa?

What you can do

Plot the whole record and add a trend line; zoom to any two years and read their peaks and troughs; and work out the rate of rise for each decade, in ppm a year.

What to record

The month of the yearly peak and trough and the size of the wiggle; the rate of rise for each decade; and a sentence explaining each pattern with photosynthesis, respiration and combustion. The data are the real monthly means measured at Mauna Loa Observatory (NOAA and Scripps), public domain.

Find out

- **The whole record.** Plot every month from 1958, then add the trend line. Describe the two patterns you see, one in a sentence each.
- **The wiggle.** Zoom to two years. In which month is carbon dioxide highest, and in which lowest? How big is the swing in ppm? Compare 1959 with 2024: has the swing changed?
- **The rise.** Work out the rate of rise for every decade. Is the rise steady, or getting faster? By how many times has it sped up since the 1960s?
- **Explain it.** Explain the wiggle with photosynthesis and respiration in the northern hemisphere, and the rise with combustion.

Record

- For two years: the month and value of each peak and trough, and the swing between them.
- For each decade: its first and last yearly means and the rate of rise in ppm a year.
- A bar chart of the rate of rise against decade, and a sentence on its trend.
- Download the CSV to keep every month.

Your question Why does the carbon dioxide in the air go up and down every year, and why does each year end higher than the last? Predict first: in which month of the year is it highest at Mauna Loa?**What you can do**Plot the whole record and add a trend line; zoom to any two years and read their peaks and troughs; and work out the rate of rise for each decade, in ppm a year.**What to record**The month of the yearly peak and trough and the size of the wiggle; the rate of rise for each decade; and a sentence explaining each pattern with photosynthesis, respiration and combustion. The data are the real monthly means measured at Mauna Loa Observatory (NOAA and Scripps), public domain.

Back to the carbon cycle

Use your results to explain the yearly swing with photosynthesis and respiration, and the long rise with combustion.

QUESTIONS ON THE LAB

QUESTION 1

In 2024 Mauna Loa read about 427 ppm in May and 422 ppm in September. Why is it lower in September?

(A) Less fossil fuel is burned in the northern summer, because people need far less heating when it is warm

(B) Northern forests have photosynthesised all summer, taking up more carbon dioxide than respiration released

(C) Warm summer seas dissolve more carbon dioxide, taking it out of the air until they cool down in winter

Answer on page 32.

QUESTION 2

The rate of rise was about 0.9 ppm a year in the 1960s and about 2.4 ppm a year in the 2010s. What does this show?

(A) The concentration has stopped rising in recent years, because the rate of rise in each decade is smaller than before

(B) The rise is steady, because the concentration goes up by about the same amount in every decade of the record

(C) The rise is speeding up, because carbon dioxide is being added faster than in the past, mainly by combustion

Answer on page 32.

QUESTION 3

Why was the observatory put on Mauna Loa, over 3,000 m up a volcano in the middle of the Pacific?

(A) Its height puts it closer to the top of the atmosphere, where most of the carbon dioxide in the air collects

(B) It is far from cities and forests, so it samples well-mixed air rather than carbon dioxide from one local source

(C) The volcano gives off carbon dioxide all the time, so it is easy to measure how much of it is in the air there

Answer on page 32.

Check yourself

The check for this guide is online: a fresh paper of past-paper style questions from the exam bank on C4.2 each time, marked as you go, and saved to your Exam practice progress when you are signed in. Scan the code, or type the link.

biologybybradford.com/exam-maker/sit?topics=C4.2&level=SL&paper=quiz&marks=15&src=ep

Answers

PREDICTIONS IN THE CHAPTERS

01 A student seals a jar with pond water, waterweed and snails and keeps it on a sunny windowsill. What must cross the glass for the jar to keep going for years?

B **Light in and heat out, because only energy has to cross: the matter inside is recycled**

Energy cannot be recycled, so light must keep coming in and heat must be able to leave. The carbon, oxygen and minerals can go round and round: the snails respire the carbon dioxide the weed needs, and the weed photosynthesises the oxygen the snails need.

02 Iron-oxidising bacteria live in a mine shaft with no light. What is the source of the carbon in their proteins?

B **Carbon dioxide, which the bacteria fix using energy released by oxidising iron ions**

They are chemoautotrophs. Oxidising iron supplies the energy, but the carbon comes from carbon dioxide, just as it does for a plant. Iron is not a part of amino acids.

