Course Companion

International Baccalaureate · IB Diploma · Environmental Systems and Societies · HL

Every topic handout in one volume

全部专题讲义合集

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Foundation

International Baccalaureate · IB Diploma · Environmental Systems and Societies · HL

Scope and prerequisites

This handout teaches Topic 1, Foundation (1.1 Perspectives, 1.2 Systems and 1.3 Sustainability), for the course first assessed in 2026. It is written for both SL and HL students. Sections marked **AHL** are for Higher Level only. HL students also apply the three HL lenses (environmental law, environmental and ecological economics, and environmental ethics, units 9 to 11) to these ideas.

Prerequisites: none beyond school science and geography. Topic 1 gives the language that every later topic uses: perspectives, systems, stores and flows, feedback, and sustainability.

Perspectives

Leave the oil in the ground?

Under the Yasuní National Park in Ecuador's Amazon rainforest lies one of the country's largest oil fields. The forest is among the most biodiverse places on Earth and home to Indigenous peoples, some living in voluntary isolation. Oil brings government income that can pay for schools and hospitals. In 2023 Ecuadorians voted in a national referendum, and 58.95% voted Yes to the Yasuní consultation, according to the final electoral result. This is a statement about the 2023 vote, not a claim that all oil activity had already ended. The same facts about oil, forest and money led different people to opposite answers. To understand environmental issues you need to understand why.

Perspectives, values and worldviews

- A **perspective** 观点 is how a person or group sees an issue. It is shaped by their values and worldview.
- **Values** 价值观 are the qualities a person thinks are important, such as freedom, equality, wealth or the welfare of nature.
- A **worldview** 世界观 is a person's whole set of beliefs about how the world works and their place in it.

Environmental value systems

An **environmental value system** 环境价值体系 (EVS) is a worldview or paradigm that shapes how a person or society sees and responds to environmental issues. It can be modelled as a system:

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- **Inputs**: education, culture, religion, family, media, economic and political situation.
- **Processes**: the person interprets these inputs through their values.
- **Outputs**: decisions, actions and the way they live, such as what they buy, how they vote, or whether they protest.

EVSs lie on a spectrum.



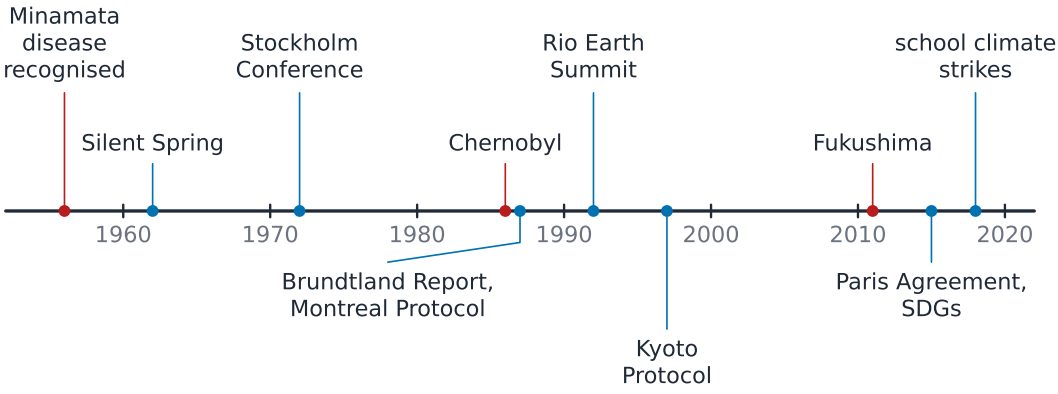
Environmental value systems form a spectrum from nature-centred to technology-centred

EVS	Central belief	Typical response to a problem
ecocentric 生态中心主义	nature has value in itself, not only for its use to people; humans are part of nature	reduce consumption, live simply and locally, protect wild areas; deep ecology challenges treating non-human life merely as a resource
anthropocentric 人类中心主义	people should manage the environment for human benefit, sustainably	environmental managers use laws, taxes, quotas, planning and international agreements
technocentric 技术中心主义	human technology and markets can solve environmental problems	invest in new technology such as renewable energy, carbon capture or new crops; cornucopians see resources as almost unlimited

Most people and societies are not at one extreme. A government might fund solar power (technocentric) while taxing pollution (anthropocentric) and protecting a national park (ecocentric).

How perspectives have changed

Events and books have shifted public perspectives over time.



Disasters and agreements that changed how people see the environment

- **Minamata, Japan (1956)**: mercury waste from a chemical factory poisoned fish and the people who ate them, showing that pollution travels through food chains.
- **Silent Spring (1962)**: Rachel Carson showed how the pesticide DDT harmed birds and other wildlife. It helped start the modern environmental movement.
- **The UN Stockholm Conference (1972)**: the first major international meeting on the environment; it set up the UN Environment Programme.
- **Bhopal (1984), Chernobyl (1986), Fukushima (2011)**: industrial and nuclear disasters that made people question the safety of technology.
- **The Brundtland Report (1987)** defined sustainable development; **the Montreal Protocol (1987)** phased out ozone-destroying chemicals.
- **The Rio Earth Summit (1992)**, **the Kyoto Protocol (1997)** and **the Paris Agreement (2015)** brought countries together on biodiversity and climate.
- **School climate strikes (2018 onwards)**: young people demanding faster action on climate change.

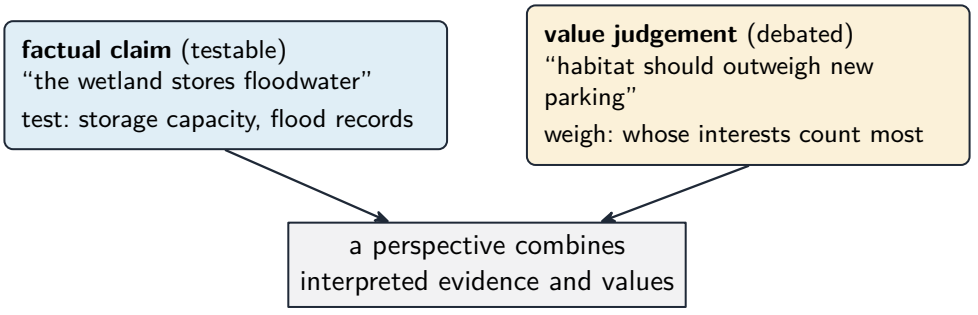
Indigenous perspectives

Many Indigenous cultures see people as part of nature, with responsibilities to the land and to future generations. Their knowledge of local ecosystems, built up over generations, is increasingly used in conservation. In New Zealand, section 14 of the Te Awa Tupua (Whanganui River Claims Settlement) Act 2017 gives Te Awa Tupua legal personhood, within a particular settlement and representation framework. This example reflects Whanganui iwi relationships with the river; it is not a claim that all Indigenous communities share one worldview. Perspectives like these challenge the idea that nature is only a resource.

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Investigating perspectives fairly

Separate a factual claim ("the wetland stores floodwater") from a value judgement ("protecting habitat should outweigh new parking"). Evidence can test storage capacity and flood risk, but does not by itself choose whose interests count most. A perspective combines interpreted evidence and values; neither a job title nor one purchase establishes a person's entire EVS. Campaigns, education, experience and new technologies can change beliefs and behaviour.



Separate testable claims from value judgements: a perspective combines both

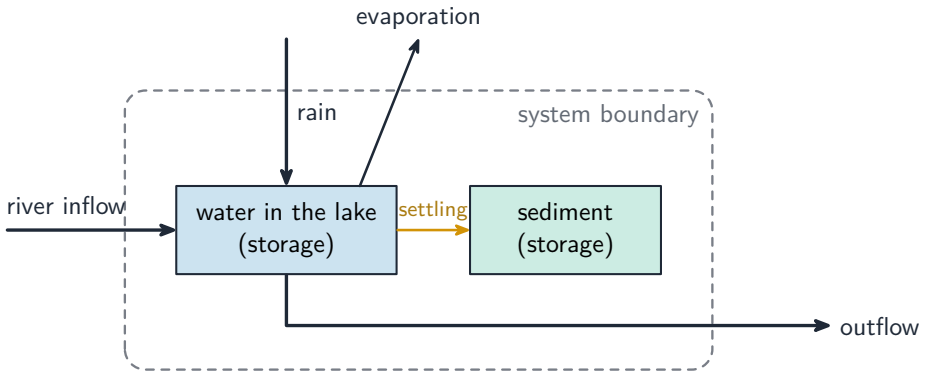
For a values survey, define the population and use neutral questions with balanced options and a chance to explain a choice. Sample beyond one friendship group, seek voluntary informed participation, and protect privacy. Compare stated attitudes with a defined behaviour over time; changing respondents, question wording or access to services can imitate a change in values. A correlation between survey answers and behaviour does not establish causation.

Systems

The systems approach

A **system** 系统 is a set of parts that interact to form a whole. The **systems approach** looks at how the parts are connected, rather than studying each part separately. Environmental issues involve natural and human parts, so this approach helps to see the whole picture.

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A systems diagram: storages as boxes, flows as arrows, inside a stated boundary

Every system has:

- **Storages** 储存 (stocks): amounts of matter or energy held at a stated time, such as water in a lake or carbon in a forest's trees.
- **Flows** 流动: movements into, out of and within the system, measured as an amount per unit time, such as rainfall in mm per year.
- **Boundaries** 边界: the edges of the system, chosen by the person studying it.

A stock is an amount at one time; a flow is a rate. Mixing them up is a common mistake.

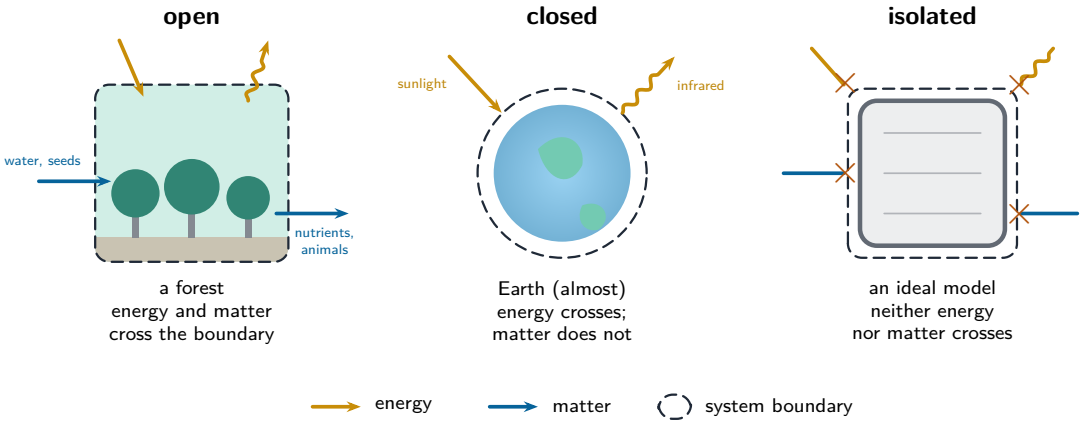
■ Transfers and transformations

Flows are of two kinds:

- **Transfers** 转移 move matter or energy from one place to another without changing its form or state: water flowing down a river, ingested biomass moving from prey to predator (subsequent digestion and respiration include transformations), heat conducted through soil.
- **Transformations** 转化 change the form or state of matter or energy: water evaporating, light energy becoming chemical energy in photosynthesis, organic matter decomposing into carbon dioxide.

■ Open, closed and isolated systems

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What crosses the boundary decides the type of system

System	Exchanges energy?	Exchanges matter?	Example
open	yes	yes	a forest, a lake, a city
closed	yes	no	the Earth (almost: a little gas escapes and meteorites arrive); a sealed terrarium
isolated	no	no	an ideal perfectly insulated, sealed model; real local examples only approximate it

Biosphere 2, a huge sealed greenhouse built in Arizona in the 1990s, tried to keep eight people alive in a closed system. Oxygen levels fell so low that extra oxygen had to be pumped in, a sign of how hard it is to copy the Earth's natural systems.

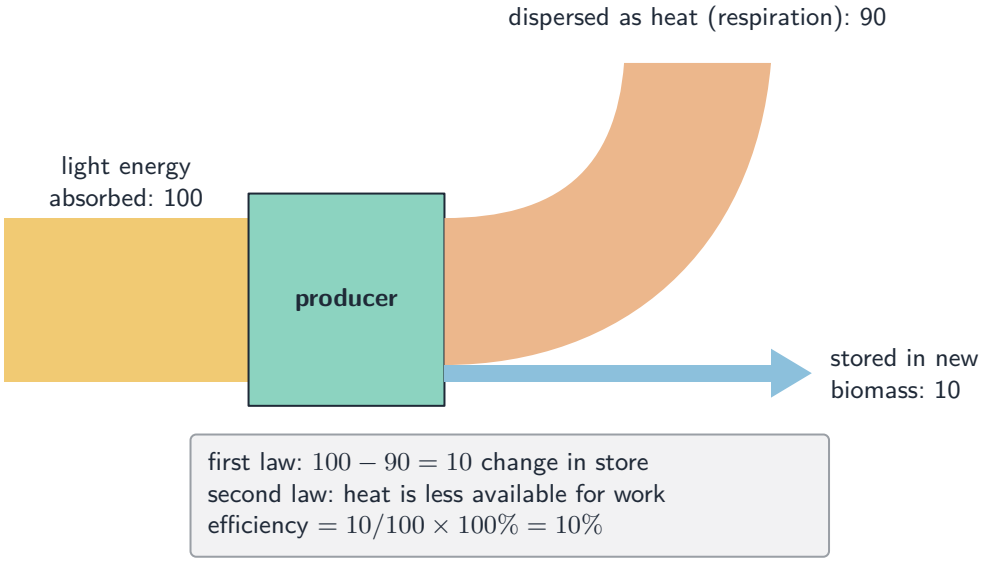
Models

A **model** 模型 is a simplified version of reality, such as a diagram, an equation or a computer simulation.

- **Strengths**: makes complex systems easier to understand; allows predictions (for example, climate models); can be changed to test "what if?" questions.
- **Limitations**: leaves things out, so it may be inaccurate; depends on its assumptions and data; different models can give different predictions; results may be presented as more certain than they are.

Energy in systems

Energy flows through ecosystems following the laws of thermodynamics.



In minus out equals the change in store; most energy leaves as heat, which is less available for further work

- **The first law**: energy cannot be created or destroyed, only changed from one form to another. Over a stated interval, energy entering minus energy leaving equals the **change** in energy stored, not the total pre-existing store.
- **The second law**: total **entropy** 熵 does not decrease in an isolated system, and irreversible processes increase it. In ecosystems, respiration and other processes disperse energy as thermal energy, reducing its availability for further biological work. This does not mean energy is destroyed or that every possible energy conversion must have a useful-output efficiency below 100%.

Food chains have limited energy available at higher trophic levels: not all biomass is eaten or assimilated, and respiration disperses energy as heat. Uneaten matter and wastes also support decomposer pathways. There is no universal four- or five-level maximum or fixed transfer efficiency for every ecosystem.

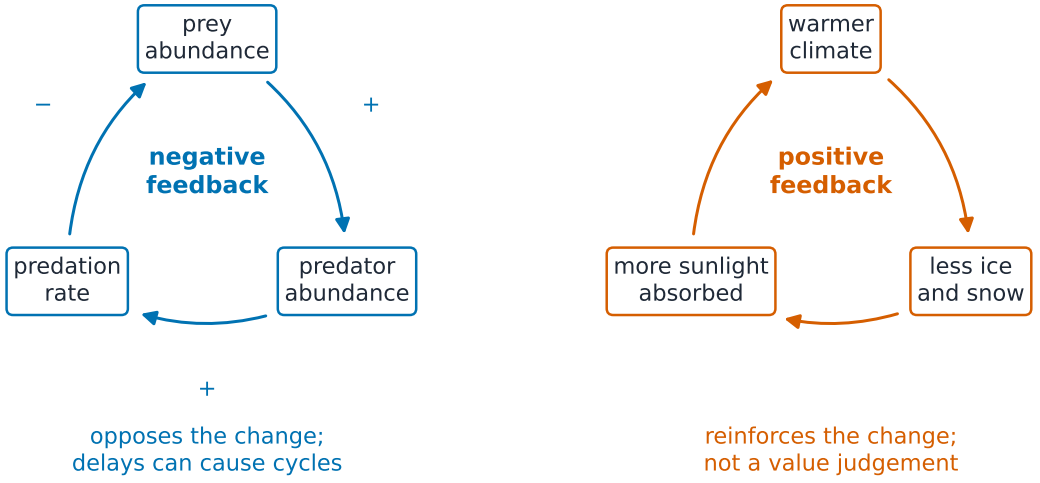
$$\text{efficiency} = \frac{\text{useful energy out}}{\text{energy in}} \times 100\,\%$$

Equilibrium and feedback

- A **steady-state equilibrium** 稳态平衡 is typical of open systems: inputs and outputs balance, so the storages stay roughly constant, although there are small changes around an average. A forest can approximate this over a chosen interval, but real forests also develop and undergo disturbance.
- A **static equilibrium** has no change at all; it does not occur in living systems.

- A **stable equilibrium** returns to its original state after a disturbance; an **unstable equilibrium** amplifies small departures rather than restoring the previous state.

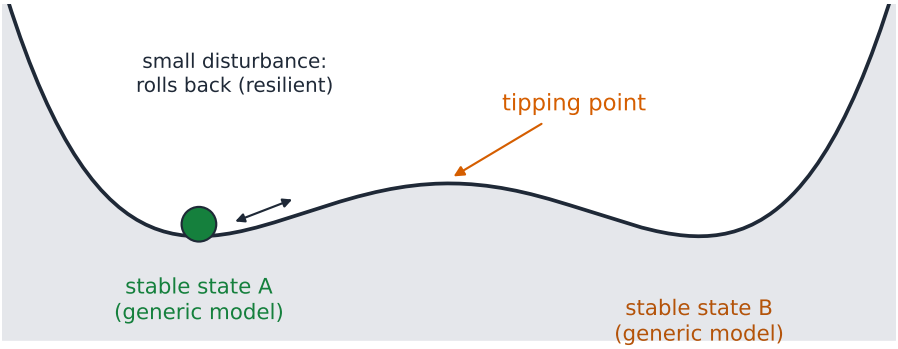
Feedback 反馈 happens when the output of a process affects its own input. In the signed causal diagram, a + link means increasing one variable tends to increase the next; a − link means it tends to decrease the next, other conditions held equal.



Negative feedback opposes a departure; positive feedback reinforces it. Delays and other processes affect the actual trajectory

- **Negative feedback** 负反馈 counteracts an initial change and can promote stability. Delays can produce oscillations rather than an immediate return. Example: when prey increase, predators have more food and increase; they eat more prey, so the prey population falls back.
- **Positive feedback** 正反馈 amplifies a change and moves the system away from its equilibrium. Examples: warming melts ice, exposing darker surfaces that absorb more sunlight and cause more warming; warming thaws permafrost, which can release carbon dioxide and methane, increasing warming. Feedback can amplify a decrease as well as an increase; "positive" is not a judgement that the outcome is beneficial.

■ Tipping points and resilience



Past the tipping point, positive feedback carries the system to a new state

- A **tipping point** 临界点 is a critical threshold. When it is passed, positive feedback carries the system into a new state, which is often hard or impossible to reverse. Rainforest loss and drying illustrate a possible interacting-feedback risk, not one known universal clearing percentage or a guaranteed uniform switch of the whole Amazon. The pictured landscape is a generic model of alternative states, not measured Amazon topography.
- **Resilience** 恢复力 is the ability of a system to stay in, or return to, its equilibrium after a disturbance. Possible contributing factors include:
  - high diversity (many species and connections, so the loss of one has less effect);
  - large storages (a large forest or a deep lake);
  - recovery traits, seed banks and connectivity appropriate to the disturbance. Fast reproduction alone does not establish resilience to every disturbance.
- Humans often reduce resilience: monocultures, overfishing and habitat loss remove diversity and shrink storages.

The **Gaia hypothesis**, proposed by James Lovelock in the 1970s, models the whole Earth as a self-regulating system in which living things and their surroundings interact, through negative feedback, to influence atmospheric composition and temperature. Lynn Margulis also developed these ideas. It does not imply conscious planetary planning or guaranteed protection against every disturbance.

In **Daisyworld**, Watson and Lovelock used an imaginary planet with dark and light daisies. Dark daisies absorb more sunlight and warm their local environment; light daisies reflect more and cool it. Growth depends on temperature, so changes in coverage can oppose changes in solar input over a limited range. At extreme conditions daisies cannot grow and regulation fails. The model demonstrates possible biological regulation through feedback, not proof that the real Earth must always remain habitable.

Earth-system interactions connect the biosphere (life), hydrosphere (water), cryosphere (ice), geosphere (rocks and soils), atmosphere (air) and anthroposphere (human systems). A city's imported food links its local consumption to water, land

and energy flows elsewhere. Choose a spatial boundary and time interval before judging whether a budget is complete.

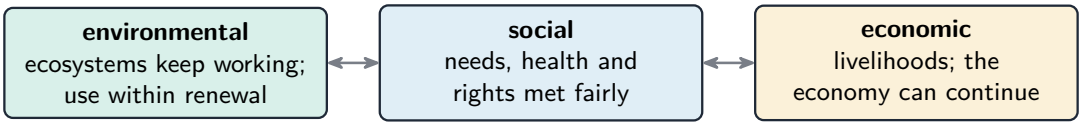
Sustainability

What sustainability means

Sustainability 可持续性 concerns long-term viability of linked human and environmental systems, including the conditions available to future generations. Renewable-resource use must respect regeneration and ecosystem recovery; a non-renewable mineral is not naturally replaced on a human timescale. Pollution, biodiversity and fair access matter as well as resource totals. It has three connected parts:



Wind turbines on farmland: sustainable resource use meets present needs without locking out future generations



Brundtland (1987): meet present needs without compromising the ability of future generations to meet their own

Three connected parts of sustainability

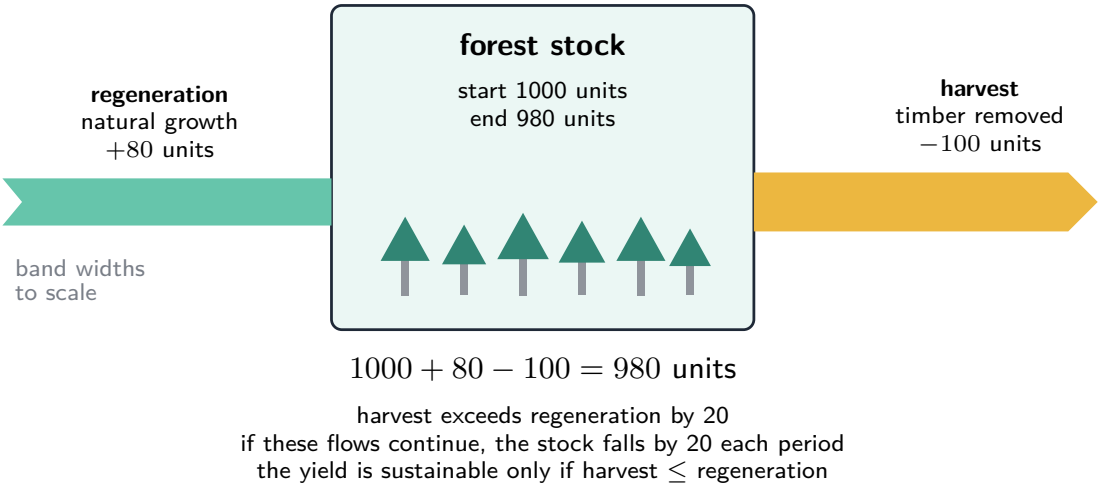
- **environmental**: ecosystems keep working and resources are not used faster than they renew;
- **social**: people's needs, health and rights are met fairly;
- **economic**: people can earn a living and the economy can continue.

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Sustainable development 可持续发展 was defined by the Brundtland Report (1987) as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs".

Natural capital and natural income

- **Natural capital** 自然资本 is the stock of natural resources, such as forests, soil, fish stocks, groundwater and minerals.
- **Natural income** 自然收入 is the yield from that capital, the amount produced each year, such as the new growth of a forest or the young fish added to a stock.



One-period model: $1000 + 80 - 100 = 980$ *units; use exceeds regeneration by 20. A sustained-yield calculation also needs uncertainty and protection of other ecosystem functions.*

For renewable resources, keeping harvest within a defensible net regeneration budget helps maintain natural capital. Growth is not always constant, and reproduction alone is not net growth if mortality and other losses are omitted. A volume balance also cannot guarantee that habitat, species diversity and soil remain intact.

Example: a forest holds 500 000 m^3 of timber and grows by 2 % a year. Its natural income is 10 000 m^3 a year. Cutting 15 000 m^3 a year uses up the capital and is unsustainable.

Ecosystem services

Natural capital provides **ecosystem services** 生态系统服务, the benefits people get from ecosystems:

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Type	Examples
provisioning	food, fresh water, timber, medicines
regulating	climate regulation by carbon storage, flood control by wetlands, pollination, water purification
supporting	soil formation, nutrient cycling, photosynthesis
cultural	recreation, tourism, spiritual and educational value

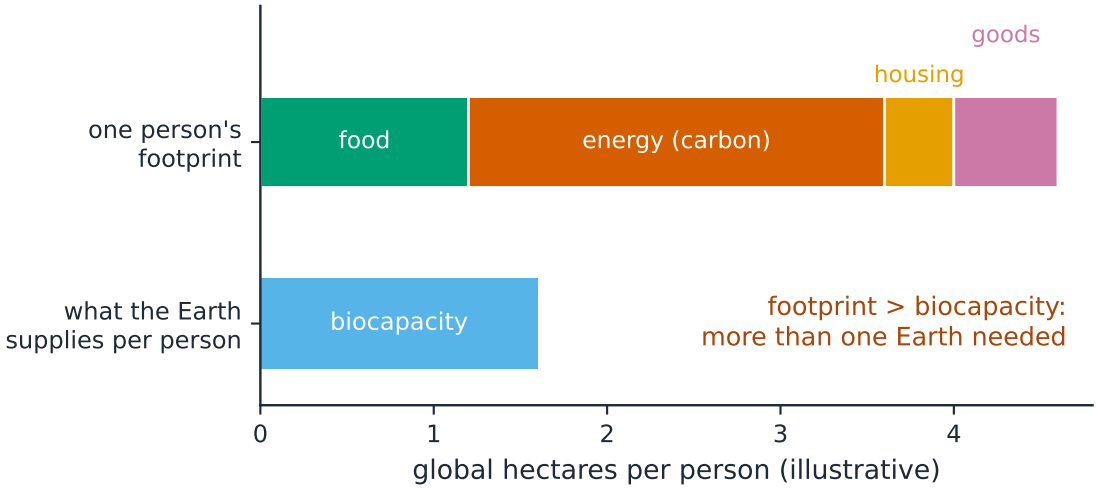
Many of these services have no market price, so they are easily ignored when decisions are made.

The Sustainable Development Goals

In 2015 the United Nations agreed 17 **Sustainable Development Goals** (SDGs) for 2030, such as no poverty, zero hunger, clean water, affordable and clean energy, climate action, life below water and life on land. They link environmental, social and economic aims. Critics point out that some goals conflict (economic growth can increase resource use) and that progress is hard to measure and uneven.

Measuring sustainability

Environmental indicators show the state of the environment, for example biodiversity, pollution levels, forest cover or atmospheric carbon dioxide.



An ecological footprint larger than the Earth's biocapacity per person

The **ecological footprint** 生态足迹 (EF) estimates biologically productive area needed for consumption and waste assimilation within its accounting scope, measured in global hectares (gha). The Global Footprint Network method includes cropland, grazing land, fishing grounds, forest products, built-up land and carbon demand; it does not measure every pollutant or all ecological harm.

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- **Biocapacity** 生物承载力 expresses the capacity of biologically productive land and water to regenerate resources and absorb wastes under the accounting method, normalised to global hectares rather than simply counting physical hectares.
- If footprint exceeds a region's biocapacity, there is an **ecological deficit**. The region may rely on imports, depletion or net carbon accumulation; the ratio alone does not identify which. Global overshoot cannot be solved by importing biocapacity from another planet.
- The 2024 estimate placed **Earth Overshoot Day** on 1 August: annual demand about 1.7 times regeneration under that accounting method. This dated estimate is not a literal day when every resource ran out; revisions affect comparisons.

Related footprints measure one part of this: a **carbon footprint** (greenhouse gases emitted, in tonnes of CO_2 equivalent) and a **water footprint** (direct and supply-chain freshwater use, with scope and period stated). Different methods distinguish consumed surface/groundwater, rainwater and a pollution-related dilution-volume indicator; not every component means water physically withdrawn.

Example: a country of 50 million people has a total ecological footprint of 2.0×10^8 gha and a biocapacity of 1.2×10^8 gha. The footprint per person is 4.0 gha, the biocapacity per person is 2.4 gha, so the deficit is 1.6 gha per person: its demand-to-biocapacity ratio is $4.0/2.4 = 1.67$. This is a normalised accounting ratio, not a direct statement that precisely that many copies of its physical land area would solve all impacts.

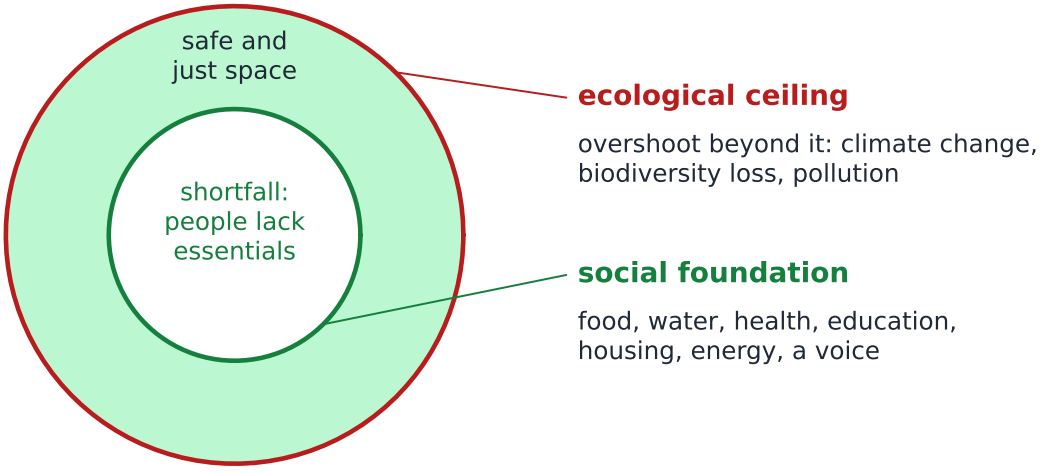
■ Planetary boundaries

The **planetary boundaries** 地球边界 model (Rockström and others, 2009) identifies nine Earth processes, including climate change, biodiversity loss (biosphere integrity), land-use change, freshwater use, nitrogen and phosphorus flows, ocean acidification and new pollutants. Each has a boundary beyond which the risk of sudden, irreversible change rises. The remaining categories are stratospheric ozone depletion and atmospheric aerosol loading. The 2023 assessment reported six crossed boundaries; the 2025 update reported seven. Date the assessment: definitions, indicators and evidence can change. A boundary is a risk-management limit with uncertainty, not an exact countdown to a single tipping event or a ready-made local pollution permit.

■ Doughnut economics

Doughnut economics 甜甜圈经济学, developed by Kate Raworth, combines planetary boundaries with human needs. Everyone should have enough to meet a social foundation (food, water, health, education, housing, energy, a political voice), without the whole of humanity overshooting the ecological ceiling. The aim is to live between these limits. **Regenerative** design restores ecological functions; **distributive** design shares opportunities and benefits fairly. The diagram helps compare aims but does not select a unique policy or measure progress without defined indicators.

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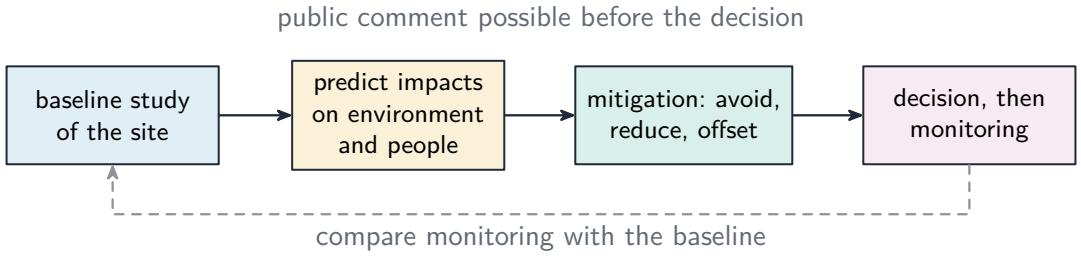
The safe and just space lies between the social foundation and the ecological ceiling

The circular economy

- In a **linear economy**, resources are taken, made into products, used and thrown away.
- In a **circular economy** 循环经济, products are designed to last and to be repaired, reused, shared and recycled, so materials stay in use and waste is designed out. Suitable uncontaminated biological materials can be returned through biological cycles. Collection losses, contamination, material degradation and energy use prevent perfect indefinite recycling; repair and reuse can avoid more resource demand than recycling alone. Lower impact per product also need not lower total impact if consumption grows.

Environmental impact assessments

An **environmental impact assessment** 环境影响评价 (EIA) is a report made before a major development, such as a dam, road or mine, to predict its effects on the environment and people. Many countries require one by law.



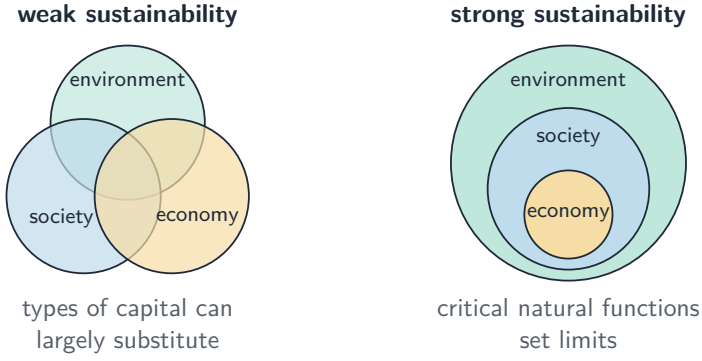
The steps of an environmental impact assessment

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- **Steps**: a baseline study of the area before development; prediction of impacts; ways to avoid, reduce or make up for them (mitigation); monitoring afterwards.
- **Strengths**: environmental effects are considered before a decision is made; the public can comment; it can lead to a better design.
- **Limitations**: predictions are uncertain; baseline studies may be short; the developer may pay for the report; the decision may still go ahead despite the findings; indirect and long-term effects are hard to measure.

Testing sustainability claims

Strong sustainability treats critical natural functions as limits that money or machinery cannot always replace: draw the economy inside society and both inside the environment. Weak sustainability allows more substitution between types of capital. A wetland's loss may not be compensated by a higher bank balance if flood storage or an irreplaceable habitat disappears. These are assumptions to debate, not labels proving a policy is sustainable.



Weak sustainability allows substitution; strong sustainability nests the economy inside environmental limits

GDP records production over a period, not a complete account of well-being or ecosystem condition. Spending on pollution cleanup can increase measured output while environmental harm persists. A green-GDP adjustment estimates environmental costs, but valuation and missing information remain limitations. Add ecological and social indicators; report distribution as well as averages.