03 Build the woodland web below, then switch to Remove a species. Before you run it, predict: the sparrowhawk eats only blue tits. If the sparrowhawks are removed, what happens?

B **The blue tits rise a lot, but the caterpillars fall only a little, because blue tits share their feeding among four kinds of prey**

The blue tits are freed from their only predator and rise by about 40%. Their extra feeding is spread over caterpillars, aphids, ladybirds and spiders, so each prey falls only a little. Now try taking out the blue tits instead: the sparrowhawks have nothing left to eat and die out, and the caterpillars rise.

04 A sheep eats grass, but much of the grass comes out again as faeces. Where does the energy in the faeces go next?

B **To dung beetles, fungi and bacteria, which feed on the faeces and release the energy in respiration**

Faeces are undigested food, still rich in carbon compounds. Decomposers feed on them and respire, so the energy leaves as heat. Plants take up only the mineral ions that decomposition releases, never the energy.

05 Turn the film's efficiency down from 10% to 5%. What happens to the owl?

B **It gets an eighth as much energy, because each of the three steps from the grass passes on half as much**

The losses multiply. At 10%: 10,000 × 0.1 × 0.1 × 0.1 = 10 kJ reaches the owl. At 5%: 10,000 × 0.05 × 0.05 × 0.05 = 1.25 kJ, an eighth as much. That is why a top predator is so sensitive to anything that cuts the levels below it.

06 A pyramid of numbers for an oak wood can be upside down: one tree feeds thousands of caterpillars. Can a pyramid of energy ever be upside down?

B **No, because each level can only pass on part of the energy it took in, so every bar is narrower than the one below**

Never. A level's energy all comes from the level below, and some of it is always lost as heat and to decomposers on the way, so each bar must be narrower. Numbers and even biomass at one moment can invert; energy flow over a year cannot.

07 Why does a tropical rainforest have a much higher net primary production than the tundra?

C **It is warm, wet and lit all year, so photosynthesis goes on fast all year, while the tundra is cold and dark for months**

Light, temperature and water limit photosynthesis. The rainforest has all three for twelve months; the tundra has a short, cool summer and frozen ground. Rainforest plants actually respire fast too, because it is warm, but they fix far more carbon.

08 A peat bog is drained for farming. Air gets into the peat. What happens to the bog's carbon?

B **Decomposers can now respire it, so the bog turns from a carbon sink into a carbon source**

Peat builds up only because waterlogging keeps oxygen out and slows decomposers. Drain it and aerobic decomposers break it down, releasing thousands of years of stored carbon as carbon dioxide.

09 A station in New Zealand, in the southern hemisphere, also measures carbon dioxide. What would you expect its wiggle to look like?

B **Much smaller, because there is far less land and forest in the southern hemisphere to drive a seasonal swing**

The southern hemisphere is mostly ocean, so its seasonal swing is small, about 1 ppm. The air mixes round the globe within a year or two, so the long rise is the same everywhere.

QUESTIONS ON THE DRY LAB

Q1 In 2024 Mauna Loa read about 427 ppm in May and 422 ppm in September. Why is it lower in September?

B **Northern forests have photosynthesised all summer, taking up more carbon dioxide than respiration released**

The swing follows the northern growing season: from May to September photosynthesis outpaces respiration and decay, so the air loses carbon dioxide. (Warm water holds less gas, not more.)

Q2 The rate of rise was about 0.9 ppm a year in the 1960s and about 2.4 ppm a year in the 2010s. What does this show?

C **The rise is speeding up, because carbon dioxide is being added faster than in the past, mainly by combustion**

A bigger rate each decade means the curve is getting steeper: the gap between what is released and what photosynthesis and the oceans take back has widened as burning of fossil fuels has grown.

Q3 Why was the observatory put on Mauna Loa, over 3,000 m up a volcano in the middle of the Pacific?

B **It is far from cities and forests, so it samples well-mixed air rather than carbon dioxide from one local source**

Local sources, a road, a town, a forest breathing at night, would swamp the signal. High above the Pacific the air has mixed over thousands of kilometres. Gas from the volcano itself is spotted by the wind direction and left out.

How this was made. The course structure, the activities and the teaching choices come from my own classroom, my presentations and my years of teaching IB and AP Biology. I use Claude, an AI, to help write and build the interactive guides, lesson plans, slides and practice questions, and to draw the diagrams and code the interactives. I direct the work and review it against the IB and AP specifications before it goes live.

Written and drawn for Biology by Bradford, biologybybradford.com. Free to print and share with a class.