Environmental justice asks who receives benefits, who bears harm, who has access to resources and whose voice counts. A landfill can impose local pollution and traffic costs on households with little influence. Across borders, exported waste can shift health risks away from consumers. Income, gender, cultural identity and unequal legal protection can affect access to clean water, food and energy. A lower city-average pollution value does not establish equal protection for every neighbourhood.

Citizen science can extend monitoring through repeated community observations, such as birds counted with a common protocol. Record effort, season, site and identifica-

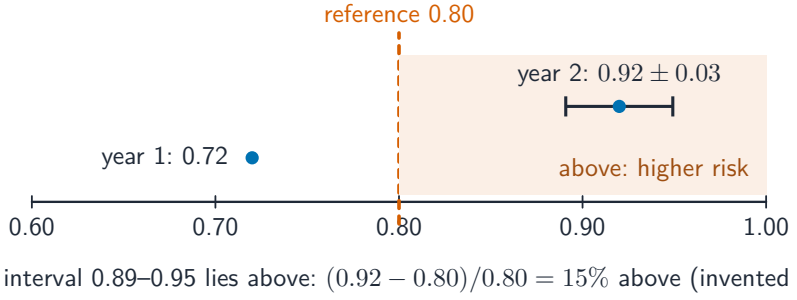
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tion confidence; volunteer locations may be biased toward accessible places. Shared methods and expert checks make data more comparable, but a growing number of submissions alone does not prove a species is increasing.

For a reservoir, initial storage is 800 m^3; mean input and output rates are 120 and 90 m^3/day for three days. Final storage is $800 + (120 - 90) \times 3 = 890$ m^3. If final measured storage is instead 875 m^3, the 15 m^3 discrepancy may represent an omitted net loss, measurement error or changing flow rates; it does not uniquely prove a leak.

AHL: Quantify a boundary comparison

Use the assessment date, named control variable, units and direction of risk before comparing values. For an **index** with an upper acceptable reference 0.80, observations 0.72 in year 1 and 0.92 ± 0.03 in year 2 imply a later interval 0.89–0.95, entirely above the reference. Its central value is $(0.92 - 0.80)/0.80 \times 100 = 15\,\%$ above the reference, not 15 percentage points. This index is not an actual planetary-boundary dataset.



Comparing an uncertain value with a reference: the whole interval lies above

If the reference itself were uncertain over 0.70–0.95, the same observations would not establish a clear crossing against the whole reference interval. For real boundaries, choose the relevant control variable and published uncertainty zone; do not treat a count of crossed boundaries as a percentage of the planet already destroyed. Law, economics and ethics then address responsibilities, costs and fair choices; the numerical comparison alone cannot settle them.

Practice

1. (a) Distinguish between a value and a worldview, and define an environmental value system. (b) Describe the inputs and outputs of an environmental value system as a system.
2. Outline how an ecocentric person and a technocentric person might each respond to a shortage of fresh water.
3. Explain how one historical event changed environmental perspectives.

4. (a) Distinguish between a storage and a flow, and give one example of each in a lake. (b) Classify each as a transfer or a transformation: (a) rain falling into a river; (b) photosynthesis; (c) a rabbit eaten by a fox; (d) water evaporating from a lake.
5. Distinguish between open, closed and isolated systems, with an example of each where possible.
6. Evaluate the use of models in environmental science.
7. Explain why less energy is generally available to higher trophic levels, distinguishing respiration from uneaten or unassimilated biomass. Does this fix one universal maximum food-chain length?
8. Distinguish between negative and positive feedback, giving an environmental example of each.
9. Explain what is meant by a tipping point, and outline two factors that increase the resilience of an ecosystem.
10. A forest holds 800 000 m^3 of timber and grows by 1.5 % a year. Calculate its natural income, and state whether harvesting 15 000 m^3 a year is sustainable.
11. A country of 20 million people has a total ecological footprint of 9.0×10^7 gha and a biocapacity of 5.0×10^7 gha. Calculate the footprint and biocapacity per person and the ecological deficit per person.
12. State one example of each type of ecosystem service.
13. Outline the doughnut economics model, and explain how it differs from aiming for economic growth.
14. Evaluate the use of environmental impact assessments.

Answers.

1. (a) A value identifies what matters; a worldview connects beliefs about the world and our place in it. An EVS models how such influences shape environmental judgements and actions. (b) Inputs: education, culture, religion, family, media, economic and political situation. Outputs: decisions and actions, such as what they buy, how they vote and how they live.
2. Ecocentric: use less water, protect wetlands and rivers, accept limits on growth. Technocentric: build desalination plants, recycle waste water, develop drought-resistant crops.
3. For example, Silent Spring (1962) showed that the pesticide DDT harmed wildlife, raising awareness that human chemicals move through food chains; it led to bans on DDT and helped start the environmental movement.
4. (a) A storage is an amount held at one time; a flow is a movement per unit time. Storage: water in the lake, or fish biomass. Flow: a river flowing in, evaporation, or fish being caught. (b) (a) Transfer. (b) Transformation of light energy into chemical energy, with chemical changes. (c) The movement of ingested biomass is a transfer; digestion and respiration also involve transformations. (d) Transformation through a change of state.

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5. Open systems exchange energy and matter, such as a forest. Closed systems exchange energy but not matter; Earth is an approximation because small material exchanges occur. Isolated systems exchange neither; a perfectly sealed, insulated model is an idealisation for practical environmental work.
6. Models simplify complex systems, make them easier to understand and allow predictions to be tested. But they leave things out, depend on assumptions and data, can give different results, and may seem more certain than they are.
7. Not all lower-level biomass is consumed or assimilated, and respiration disperses energy as heat, reducing energy available in higher-level biomass. Uneaten material and wastes can enter decomposer pathways. Total energy is conserved; chain length and transfer efficiency vary, so this is not an exact four- or five-level law.
8. Negative feedback counteracts a change; increased prey can support more predators, whose feeding reduces prey, with delays potentially causing oscillations. Positive feedback reinforces a change; warming reduces reflective ice, increasing absorbed sunlight and further warming. Neither feedback sign is a judgement of social benefit.
9. A tipping point is a critical transition threshold, not necessarily an exactly known number. Functional diversity and suitable recovery traits/connectivity can help resilience, depending on the disturbance. Large stores or fast reproduction alone do not guarantee recovery.
10. $0.015 \times 800\,000 = 12\,000$ m^3 a year. Harvest exceeds this net growth by 3000 m^3, reducing the stock. Harvest within this modelled income would still require checks on growth assumptions and habitat impacts.
11. Footprint: $\dfrac{9.0 \times 10^7}{2.0 \times 10^7} = 4.5$ gha per person. Biocapacity: 2.5 gha per person. Deficit: 2.0 gha per person. The ratio is 1.8; this is a regional accounting deficit, which needs trade, depletion and carbon-emission evidence for interpretation.
12. Provisioning: food or timber. Regulating: carbon storage or flood control. Supporting: soil formation or nutrient cycling. Cultural: recreation or spiritual value.
13. The inner limit is the social foundation; the outer limit is the ecological ceiling. Success means meeting needs within these limits, not maximising production alone.
14. EIAs assess impacts before decisions and support public participation. Weak baselines, uncertain predictions and conflicts of interest limit reliability; approval and effective mitigation are not guaranteed.

Exam tips

- Show working and units; trace feedback; separate evidence, assumptions and values; justify a balanced conclusion at a stated scale.

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Ecology

International Baccalaureate · IB Diploma · Environmental Systems and Societies · HL

Scope and prerequisites

This handout teaches Topic 2, Ecology (2.1 Individuals, populations, communities and ecosystems; 2.2 Energy and biomass in ecosystems; 2.3 Biogeochemical cycles; 2.4 Climate and biomes; 2.5 Zonation, succession and change in ecosystems), for the course first assessed in 2026. It is written for both SL and HL students. Sections marked **AHL** are for Higher Level only. HL students also apply the three HL lenses (environmental law, environmental and ecological economics, and environmental ethics, units 9 to 11) to these ideas.

Prerequisites: Topic 1 (systems, storages and flows, feedback, the laws of thermodynamics). Simple biology helps: photosynthesis, respiration and food chains.

Individuals, populations and communities

Fourteen wolves

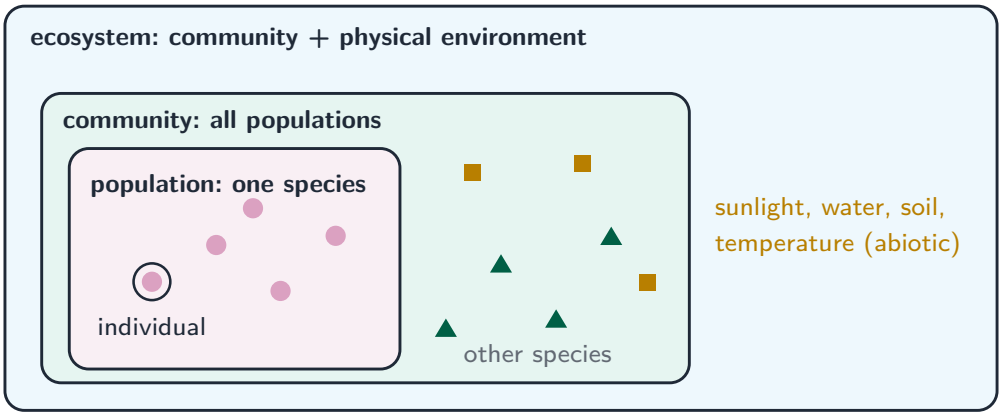
In 1995, 14 grey wolves were reintroduced to Yellowstone; more followed. Predator recovery created opportunities to investigate links among wolves, elk, vegetation and other species. Some vegetation changes are consistent with a trophic cascade, but the size and causes of particular effects require evidence about other predators, hunting, water, climate and site selection. The National Park Service describes this continuing research. A before-and-after association is not by itself proof that wolves alone changed every river. The central question is how direct and indirect interactions connect a community.

Levels of organisation

- Under the biological species concept, a **species** 物种 comprises populations capable of interbreeding to produce viable fertile offspring and reproductively isolated from others. This concept has limits for fossils, asexual organisms and some hybridising groups; identification can use several kinds of evidence.
- A **population** 种群 is a group of organisms of the same species living in the same area at the same time.
- A **community** 群落 is all the populations of different species living and interacting in an area.
- An **ecosystem** 生态系统 is a community together with its physical (non-living) environment.
- A **habitat** 栖息地 is the place where a species normally lives.

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- A **niche** 生态位 is the role of a species in its ecosystem: where it lives, what it eats, when it is active and how it interacts with other species.



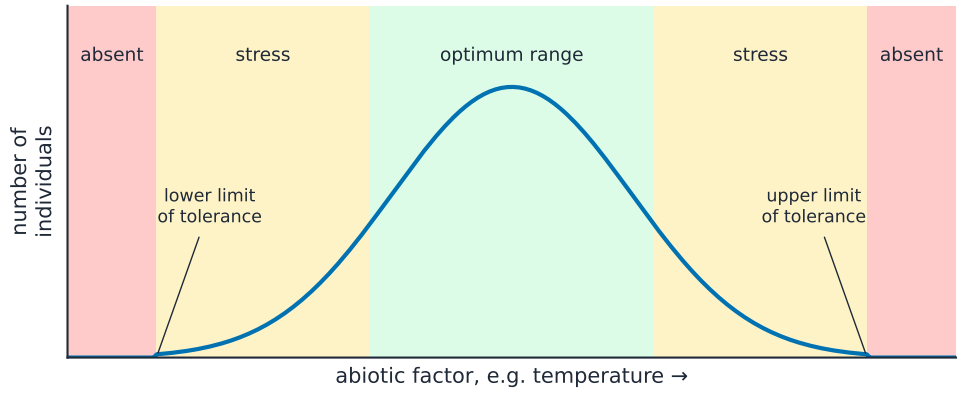
Individual, population, community, ecosystem: each level contains the one before.

Record scientific names as genus followed by specific epithet, for example *Canis lupus*; a shared genus alone does not identify the species. To help identify the species you sample, use a **dichotomous key** 二歧检索表: a series of paired questions ("leaves opposite or alternate?") that leads to one name.

Abiotic and biotic factors

- **Abiotic factors** 非生物因素 are the non-living parts of the environment: temperature, light, water, pH, salinity, soil type, wind and oxygen.
- **Biotic factors** 生物因素 are the living parts: food, predators, competitors, parasites and disease.

Each species can survive only within a range of each abiotic factor, its **range of tolerance** 耐受范围.



A tolerance curve: a species does best in its optimum range and is absent beyond its limits

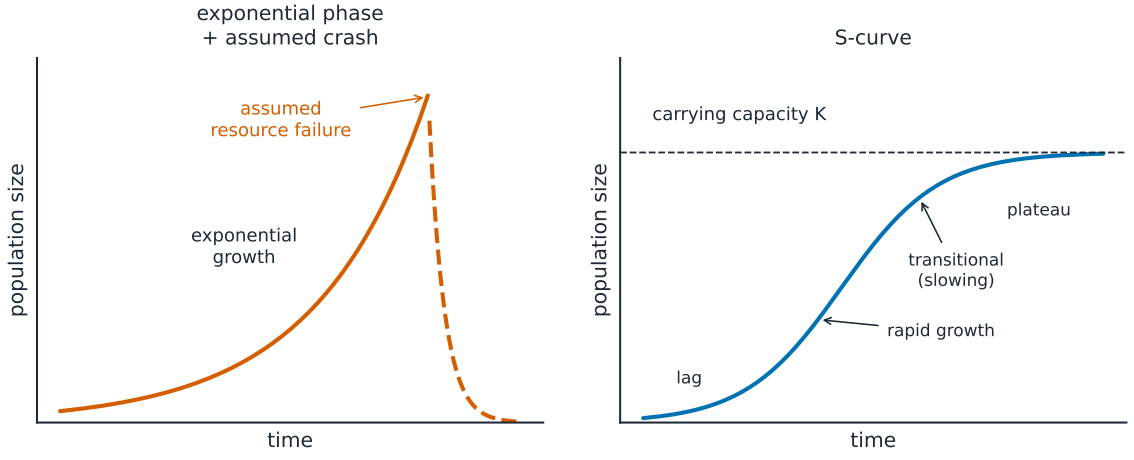
You can measure abiotic factors in the field: a thermometer or temperature probe, a light meter, a pH meter or indicator, a soil moisture probe, an anemometer for wind speed, and a dissolved oxygen meter for water. Measure at the same time of day, repeat the readings, and record the weather, because many factors change through the day.

How populations grow

With plenty of food and space and no predators, a population grows faster and faster: each new generation has more parents than the last. This **exponential growth** 指数增长 gives a **J-curve**. The exponential model does not itself contain a crash. Resource depletion, a changed environment or delayed regulation can end that phase; a boom-and-bust model needs an additional assumption.

More often, growth slows as the population gets bigger, giving an **S-curve** (a **sigmoid curve** 逻辑斯谛曲线):

- **lag phase**: few individuals, so few births;
- **exponential phase**: resources are plentiful and numbers grow quickly;
- **transitional phase**: **limiting factors** 限制因素 such as food, space, predators and disease slow the growth;
- **plateau**: in the simple closed model births equal deaths, and the population stays near its **carrying capacity** 环境承载力 (K), the largest population the environment can support for a long time.



Growth models: a crash requires changed conditions; logistic growth slows under density dependence

The plateau is kept steady by **negative feedback** 负反馈 (Topic 1). Above K, food runs short, so deaths rise and numbers fall; below K, there is more food per individual, so numbers rise. **Density-dependent factors** 密度制约因素 (food supply, disease, predation) act more strongly in a crowded population. **Density-independent factors** 非密度制约因素 (a flood, a frost, a fire) act without their intensity being deter-

mined primarily by population density. Exposure and vulnerability can still vary; the label does not guarantee an identical fraction dies in every population.

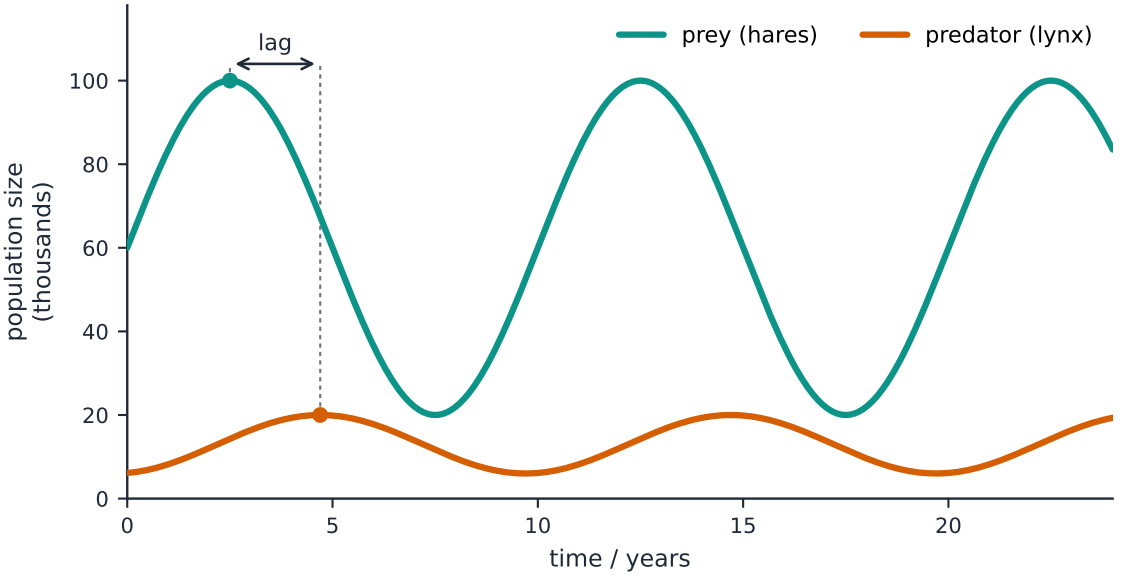
Interactions between species

Interaction	What happens	Example
Competition 竞争	Both need the same limited resource; both lose	Lions and hyenas for prey (between species); two oak seedlings for light (within a species)
Predation 捕食	A predator kills and eats its prey	Wolf and elk; lynx and snowshoe hare
Herbivory 植食	An animal eats plants	Elk browsing on willows
Parasitism 寄生	A parasite lives on or in a host and harms it	Tapeworm in a pig; mistletoe on a tree
Mutualism 互利共生	Both species gain	Bees pollinate flowers and get nectar; nitrogen-fixing bacteria in bean roots
Disease 疾病	A pathogen harms the host	Chytrid fungus killing frogs worldwide



Clownfish shelter among sea-anemone tentacles while the anemone gains food scraps and defence: a mutualism

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The predator population peaks a little after the prey population, because predators need time to breed

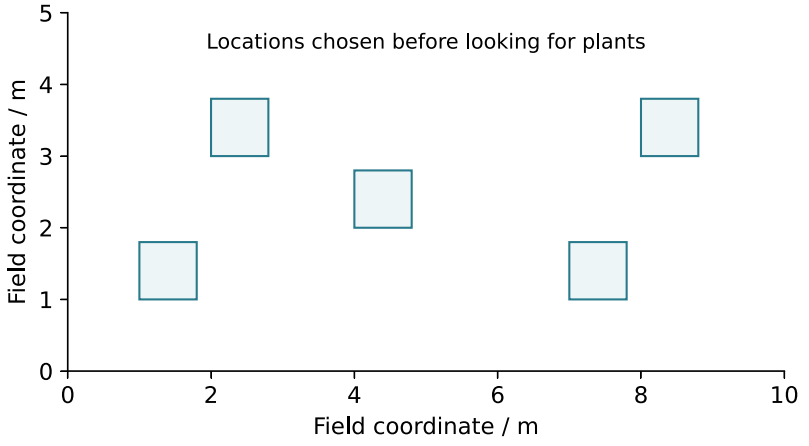
Predator and prey numbers often rise and fall in linked cycles: more prey feeds more predators; more predators eat more prey, so prey numbers fall; then predators starve and fall, and the cycle repeats. This is negative feedback.

A **keystone species** 关键物种 has a much larger effect on its ecosystem than its numbers suggest. Remove it and the community changes greatly. Wolves in Yellowstone, sea otters (which eat sea urchins that would otherwise destroy kelp forests) and beavers are examples.

■ Sampling populations

A complete census may be impractical, so representative sampling can estimate abundance with uncertainty. A **random** 随机 design gives eligible locations a known selection chance. A **systematic** 系统 design samples at fixed intervals, preferably with a random start; periodic habitat structure can still bias it. Stratify a patchy habitat and sample each stratum with appropriate area weighting rather than choosing the richest patches.

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Quadrat positions chosen before looking at the plants avoid sampling bias

- A **quadrat** 样方 is a square frame of known area, such as 0.25 m^2 (50 cm × 50 cm). Place quadrats at random coordinates using random numbers on a grid.
- A **transect** 样带 is a line across a habitat where you sample at regular intervals. Use it where conditions change, such as from a path into a wood or up a beach. Record an abiotic factor at each point too.
- In a quadrat you can record **population density** 种群密度 (number per m^2), **percentage cover** 覆盖度 (how much of the quadrat a species covers, for plants hard to count) or **frequency** 频度 (the percentage of quadrats in which a species appears).

> **Worked example: estimating a plant population.** In a 2000 m^2 field, ten random 0.25 m^2 quadrats contain 46 daisy plants in total.

- Mean per quadrat $= 46 \div 10 = 4.6$ plants.
- Density $= 4.6 \div 0.25 = 18.4$ plants per m^2.
- Estimated population $= 18.4 \times 2000 = 36\,800$ plants.

Quadrats can suit sessile or sufficiently slow-moving animals as well as plants. For suitable mobile animals, use **capture–mark–release–recapture** 标志重捕法 and the **Lincoln index** 林肯指数:

$$N = \frac{M \times C}{R}$$

where M is the number caught and marked the first time, C the total caught the second time, and R the number in the second catch that were already marked.

> **Worked example.** 40 beetles are caught, marked with a dot of paint and released. Two days later 50 are caught, and 8 of them have marks. $N = (40 \times 50) \div 8 = 250$ beetles.

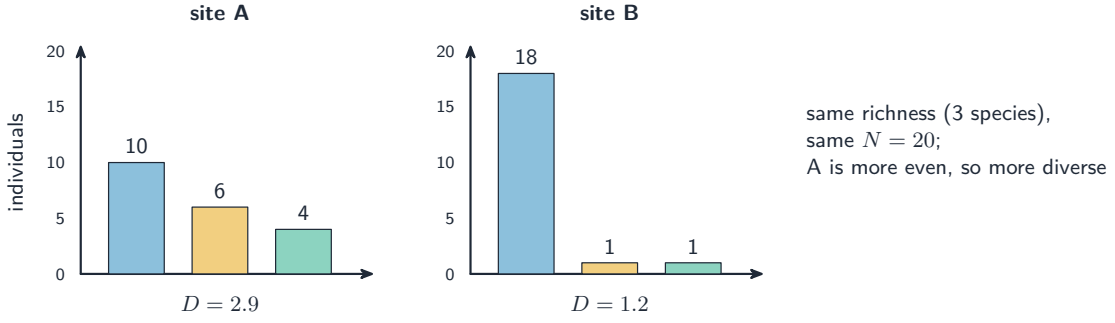
The method assumes that marked animals mix fully into the population, that marks are retained and marking does not affect survival or capture probability, and that no

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animals are born, die, arrive or leave between the two samples. Violations can bias the estimate, with the size and direction depending on the mechanism; sampling variation remains even when assumptions are reasonable. For example, if marks wear off, R is too small and N is too large.

Comparing communities

Species richness 物种丰富度 is the number of species. **Species diversity** 物种多样性 also takes into account how evenly the individuals are shared among the species. **Simpson's reciprocal index** 辛普森倒数指数 measures diversity:



Same richness, different evenness: the more even site has the higher diversity index

$$D = \frac{N(N-1)}{\sum n(n-1)}$$

where N is the total number of individuals and n the number of each species. A higher D indicates greater richness/evenness under this specified index. It is undefined for fewer than two individuals or a zero denominator, so do not divide by zero. Do not mix this reciprocal formula with another index also called Simpson's index.

> **Worked example.** Site A has three species with 10, 6 and 4 individuals; site B has the same three species with 18, 1 and 1.

- Both: $N = 20$, so $N(N-1) = 20 \times 19 = 380$.
- Site A: $\sum n(n-1) = 90 + 30 + 12 = 132$, so $D = 380 \div 132 = 2.9$.
- Site B: $\sum n(n-1) = 306 + 0 + 0 = 306$, so $D = 380 \div 306 = 1.2$.

The richness is the same, but site A is more diverse because its individuals are shared more evenly. A low or falling index can be a sign of pollution or disturbance. Only compare indices for similar habitats sampled in the same way.

Energy and biomass in ecosystems

Producers, consumers and decomposers

- **Producers** 生产者 (autotrophs) make their own food. Most use sunlight in **photosynthesis** 光合作用:

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$$6CO_2 + 6H_2O \xrightarrow{\text{light}} C_6H_{12}O_6 + 6O_2$$

- **Consumers** 消费者 (heterotrophs) get their energy by eating other organisms. Herbivores are primary consumers; carnivores that eat them are secondary consumers, and so on.
- **Decomposers** 分解者 (bacteria and fungi) break down dead matter and wastes and release nutrients back to the soil.
- Aerobic **respiration** 呼吸作用 of glucose uses oxygen:

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

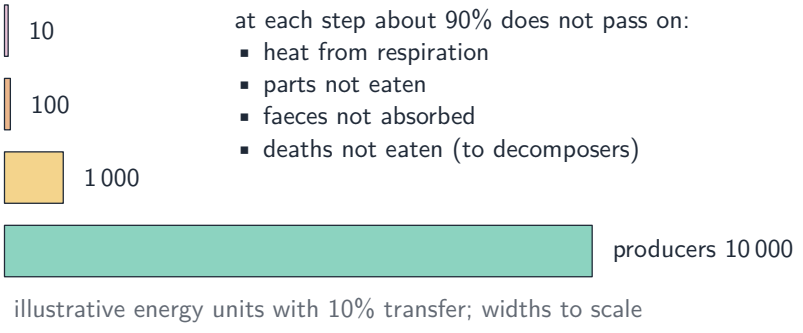
Photosynthesis transforms light energy into chemical energy and stores it in biomass. Respiration transforms that chemical energy into energy the organism can use, and finally into heat, which leaves the ecosystem.

■ Food chains, food webs and trophic levels

A **food chain** 食物链 shows one route of energy from a producer through consumers: grass → rabbit → fox. The arrow means "is eaten by", so it shows the direction energy moves. Each step is a **trophic level** 营养级. Real feeding links form a **food web** 食物网, where most animals eat, and are eaten by, several species.

■ Why food chains are short

Energy enters as sunlight and leaves as heat: it flows through the ecosystem in one direction and is not recycled. At each trophic level, most of the energy taken in is not passed on, because:



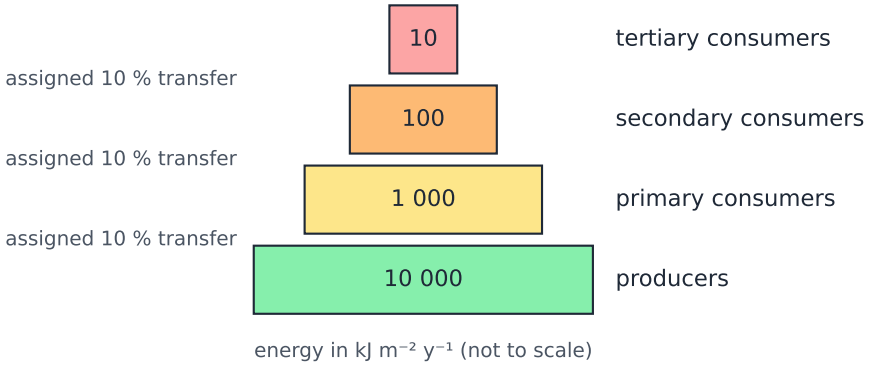
Each trophic level passes on only about a tenth, so chains stay short

- most is released as heat in respiration (the second law of thermodynamics);
- some parts are not eaten (roots, bones, fur);
- some is not absorbed and leaves as faeces;
- some organisms die and are not eaten, so their energy goes to decomposers.

Transfer efficiency varies greatly with organisms and conditions. The illustrated 10% steps are an assigned model, not a universal fixed value or a reliable cross-ecosystem average. Limited production constrains higher trophic levels but does not set an exact four- or five-level maximum.

Ecological pyramids

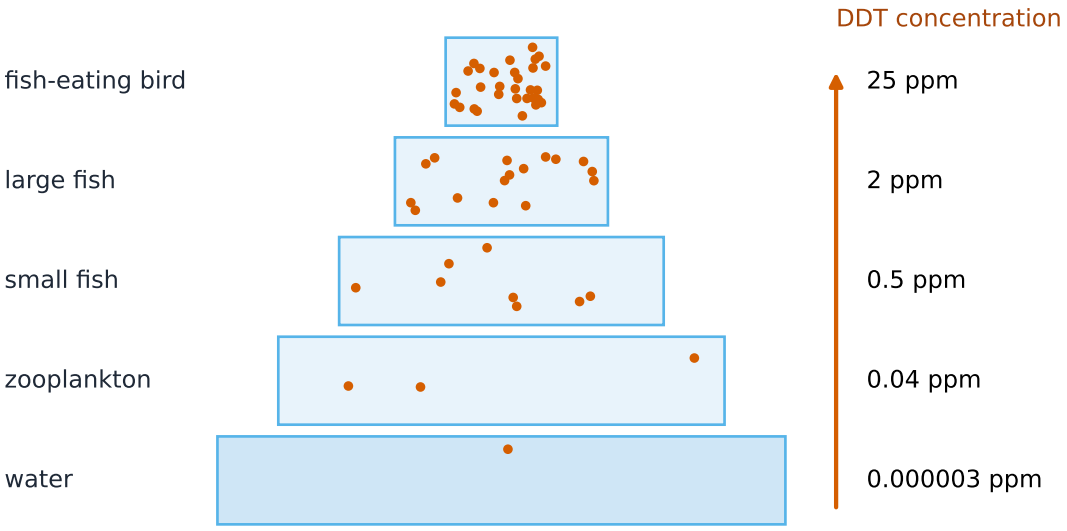
- A **pyramid of numbers** 数量金字塔 shows how many organisms are at each level. It can be inverted: one oak tree supports thousands of caterpillars.
- A **pyramid of biomass** 生物量金字塔 shows the mass of living material at each level, in g m^{-2} (dry mass). It is usually a pyramid, but can be inverted in the sea, where tiny algae reproduce so fast that a small mass at one moment feeds a larger mass of zooplankton.
- A **pyramid of productivity** 生产力金字塔 (pyramid of energy) shows the flow of energy through each level over time, in kJ m^{-2} y^{-1}. It is never inverted, because each level can only pass on part of the energy it receives.



Assigned productivity values illustrate 10% transfers; actual efficiencies vary

Biomagnification

Bioaccumulation is an increasing body burden over time when uptake exceeds elimination. **Biomagnification** 生物放大 is increasing concentration across trophic levels in a food web. Persistence, uptake, elimination and diet all matter; an organism does not retain every molecule from every prey item forever. Some DDT-related compounds are fat-associated, but methylmercury binds strongly to proteins in fish muscle, as described in EPA's fish-contaminant guidance. "All mercury is stored in fat" is incorrect.



Biomagnification: DDT concentration rises at each trophic level

Concentration example: water 0.00005 ppm, plankton 0.04 ppm, small fish 1 ppm and a fish-eating bird 25 ppm, on stated comparable analytical bases. The bird-to-water ratio is $25/0.00005 = 500\,000$. These are not claimed measurements from a named marsh study. A ratio alone does not establish the mechanism; distinguish tissue type, wet/dry mass, chemical form and exposure. DDT-related DDE can cause eggshell thinning in susceptible birds, but that effect is not a property of every persistent pollutant.

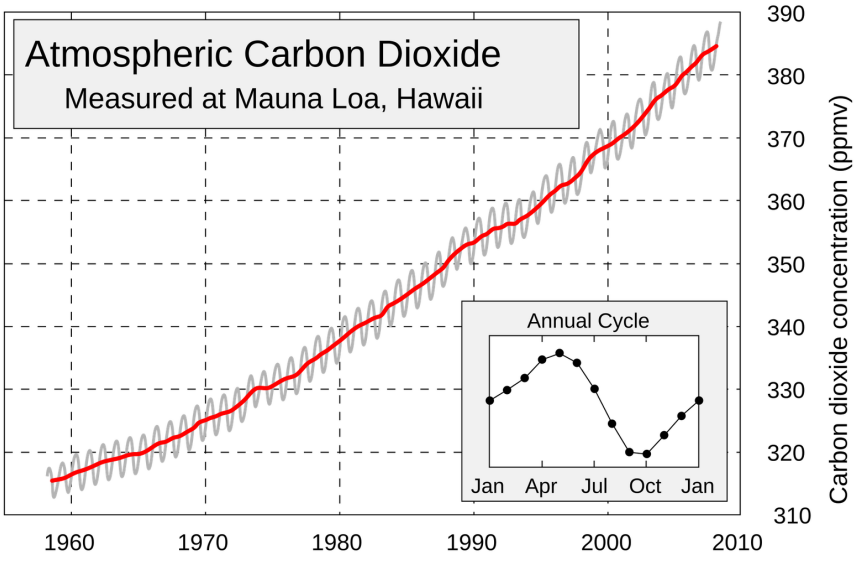
Microplastics can be ingested and can carry sorbed contaminants or additives. Their importance as a chemical-exposure route depends on the material, chemical, environment and other exposure routes; ingestion alone does not establish biomagnification or identical harm in every species.

Biogeochemical cycles

■ Matter cycles, energy flows

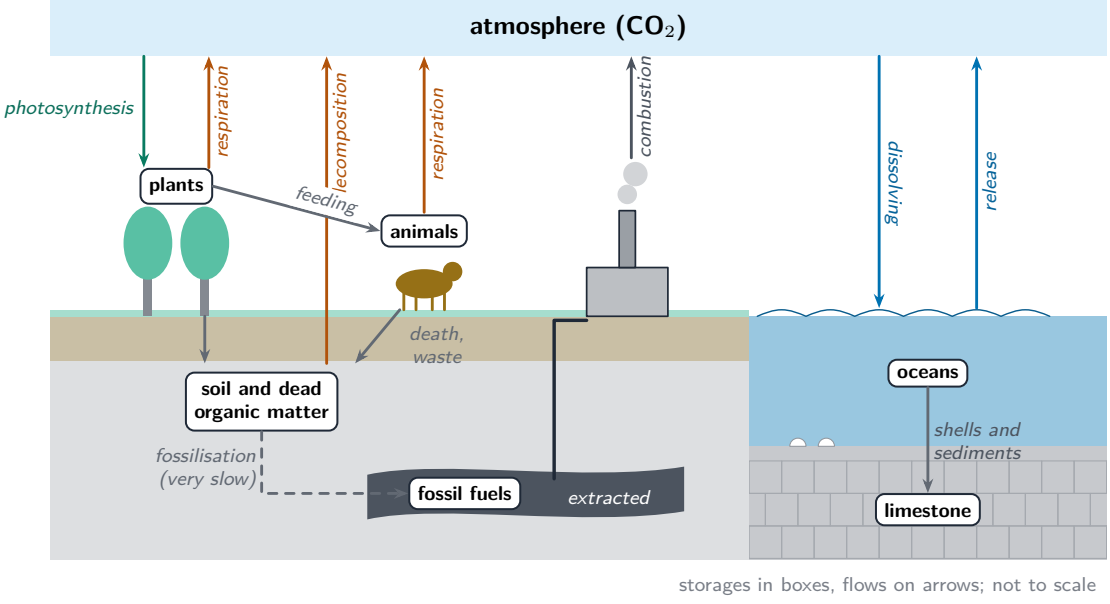
The Earth is almost a closed system for matter, so the same atoms are used again and again. A **biogeochemical cycle** 生物地球化学循环 moves an element such as carbon or nitrogen between living things (bio), rocks (geo) and the air and water (chemical). A store is an amount; a **sink** 汇 takes up more than it releases over a stated interval, while a **source** 源 releases more than it takes up. A large store can change from sink to source, so size alone does not determine its net role.

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Carbon dioxide measured at Mauna Loa since 1958: a yearly ripple on a steady rise

The carbon cycle



The carbon cycle: storages (boxes) and flows (arrows)

Rounded carbon-store scales are approximate teaching estimates, not one contemporaneous measured inventory. Use Gt C for carbon mass; Gt CO_2 differs by a factor 44/12.

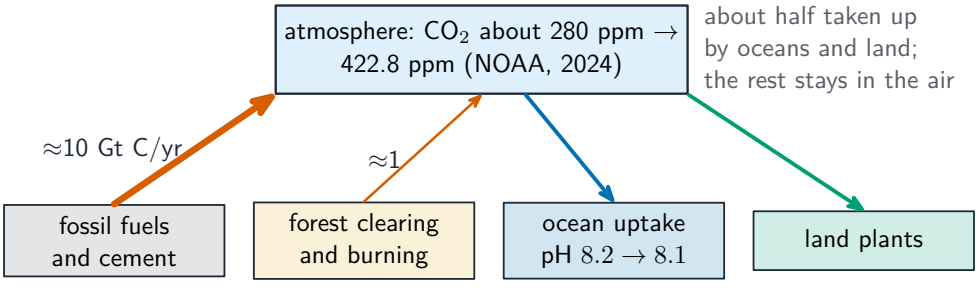
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Storage	Carbon (approximate, Gt C)
Atmosphere	900
Living plants and animals	450 to 650
Soil and dead organic matter	1500 to 2400
Oceans (mainly dissolved)	38 000
Fossil fuels	1000 or more
Sedimentary rock (limestone)	more than 60 000 000

Carbon moves between storages by **flows** at very different rates. Large opposing natural fluxes occur through photosynthesis and respiration; distinguish plant respiration from total land respiration and use a dated dataset for numerical budgets. Even large fluxes can nearly cancel, so a smaller imbalance can drive atmospheric change; carbon can stay in limestone for millions of years. The time a carbon atom typically stays in a storage is its **residence time** 停留时间.

People and the carbon cycle

- Burning fossil fuels and making cement add about 10 Gt C a year to the atmosphere. Clearing and burning forests adds about 1 Gt C more.
- About half of this extra carbon is taken up by the oceans and by land plants; the rest stays in the air. The carbon dioxide concentration in the atmosphere has risen from about 280 ppm before the Industrial Revolution to a NOAA global annual mean of 422.8 ppm in 2024. This strengthens the greenhouse effect (Topic 6).
- Carbon dioxide dissolving in the oceans makes them more acidic. Average surface pH has fallen from about 8.2 to 8.1, which gives a hydrogen-ion activity ratio $10^{0.1} = 1.259$, about 26% higher for these rounded values. This is **ocean acidification** 海洋酸化. The ocean remains alkaline overall, but reduced carbonate availability can make it harder for corals, shellfish and some plankton to build their calcium carbonate shells.
- People can increase carbon sinks by planting forests, protecting wetlands and peat, and storing carbon underground (carbon capture and storage).



Human carbon additions and where they go

Climate and biomes

Weather and climate

Weather 天气 is the state of the atmosphere at a place and time: today's temperature, rain and wind. **Climate** 气候 describes weather statistics, including averages, variability and extremes, over an appropriate long period; 30-year normals are commonly used.



A tropical rainforest: warm and wet all year, with dense, layered vegetation competing for light



A desert: very low precipitation, so only sparse, drought-adapted life survives

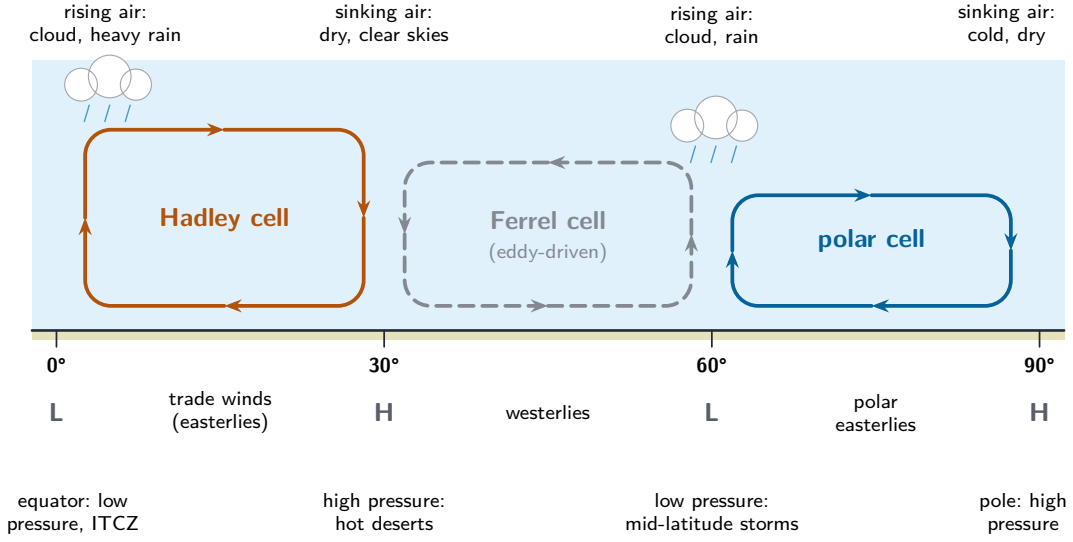
The equator receives more sunlight per square metre than the poles. There the Sun

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is high in the sky and its rays pass through less atmosphere. Near the poles the same energy is spread over a larger area. The atmosphere and oceans move heat from the equator towards the poles.

The tricellular model

The **tricellular model** 三圈环流模型 explains the main pattern of winds and rain in each hemisphere with three cells of circulating air.



The tricellular model of atmospheric circulation (one hemisphere)

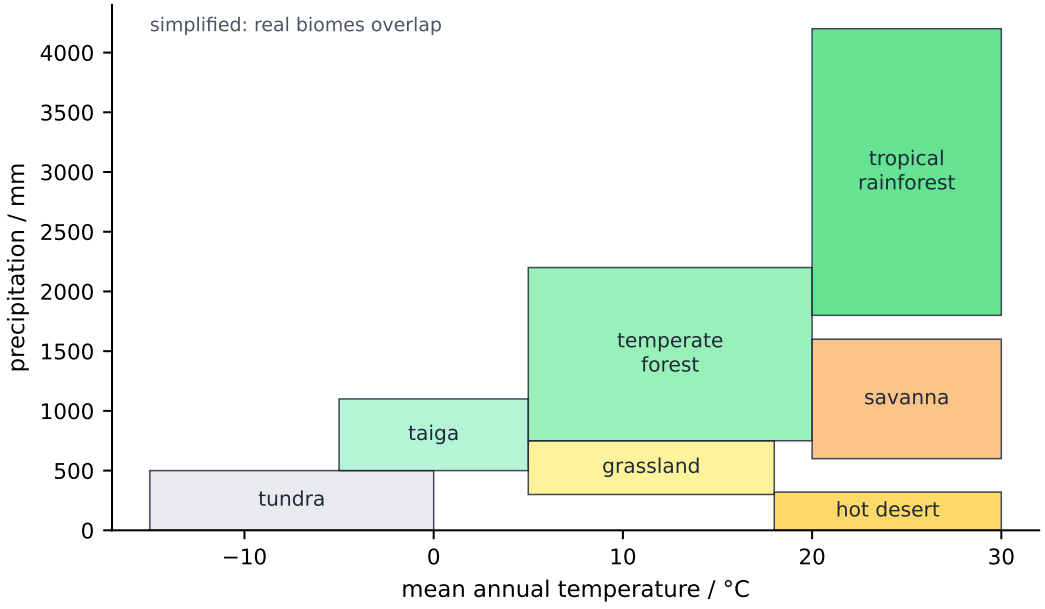
- At the equator, strong heating makes air rise. Rising air cools, and its water vapour condenses to form clouds and heavy rain. This belt of low pressure is the **inter-tropical convergence zone** 热带辐合带 (ITCZ).
- The air flows towards the poles high up, cools and sinks at about 30° north and south. Sinking air warms and becomes dry, giving high pressure and clear skies. Most hot deserts, such as the Sahara, lie here.
- Air rises again at about 60°, giving rain in places such as north-west Europe, and sinks at the poles, which are cold and dry.

The ITCZ moves north and south with the seasons, which is why many tropical places have a wet season and a dry season. Ocean currents also carry heat; for example, the North Atlantic Drift keeps western Europe mild.

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Biomes

A **biome** 生物群系 is a group of ecosystems with similar climate and similar types of plants and animals, such as tropical rainforest or desert. Temperature and precipitation strongly influence biome distributions through water availability and growth, alongside seasonality, soil, disturbance, topography and human land use.



A simplified climatic envelope helps interpret biomes; annual means do not uniquely determine every local community

Biome	Climate	Productivity and features
Tropical rainforest	Hot all year, more than 2000 mm rain	Often high NPP/diversity; rapid cycling and leaching; soil depth/fertility vary
Desert	Less than 250 mm rain	Low NPP; plants store water, animals active at night
Temperate grassland	Mild, 250 to 750 mm rain	Grasses; deep fertile soil, much used for farming
Temperate forest	Mild, wet, four seasons	Deciduous or evergreen forests, depending on climate
Taiga (boreal forest)	Long cold winters, short summers	Conifers; slow decomposition, acid soils; large carbon store
Tundra	Very cold, short growing season; permafrost common	Low NPP; mosses, lichens, small plants; huge carbon store in frozen soil

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Climate change is moving biome boundaries towards the poles and up mountains. Species that cannot move fast enough, or that are already on mountain tops, may die out. Thawing permafrost releases carbon dioxide and methane, a positive feedback that adds to warming.

Zonation and succession

Zonation

Zonation 分带现象 is the change in communities across space along an environmental gradient. Examples are bands of vegetation up a mountain, as temperature falls with height, and bands of seaweeds and animals up a rocky shore, as the time out of the water increases. Zonation is a pattern in space; succession is a change over time.

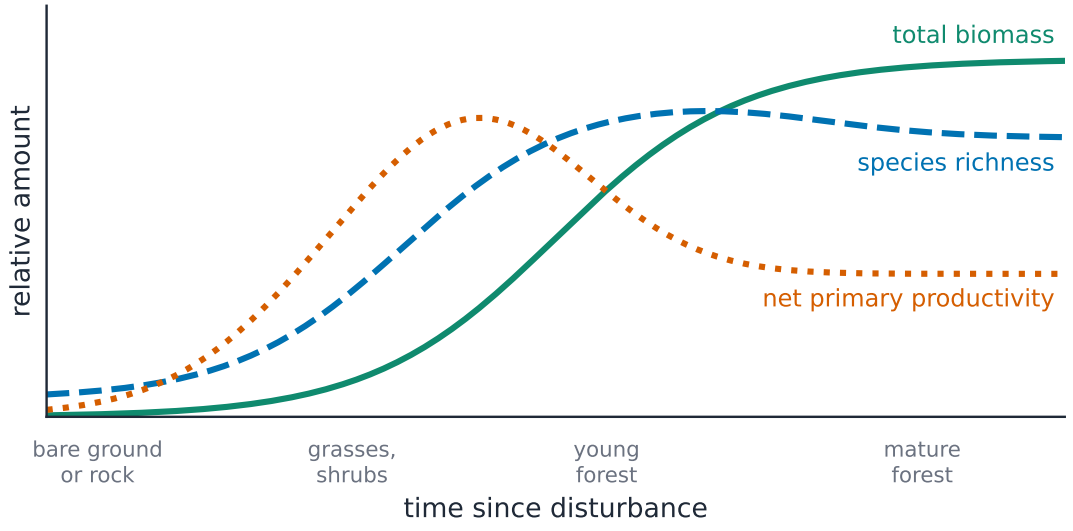
Succession

Succession 演替 is directional community change over time through colonisation, interactions, environmental change and disturbance. Different pathways can occur, rather than one inevitable march to forest. A **seral stage** 演替阶段 is one community in the sequence; a sere is the whole succession sequence.



Lichens growing straight on bare rock. As pioneer species they slowly break the rock down and build the first thin soil

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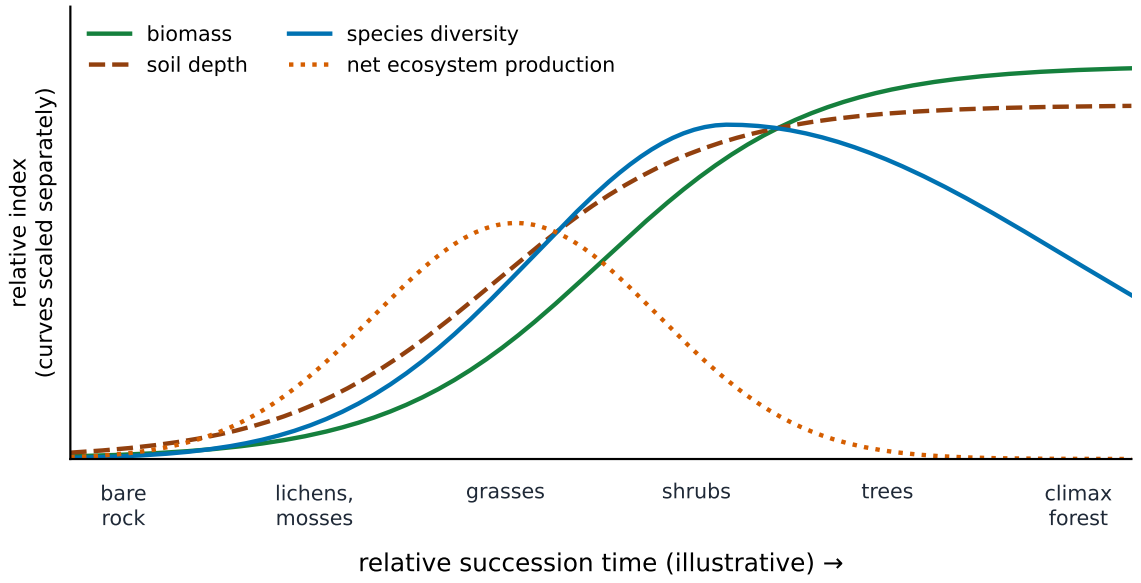


During succession, total biomass climbs and levels off, species richness rises then levels, and net primary productivity peaks in the middle stages

- **Primary succession** 原生演替 starts on bare ground with no soil, such as new volcanic rock, sand dunes or ground left by a retreating glacier.
- **Secondary succession** 次生演替 starts where soil already exists but the community has been removed, as after a fire, a flood or an abandoned field. Recovery is often faster when soil, roots or seed banks remain, but disturbance intensity and subsequent conditions matter.

A typical primary succession on bare rock:

1. **Pioneer species** 先锋物种 such as lichens and mosses arrive first. They tolerate extreme conditions. They slowly break up the rock, and when they die they add organic matter, so a thin soil begins to form.
2. Grasses and small plants grow in the thin soil. Their roots and dead remains make the soil deeper and better at holding water and nutrients.
3. Shrubs, then fast-growing trees, shade out the smaller plants.
4. A relatively persistent **climax community** 顶极群落 is a useful classical model for the prevailing conditions. It need not be oak forest, and disturbances can maintain a shifting mosaic rather than one permanent endpoint.



How an ecosystem changes during succession

During succession:

- soil becomes deeper and richer in organic matter and nutrients;
- biomass, food-web complexity and gross productivity increase;
- life-history traits can change as establishment conditions and competition change; there is no obligatory binary replacement rule;
- species diversity usually rises, and may fall a little at the climax when a few dominant species out-compete others;
- **net ecosystem production**, NEP = GPP − $R_{\text{ecosystem}}$, can approach zero when total ecosystem carbon uptake and respiration balance. **NPP** subtracts producer respiration only and can remain substantial in a mature ecosystem, supporting consumers and decomposers. Near-constant biomass is not evidence that photosynthesis or NPP has stopped.

Rapid maturity and many offspring (r-associated tendencies) can favour colonisation; longer life and greater competitive persistence (K-associated tendencies) can suit established communities. These traits overlap. A classical climax is a dynamic model, not an inevitable endpoint: the Vera wood-pasture hypothesis proposes that large herbivores can help maintain mosaics of open and wooded habitat. Grazing, fire and other disturbances can sustain alternative states.

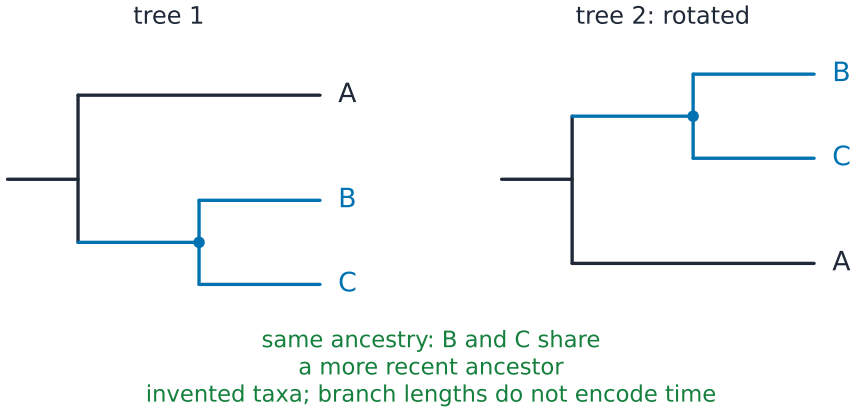
■ Plagioclimax

Human activities can stop succession before the climax. The community held at that stage is a **plagioclimax** 偏途顶极. Examples are grazed grassland and moorland managed by burning. If grazing or burning stops, succession may change direction again, depending on climate, soils, seed sources and disturbance; woodland is not the

inevitable outcome everywhere.

AHL: Classification, niches and life cycles

A **clade** 演化支 contains a common ancestor and all its descendants. A branching diagram represents relative ancestry, not a ladder of progress; rotating branches at a node does not change relationships.



Rotating nodes changes the drawing, not the common ancestry

Traditional ranks (kingdom, phylum, class, order, family, genus, species) are useful labels, but groups of the same rank need not have equal ages or evolutionary distances. Use shared derived characters and sequence evidence to test groupings, not overall resemblance alone.

The **fundamental niche** 基本生态位 is the full range of conditions a species could use. The **realised niche** 实际生态位 is the part it actually uses, usually smaller because of competition. In a simple stable model, species competing for the same limiting resources cannot coexist indefinitely in identical niches. Environmental variation, spatial differences and other interactions affect outcomes in real communities.

The Ecological Society's account of Connell's barnacle work describes how removing competing *Balanus* improved survival of *Chthamalus* lower on the shore. Competition helped restrict its realised distribution; physical stress and other interactions still matter. An observed absence is not by itself proof that conditions lie outside the fundamental niche. The paper's names are historical; a name and a biological claim both require context.

■ Life-history tendencies

Species follow different **reproductive strategies** 繁殖策略:



A young rabbit: r-selected species produce many offspring quickly with little parental investment

- **r-strategists** produce many small offspring quickly, give little parental care, and most offspring die young. They mature early and live short lives. Insects, weeds and mice are examples. They do well in unstable or new habitats.
- **K-strategists** produce few, large offspring and care for them, with relatively greater investment per offspring. They mature late and live long. Elephants and some whales are examples. They do well in stable habitats near carrying capacity, but recover slowly when numbers fall, so they are more at risk of extinction.

A **survivorship curve** 存活曲线 shows how many of a group of newborns are still alive at each age. Type I (most survive to old age, then die: humans, elephants) suits K-strategists. Type III (most die very young; the few survivors live long: oysters, many fish) suits r-strategists. Type II (roughly constant per-capita mortality risk across age, not the same number of deaths each year: some birds) lies between.

These are broad, historically useful life-history tendencies, not two exclusive types determined by one trait. Oaks, for example, can be long-lived while producing many acorns with little direct parental care. Warming can alter flowering, insect emergence and breeding at different rates, producing phenological mismatch rather than forcing every life cycle to shift together.

AHL: Production, efficiency and harvest

Ecological efficiency 生态效率 is the percentage of energy at one level that becomes new biomass at the next:

$$\text{ecological efficiency} = \frac{\text{energy used for new biomass}}{\text{energy supplied}} \times 100\,\%$$

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In the pyramid, from primary to secondary consumers: $100 \div 1000 \times 100\,\% = 10\,\%$.

Productivity

Productivity 生产力 is the rate at which biomass (or the energy in it) is gained, in kJ m^{-2} y^{-1} or g m^{-2} y^{-1}.

- **Gross primary productivity** 总初级生产力 (GPP): the rate at which producers make biomass by photosynthesis.
- **Net primary productivity** 净初级生产力 (NPP): what is left after the producers' own respiration (R). This is the food available to consumers.

$$\text{NPP} = \text{GPP} - R$$

- **Gross secondary productivity** 总次级生产力 (GSP): the energy consumers absorb from their food.

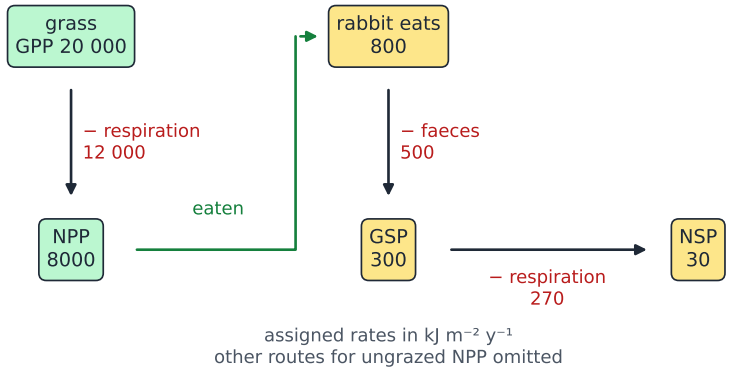
$$\text{GSP} = \text{food eaten} - \text{faecal loss}$$

- **Net secondary productivity** 净次级生产力 (NSP): what consumers add to their biomass after respiration.

$$\text{NSP} = \text{GSP} - R$$

> **Worked example.** Grass in a meadow has a GPP of 20 000 kJ m^{-2} y^{-1} and respires 12 000. Rabbits eat 800 of the grass; 500 leaves in faeces, and the rabbits respire 270.

- NPP $= 20\,000 - 12\,000 = 8000$ kJ m^{-2} y^{-1}.
- GSP $= 800 - 500 = 300$ kJ m^{-2} y^{-1}.
- NSP $= 300 - 270 = 30$ kJ m^{-2} y^{-1}.



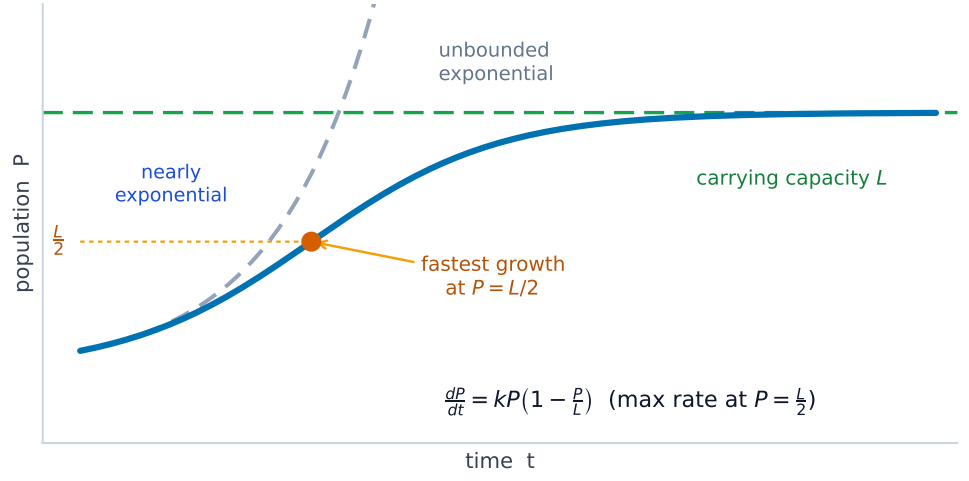
Energy through a producer and a primary consumer (kJ m^{-2} y^{-1})

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Endotherms can have substantial respiratory costs; activity, growth and conditions affect the actual partition. NPP is highest in tropical rainforests, coral reefs and estuaries, under combinations of favourable energy and resource supply; nutrients can still limit production, and lowest in deserts, tundra and the open ocean.

Maximum sustainable yield

If we harvest a population (fish, timber), we can take its natural income without reducing its natural capital (Topic 1). In the simple fixed-parameter logistic model $dN/dt = rN(1 - N/K)$, net population increase is greatest at $N = K/2$, with value $rK/4$. The **maximum sustainable yield** 最大可持续产量 (MSY) is the largest harvest that can be taken every year without reducing the population: take only a defensible net production budget; the logistic maximum is a model result, not a universal target stock for every managed population. In practice MSY is hard to apply. Population sizes are uncertain, they change from year to year, and other species depend on the harvested one. So managers set catches below the estimated MSY to leave a safety margin.



logistic: $dP/dt = kP(1 - P/L)$ · $P \to L$ as $t \to \infty$

The logistic model grows fastest at P=L/2 and levels off at the carrying capacity L

Measuring production

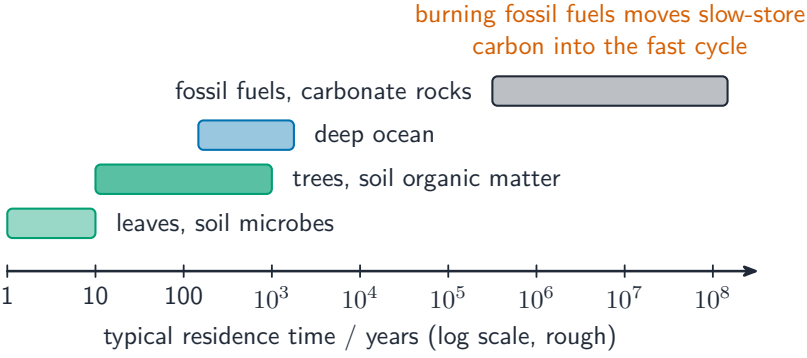
Dry authorised plant samples to constant mass and scale representative samples by area; drying removes water but some inorganic material remains. Record interval and sampling uncertainty. In a simple light/dark oxygen-bottle model, light-bottle change estimates net production and dark-bottle loss estimates respiration, assuming comparable respiration and no significant gas exchange or other oxygen demand. With initial dissolved oxygen 8.0 mg/L, light final 10.0 and dark final 7.0 over two hours, net

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rate is 1.0 mg/L/hour, respiratory rate 0.5 and inferred gross rate 1.5. These oxygen rates are not automatically carbon-mass rates without a conversion model.

AHL: Geological carbon, methane and nitrogen

Long-term carbonate rocks and fossil fuels have much longer residence times than many biological stores. Coal formed from accumulated organic matter from land plants; much oil and gas originated from organic-rich sediments, often including marine microorganisms. Burial conditions, time and geology matter; not all dead biomass becomes fuel. Calcium carbonate can form through biological and non-biological routes, and limestone is not made exclusively from shells.



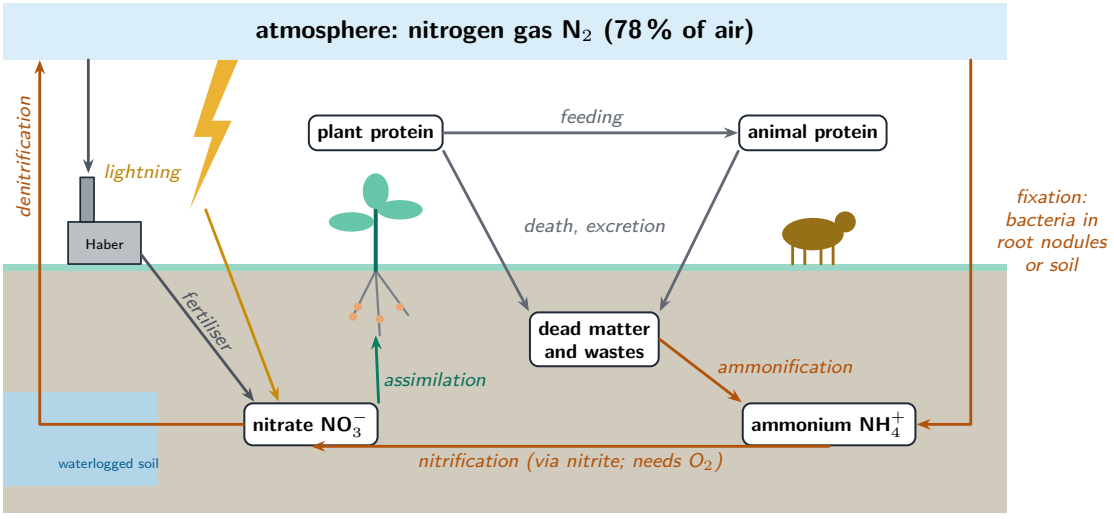
Residence times differ: burning fossil fuels moves slow-store carbon into the fast cycle

Methanogenic **archaea**, rather than bacteria in modern classification, produce methane under anaerobic conditions, including some wetlands and ruminant digestive systems. Atmospheric methane persists on an order-of-a-decade timescale, depending on the lifetime definition and chemistry, and is largely oxidised to carbon dioxide. A residence-time estimate does not mean every methane molecule disappears exactly on one birthday.

The nitrogen cycle

Nitrogen is needed for proteins and DNA. About 78 % of the air is nitrogen gas (N_2), but most organisms cannot use it directly. It must first be changed into ammonium or nitrate.

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The nitrogen cycle: bacteria do most of the work

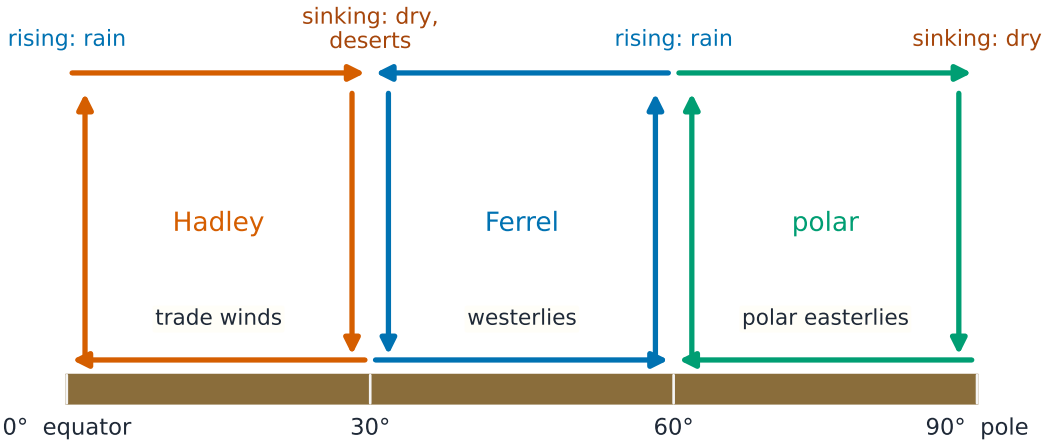
- **Nitrogen fixation** 固氮作用: nitrogen-fixing bacteria (free in the soil, or in the root nodules of beans and clover) change N_2 into ammonium. Lightning also fixes some nitrogen. People fix nitrogen in the **Haber process** 哈伯法 to make fertiliser.
- **Assimilation** 同化作用: plants can absorb nitrate or ammonium through their roots and incorporate nitrogen into organic compounds. Animals get nitrogen by eating plants.
- **Ammonification** 氨化作用: decomposers break down dead organisms and wastes and release ammonium.
- **Nitrification** 硝化作用: nitrifying bacteria change ammonium into nitrite and then nitrate. They need oxygen.
- **Denitrification** 反硝化作用: denitrifying bacteria change nitrate back into N_2. They live in waterlogged soil with little oxygen.

■ People and the nitrogen cycle

Industrial fixation and agricultural inputs substantially alter reactive-nitrogen flows. Fertiliser can increase crop yields, while unused nutrients can leach or run off into water bodies. There it causes **eutrophication** 富营养化 (Topic 4): algae grow fast, die and are decomposed by bacteria that use up the oxygen, so fish die. Burning fuels also releases nitrogen oxides that cause acid rain. The planetary boundary for nitrogen (Topic 1) has already been crossed.

AHL: Climate mechanisms and local variation

Tropical climates include equatorial and seasonally wet/dry patterns; temperate climates include maritime and continental patterns; polar climates have long cold seasons and short growing periods. Ocean proximity moderates seasonal temperature ranges, while continental interiors can have larger ranges. A climate envelope predicts potential vegetation, not the actual land cover if agriculture, grazing, urban development, soils or disturbance change establishment conditions.



Three circulation cells per hemisphere set the prevailing surface winds and the wet and dry belts

Thermohaline circulation involves density contrasts produced by temperature and salinity: cooling and increased salinity can make water denser and favour deep-water formation. Surface winds, mixing and basin geometry also matter. The connected circulation transports heat and materials; it is not a single uniform conveyor that completes one identical circuit for every water parcel.

ENSO couples Pacific ocean conditions and atmospheric circulation. During El Niño, weakened trade winds and changed Walker circulation allow warmer surface water farther east, often suppressing nutrient-rich upwelling near Peru and reducing marine productivity there. La Niña tends toward strengthened trades and enhanced upwelling, but impacts depend on place, season and event. Events are irregular, not a fixed clock; remote rainfall effects are probabilistic rather than the same everywhere.

Tropical cyclones draw energy from warm ocean surfaces and moist air, but also require suitable atmospheric conditions. Hurricanes and typhoons are regional names for sufficiently strong tropical cyclones. Warming can intensify rainfall and the strongest storms, yet NOAA distinguishes intensity from global storm frequency; it is inaccurate to claim that all cyclone counts must rise everywhere as temperature rises. Compare a named basin, period, metric and observational coverage before inferring a trend.

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Practice

1. Distinguish between a habitat and a niche, and between a fundamental and a realised niche.
2. (a) Describe the phases of an S-shaped population growth curve, and explain why the population levels off. (b) Distinguish between density-dependent and density-independent factors, with an example of each.
3. Explain what is meant by a keystone species, with an example.
4. Compare r-strategists and K-strategists, and state the survivorship curve typical of each.
5. Twelve 0.5 m^2 quadrats contain a total of 30 thistles in a 600 m^2 field. Estimate the thistle population.
6. 60 snails are marked and released. Later, 45 snails are caught, of which 9 are marked. Use the Lincoln index to estimate the population, and state two assumptions of the method.
7. A pond has three species with 12, 5 and 3 individuals. Calculate Simpson's reciprocal index.
8. (a) Explain why a pyramid of productivity can never be inverted, but a pyramid of numbers can. (b) Outline three reasons why energy is lost between trophic levels.
9. A forest has a GPP of 45 000 kJ m^{-2} y^{-1} and an NPP of 18 000 kJ m^{-2} y^{-1}. Calculate the energy used in respiration. Deer eat 2200 kJ m^{-2} y^{-1}, lose 1300 in faeces and respire 820. Calculate their GSP and NSP.
10. Explain biomagnification, using DDT as an example.
11. Outline how human activities change the carbon cycle, and describe one effect of this.
12. Describe the roles of bacteria in the nitrogen cycle.
13. Use the tricellular model to explain why tropical rainforests are found at the equator and hot deserts at about 30° north and south.
14. Describe and explain changes in soil, biomass and diversity during primary succession, distinguish producer NPP from whole-ecosystem net production, and explain what is meant by a plagioclimax.

Answers.

1. A habitat is the place where a species lives; a niche is its whole role (where it lives, what it eats, its interactions). The fundamental niche is the full range of conditions it could use; the realised niche is the part it actually uses, usually smaller because of competition.
2. (a) A simple S-curve has slow initial absolute increase, rapid growth, a transitional slowing and an approximate plateau under density dependence. In a closed model births balance deaths; immigration and emigration also matter in open populations. Conditions and carrying capacity can change. (b) Density-dependent factors act more strongly as the population becomes more crowded (food supply, disease).

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Density-independent factors affect the population whatever its density (a flood, a frost).

3. A species whose effect on the ecosystem is much larger than its numbers suggest; removing it changes the community greatly. Sea otters eat sea urchins; without otters, urchins destroy kelp forests.
4. r/K tendencies compare offspring number, investment, maturity and longevity, but form overlapping trait combinations rather than exclusive categories. Type III curves often accompany high early mortality, and Type I low early mortality with later decline. Long-lived oaks still produce many acorns, so one trait is insufficient.
5. Mean $= 30 \div 12 = 2.5$ per quadrat; density $= 2.5 \div 0.5 = 5$ per m^2; population $= 5 \times 600 = 3000$ thistles.
6. $N = (60 \times 45) \div 9 = 300$ snails. Assumptions (any two): marked snails mix fully with the population; marks are not lost; marking does not change survival; no births, deaths or migration between samples.
7. $N = 20$, $N(N-1) = 380$; $\sum n(n-1) = 132 + 20 + 6 = 158$; $D = 380 \div 158 = 2.4$.
8. (a) Productivity is energy flow over time, and each level receives only part of the energy of the level below, so each bar must be smaller. Numbers can be inverted because one large producer (a tree) can feed many small consumers. (b) Any three: energy released as heat in respiration; parts not eaten (roots, bones); food not absorbed and lost in faeces; organisms that die and are not eaten pass their energy to decomposers.
9. $R = 45\,000 - 18\,000 = 27\,000$ kJ m^{-2} y^{-1}. GSP $= 2200 - 1300 = 900$ kJ m^{-2} y^{-1}. NSP $= 900 - 820 = 80$ kJ m^{-2} y^{-1}.
10. Persistent DDT-related compounds can be taken up faster than they are eliminated, with concentrations increasing across feeding levels under appropriate conditions. DDE can thin susceptible birds' eggshells. Not every pollutant is fat-stored or completely retained; the body example is explicitly invented, not evidence from a named historical marsh.
11. Fossil-fuel combustion, cement production and land-use change alter net carbon flows; natural uptake removes part of the additional carbon. NOAA's dated global annual mean was 422.8 ppm in 2024, versus about 280 ppm pre-industrially. Effects include enhanced greenhouse warming and lower ocean pH/carbonate availability; the ocean need not become acidic below pH 7.
12. Nitrogen-fixing bacteria change N_2 into ammonium; decomposers release ammonium from dead matter (ammonification); nitrifying bacteria change ammonium into nitrite and nitrate (nitrification); denitrifying bacteria in waterlogged soil change nitrate back into N_2.
13. In the idealised circulation model, warm moist air rises near the equator, cools and can produce rain. Descending subtropical air warms, lowering relative humidity and favouring dry regions. Seasonal convergence-zone shifts and local conditions mean neither uniform year-round equatorial rain nor a desert at every 30-degree

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location is guaranteed.

14. Primary succession begins without developed soil; secondary succession retains soil or other biological legacies. In a classical bare-rock model, colonists alter soil and allow other plants, while biomass and diversity trajectories depend on conditions and disturbance. Near-zero net ecosystem production concerns total respiration balancing GPP; NPP subtracts producer respiration only and can remain positive. Repeated human intervention can maintain a plagioclimax, with later change depending on local conditions.

Exam tips

- Show units and assumptions; distinguish stocks from rates, zonation from succession, and producer NPP from ecosystem balance.

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Biodiversity and conservation

International Baccalaureate · IB Diploma · Environmental Systems and Societies · HL

Scope and prerequisites

This handout teaches Topic 3, Biodiversity and conservation (3.1 Biodiversity and evolution, 3.2 Human impact on biodiversity, 3.3 Conservation and regeneration), for the course first assessed in 2026. Sections marked **AHL** are for Higher Level only. HL students also apply the three HL lenses (environmental law, environmental and ecological economics, and environmental ethics, units 9 to 11) to these ideas.

Prerequisites: Topic 1 (perspectives, systems and sustainability) and common Topic 2 ideas about populations, habitats and representative sampling.

Biodiversity and evolution

The goddess of the Yangtze

The baiji (*Lipotes vexillifer*) is a Yangtze river dolphin listed as Critically Endangered (Possibly Extinct) in the cited IUCN assessment. Failure to find it in a major survey is grave evidence, but 'possibly extinct' and a confirmed extinction category are different claims. Its neighbour, the Yangtze finless porpoise, faces fishing, traffic and habitat pressures too. A 2022 survey reported 1249 porpoises; a dated estimate is not an exact census or proof that recovery is permanent. Conservation starts by naming the organism, evidence and uncertainty accurately.

What biodiversity means

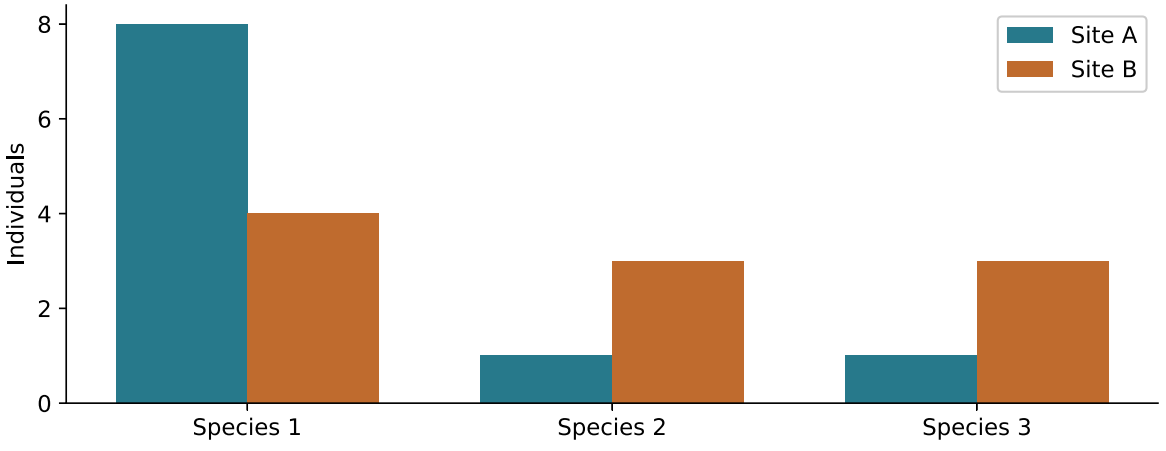
Biodiversity 生物多样性 is the variety of life on Earth. It has three levels:

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A coral reef is one of the most biodiverse habitats on Earth: many species of coral, fish and invertebrates share it

- **Genetic diversity** 遗传多样性: inherited variation within a species. Variation can provide different responses to disease or environmental change; more variants do not guarantee survival in every circumstance.
- **Species diversity** 物种多样性: the variety of species in an area. It depends on **species richness** 物种丰富度 (the number of species) and **evenness** 均匀度 (how equally the individuals are shared among them).
- **Habitat diversity** 生境多样性: the variety of habitats or ecosystems in an area, such as forest, river, marsh and grassland.



Same richness, different evenness: site B is more even

Worked example. Both sites have 3 species and 10 individuals, so $N(N-1) = 10 \times 9 = 90$. Using Simpson's reciprocal index (Topic 2):

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- Site A: $\sum n(n-1) = 8 \times 7 + 0 + 0 = 56$, so $D = 90 \div 56 = 1.6$.
- Site B: $\sum n(n-1) = 4 \times 3 + 3 \times 2 + 3 \times 2 = 24$, so $D = 90 \div 24 = 3.8$.

Under this formula, site B is more diverse. The finite-sample expression can exceed the observed richness; do not force it into a 0–1 range or mix it with another Simpson convention. Dominance alone does not prove impending community collapse: functions, interactions and the disturbance matter.

How many species?

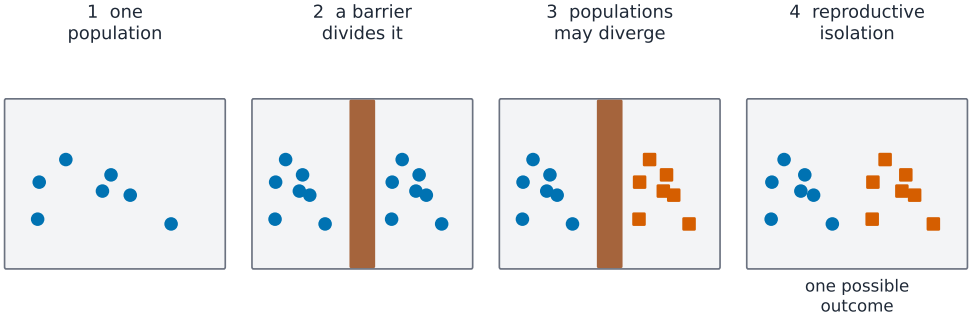
A species catalogue counts described taxa; an estimate of total richness also includes organisms not yet described. Mora and colleagues' 2011 model estimated about 8.7 million eukaryotic species, including groups beyond animals, plants and fungi. This is a model estimate, not an exact current inventory or a total for bacteria and archaea. Identification effort and taxonomic revision change recorded counts. Local citizens, trained parabiologists, museums and agencies can help document biodiversity when records have locations, dates, identification evidence and suitable permissions.

Evolution by natural selection

Evolution 进化 is change in inherited characteristics across generations; not every evolutionary change creates a new species. **Natural selection** 自然选择 acts through differences in reproductive success:

1. Individuals in a population vary, and much of this variation is inherited. New variation comes from mutation and sexual reproduction.
2. Populations produce more offspring than the environment can support, so there is a struggle to survive.
3. Individuals differ in survival and reproductive success under the stated conditions. Fitness concerns contribution to later generations, not simply strength or lifespan.
4. They pass these characteristics to their offspring, so the characteristics become more common over generations.

Speciation 物种形成 is the formation of a new species. It often happens when populations are separated by a barrier.



Speciation by geographical isolation

A barrier can reduce gene flow: **geographical isolation** 地理隔离 allows separated populations to diverge through selection, mutation and drift. Reproductive isolation may eventually develop, but a barrier does not guarantee it. Habitat or mating differences can also restrict interbreeding without a complete physical barrier. Use evidence about inherited differences and reproduction, not appearance alone.

Human impact on biodiversity

The scale of the loss

- The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) estimated in 2019 that about 1 million species are threatened with extinction.
- The 2024 Living Planet Report reported a 73% decline in its index of monitored vertebrate populations between 1970 and 2020. This concerns proportional population trends, not 73% of species becoming extinct or a census showing 73% of all individual animals lost.
- The planetary boundary for biosphere integrity (Topic 1) has been crossed.



Clearing forest destroys habitats and reduces biodiversity.

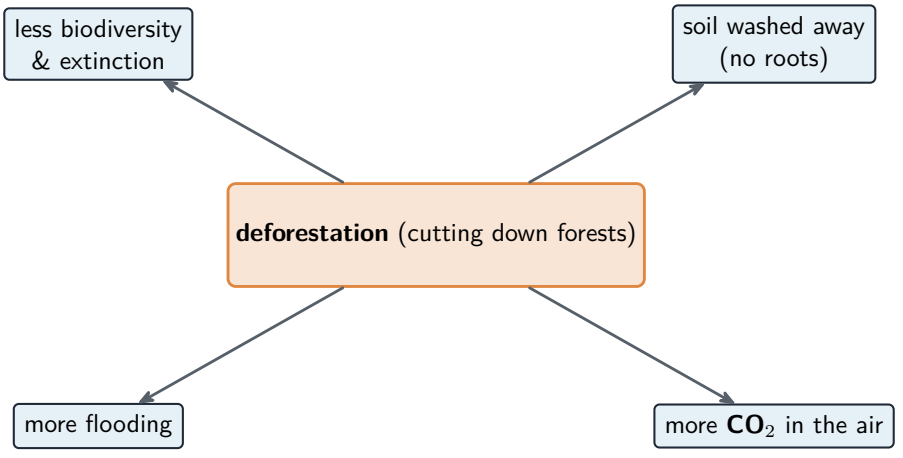
Causes of biodiversity loss

The main causes of loss are often remembered as HIPPO, plus climate change:

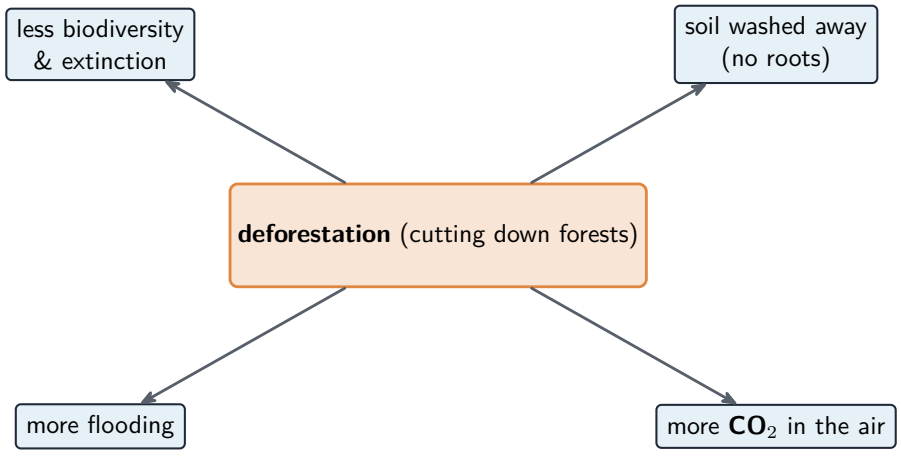
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The invasive vine kudzu smothering a stand of trees. With no natural predators in its new home, it blankets and kills what it covers



Deforestation lowers biodiversity and causes erosion, flooding, and higher CO2



Deforestation lowers biodiversity and causes erosion, flooding, and higher CO2

Cause	How it harms biodiversity	Example
Habitat loss 栖息地丧失 and **fragmentation** 生境破碎化	Clearing land for farms, towns and roads destroys habitats and cuts the rest into small, isolated patches	Rainforest cleared for cattle, soya and oil palm
Invasive species 入侵物种	Some introduced species establish and spread, competing with, consuming or infecting native species	Cane toads in Australia; water hyacinth in Chinese lakes
Pollution 污染	Pesticides, fertiliser runoff, plastics and noise harm organisms	Eutrophication killing fish (Topic 4)
Population growth and consumption	More people using more resources increases every other pressure	Growing demand for food, land and water
Overharvesting 过度捕捞	Hunting, fishing and collecting faster than populations can recover	Overfishing of cod; poaching of rhinos for horn
Climate change 气候变化	Species cannot move or adapt fast enough as conditions change	Coral bleaching; mountain species with nowhere higher to go

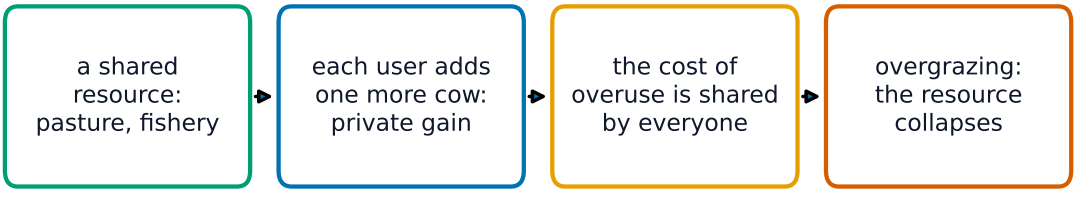
The dominant pressures differ among ecosystems. Land/sea-use change and direct exploitation are major drivers; climate, pollution and invasive species interact with them. An introduced species is not automatically invasive, and a native outbreak is not automatically an alien invasion.

Fragmentation makes small patches with a lot of edge. At an **edge** the conditions

change: more light, more wind, drier air, and more predators and invasive species. These **edge effects** 边缘效应 mean a small patch has little true interior habitat. Small isolated populations face drift and inbreeding; restricted gene flow can increase vulnerability. Edge conditions depend on the boundary and species: an edge can favour some organisms while harming interior specialists.

Shared resources and interacting pressures

An open-access resource can be overused when each user gains privately from an extra harvest but shares the resulting depletion with everyone. This is a tragedy-of-the-commons mechanism, not proof that all shared ownership fails. Communities can set enforceable rules, access rights, seasonal closures and monitoring. Overfishing and plastic inputs to shared seas illustrate different problems: one removes organisms, the other adds persistent material. Prevention needs attention to incentives, enforcement and alternatives, not simply a request that individual users care more.



solutions: regulation, quotas, fees, private or community ownership

The tragedy of the commons: private gain, shared cost

For a fishery, annual stock growth is 120 tonnes and combined catches are 150 tonnes; ignoring other flows, the stock falls by 30 tonnes. Dividing a 120-tonne allowance among boats does not establish that it is safe under changing recruitment or ecological needs. Warming, fragmented nursery habitat and pollution can lower recovery simultaneously. Compare threatened populations before and after management using suitable controls rather than attributing every improvement to the most visible action.

Why some species are more at risk

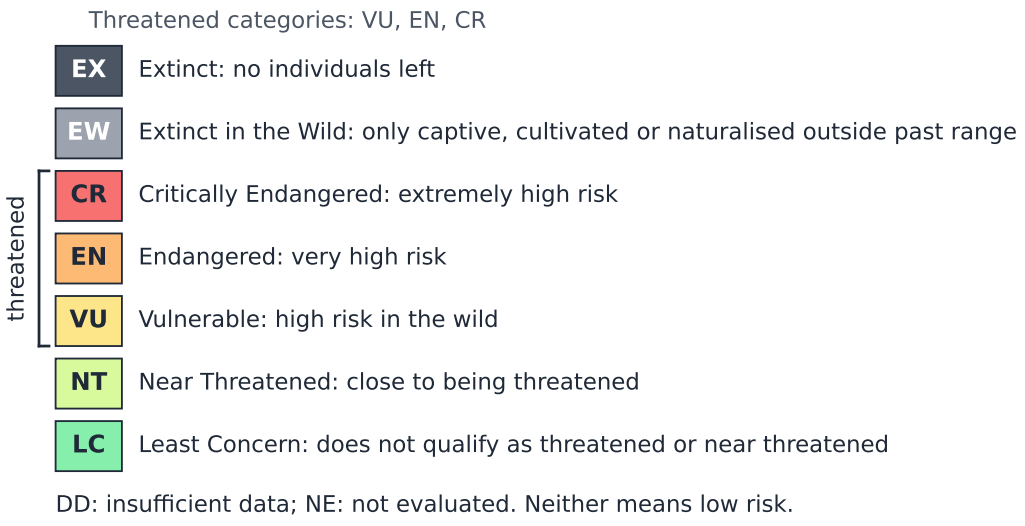
A species is more likely to become extinct if it has:

- a small population or a small geographical range;
- a narrow niche, such as one food source (the giant panda eats almost only bamboo);
- a low reproductive rate (K-strategists, such as elephants and great apes);
- a large body and a high trophic level, needing a large area;
- low genetic diversity;

- commercial value, so it is hunted or collected;
- a migration route that crosses many countries, so it depends on habitat in all of them.

The IUCN Red List

The International Union for Conservation of Nature (IUCN) publishes the **Red List** 红色名录, which assesses the risk of extinction of species. It uses criteria such as population size, rate of decline, geographical range, degree of fragmentation, and the number of mature individuals.



IUCN Red List categories

The list raises awareness, guides where conservation money is spent, and supports laws. Its limits are that most species have never been assessed, data are often poor (the category **Data Deficient** 数据缺乏 is used for these), and listing a species does not by itself protect it.

Three case histories

- **Extinct: the passenger pigeon.** In the 1800s it was probably the most common bird in North America, with flocks of billions. It was hunted on a huge scale and its forests were cleared. Colonial breeding and typically single-egg clutches could constrain recovery; a clutch count must not be turned into an unsupported fixed number per year. The last one, Martha, died in Cincinnati Zoo in 1914.
- **Critically endangered: the Yangtze finless porpoise.** It is threatened by fishing nets, boat strikes, dams, sand dredging and pollution. The 2021 fishing ban, protected reserves along the river and moving some porpoises to safe oxbow lakes have helped. The 2022 count was higher than in 2017.
- **Recovering: the giant panda.** Its habitat was cut into small fragments by

farming and roads. China banned logging in its forests and created more than 60 panda reserves linked by corridors. The wild population rose to about 1860 in a national survey published in 2015, and in 2016 the IUCN moved the panda from Endangered to Vulnerable.

passenger pigeon
extinct (last died 1914)
pressures: huge-scale hunting,
forest clearance
colonial breeding, small clutches
limited recovery

Yangtze finless porpoise
critically endangered
pressures: nets, boat strikes, dams, sand dredging
response: 2021 fishing ban, reserves, oxbow-lake refuges

giant panda
Endangered → Vulnerable (2016)
pressure: habitat fragmented by farming and roads
response: logging ban, 60+ reserves linked by corridors

Three case histories: the pressures behind each conservation status

Conservation and regeneration

Why conserve biodiversity?

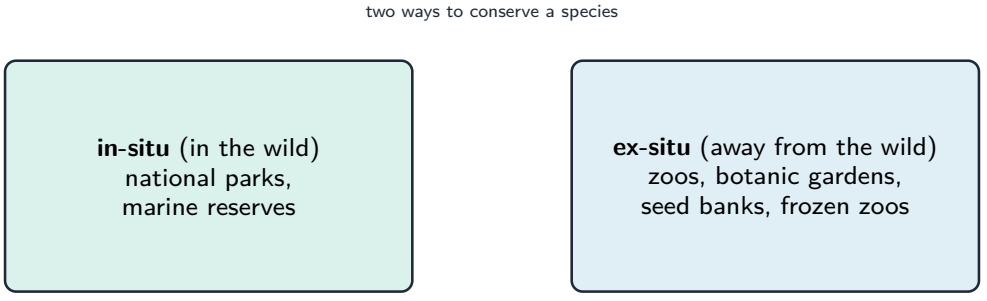
Arguments depend on values (Topic 1):

- **Intrinsic value** 内在价值: every species has a right to exist, whatever its use to people. This is an ecocentric view.
- **Instrumental value** 工具价值: biodiversity is useful to people. It provides food, timber and medicines; for example, the malaria drug artemisinin comes from **sweet wormwood** 青蒿, work that won Tu Youyou a Nobel Prize in 2015. It also provides ecosystem services such as pollination, clean water and flood control, and cultural, aesthetic and scientific value.
- Functional diversity can support **resilience** (Topic 1), especially when species respond differently to disturbance; richness alone does not guarantee a particular recovery rate.

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Who does conservation?

	Governmental organisations	Non-governmental organisations
Examples	United Nations Environment Programme (UNEP); national forestry and parks agencies	WWF (World Wide Fund for Nature); Greenpeace; local community groups
Funding	Taxes and governments	Donations and members
Approach	Laws, international agreements, protected areas	Campaigns, media, fieldwork, direct action
Strengths	Some agencies enforce law; resources vary	Campaigns and fieldwork; independence varies
Limits	Mandate and political constraints	No legislative power; funding constraints



In-situ and ex-situ conservation protect species

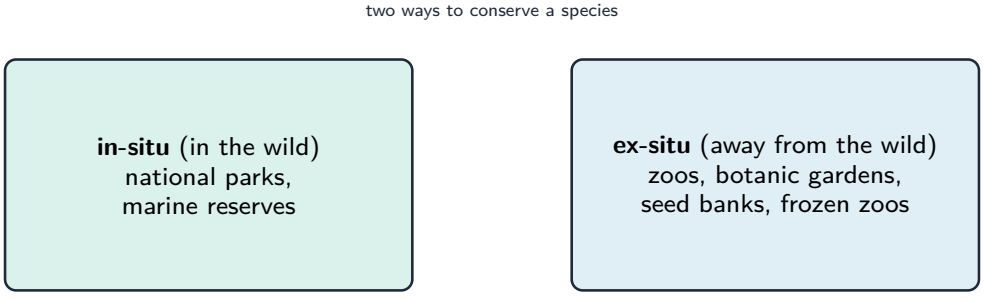
International agreements include the **Convention on International Trade in Endangered Species** 濒危野生动植物种国际贸易公约 (CITES, 1973), which bans or controls trade in threatened species, and the Convention on Biological Diversity. In 2022 its members adopted the Kunming-Montreal Global Biodiversity Framework, whose Target 3 aims for at least 30% of terrestrial/inland-water areas and 30% of marine/coastal areas to be effectively conserved by 2030. Representation, connectivity, equitable governance and Indigenous/local rights matter as well as area. CITES regulates international trade in listed species; it does not itself ban every domestic hunt. The CBD also addresses sustainable use and fair sharing of benefits from genetic resources, including through the Nagoya Protocol. Species protection can be in situ (in natural habitat) or ex situ (outside it); a trade agreement is a legal measure, not a place where an animal lives.

Species-based conservation

These approaches protect a particular species:



The Svalbard Global Seed Vault stores seeds of crop varieties deep in Arctic rock: ex situ conservation of genetic diversity



Conservation is either in-situ (protecting species in their own habitat) or ex-situ (keeping and breeding them away from the wild)

- **Captive breeding** 圈养繁殖 and **reintroduction** 重新引入: breeding animals in zoos and releasing them into the wild. Przewalski's horse, extinct in the wild by the 1960s, has been bred in zoos and returned to Mongolia and to Xinjiang and Gansu in China.
- **Seed banks** 种子库 and botanical gardens store seeds and plants. The Svalbard Global Seed Vault in Norway holds more than a million seed samples of crops from around the world.
- **Legal protection**: hunting bans, trade bans (CITES) and fishing bans.

Conservation often uses a **flagship species** 旗舰物种, a large, appealing animal such

as the panda or the tiger, to raise money and public support. Protecting its habitat can benefit other species, but a flagship's needs do not automatically represent every organism.

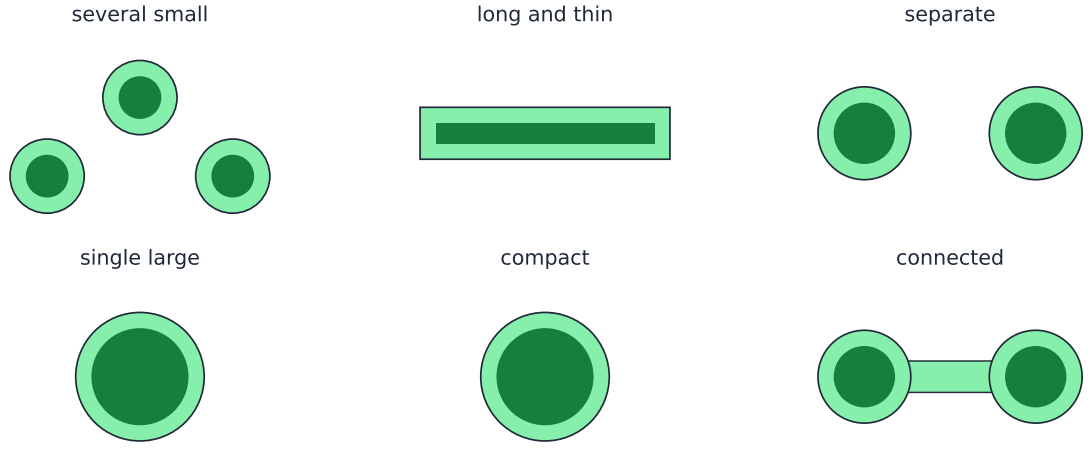
Species-based conservation can save a species on the edge, but it is expensive, protects few species, and captive animals may lose genetic diversity or wild behaviour. Reintroduction can fail if suitable habitat is absent or the original threat remains unaddressed.

Habitat-based conservation

These approaches protect habitats and ecological processes, benefiting many species without guaranteeing that every population is safe:

- **Protected areas** 保护区: national parks and nature reserves where development, hunting or logging is limited.
- **Ecological restoration** 生态修复: returning damaged land to a healthy ecosystem, such as replanting native forest or blocking drains to rewet peatland.
- **Rewilding** 再野化: restoring natural processes on a large scale and then letting nature manage itself, sometimes by reintroducing missing keystone species, as with the wolves of Yellowstone (Topic 2).

The design of a protected area affects how well it works. The ideas come from studies of islands: larger islands, and islands close to the mainland, hold more species.



Size/shape pairs have equal total area; corridor adds area.
Dark green: interior under an assigned edge-depth model; trade-offs vary.

Interior habitat under an assigned edge-depth model; no boundary is guaranteed free of every external influence

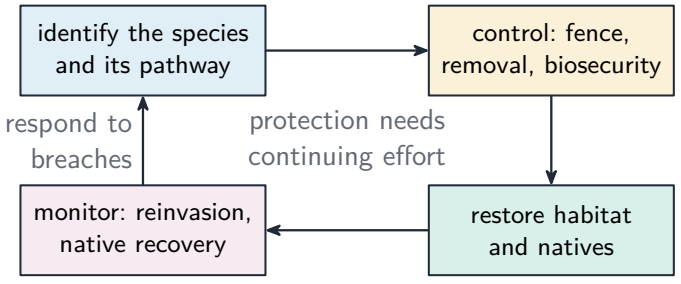
- **Size**: larger areas support larger populations and species with large ranges. But several smaller reserves spread risk: one disease or fire cannot destroy them all. This is the SLOSS debate ("single large or several small").
- **Shape**: a round shape has less edge for its area than a long thin one, so less edge effect and more core habitat.
- **Corridors** 生态廊道: strips of habitat linking reserves let animals move and populations mix genes. They can also spread disease or fire.
- **Buffer zones** 缓冲区: land around the core where some human use is allowed, which reduces disturbance at the core.
- **Local people**: reserves work better when local communities benefit, through jobs in ecotourism or a share in decisions, than when people are simply excluded.

Comparing the approaches

Habitat-based conservation can protect many interacting organisms and their functions; comparative value depends on the conservation goal, threats, feasibility and costs. Species-based conservation is needed when a species is so rare that its habitat alone cannot save it. Most real projects combine both. The panda programme uses reserves and corridors (habitat) and captive breeding (species).

Turn protection into a monitored project

An invasive-species plan needs identification, introduction pathways, a realistic control method and follow-up. At Zealandia in Wellington, a mammalian predator-exclusion fence is combined with pest removal and continued management. A fence needs inspection and responses to reinvasion; exclusion of selected mammals is not exclusion of every organism or permanent protection without effort.



An invasive-species plan is a monitored cycle, not a one-off fence

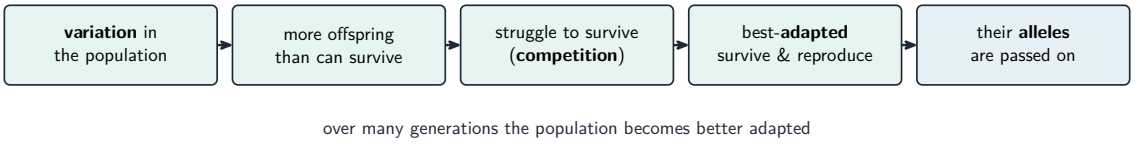
Habitat restoration can require active intervention: restore drainage patterns, control damaging introduced herbivores or regenerate native vegetation before reducing intervention. Rewilding seeks functioning ecological processes, not simply an unmanaged vacant site. In a UNESCO biosphere-reserve model, a protected core is supported by a buffer and a transition zone with compatible livelihoods; zoning alone is not evidence of effective enforcement. Wuyishan provides a named subtropical-forest example. Evaluate recreation, roads, surrounding farming, local access and fire or water

movement across the boundary.

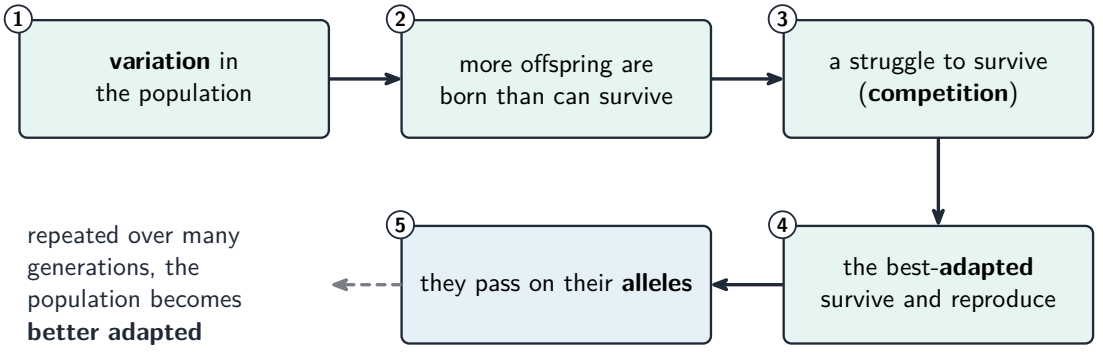
Monitor survival, breeding, native regeneration, habitat quality and local acceptance, not just money spent or hectares announced. Citizen observations need comparable effort, seasonal coverage, identification checks and protection of sensitive location information. Threatened status, local abundance and global extinction are different quantities: a species may recover locally while remaining at risk elsewhere.

AHL: Variation, isolation and human selection

Mutation can create a new allele; meiosis and fertilisation reshuffle existing alleles into new combinations. Mutation is not directed toward what an organism needs. Selection changes the reproductive success of variants already present or arising. Drift can also change allele frequencies, especially in small populations. A trait becoming common is not automatically a new species.



Natural selection: the best-adapted survive, reproduce, and pass on their alleles



Natural selection: the best-adapted survive, reproduce and pass on their alleles

Reproductive isolation can develop through geography, habitat use, breeding time or mate recognition. A barrier reduces gene flow, but separation alone does not guarantee speciation. Divergence can be reversed by renewed gene flow. A biological-species test concerns successful reproduction, rather than how different two drawings look; fossils and asexual organisms need other evidence.

Two contemporary research examples show different routes. The 2018 finch study traced a hybrid lineage on Daphne Major after an immigrant *Geospiza conirostris* bred with a resident *G. fortis*. Descendants formed a reproductively isolated lineage during the observations; this does not mean all hybrids become lasting species. In apple and

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hawthorn host races of *Rhagoletis pomonella*, host-associated odour preferences and timing reduce gene flow without a complete geographical barrier. Isolation is partial: this is evidence of ongoing divergence, not proof that the two host races are already fully separate species.

People can change selection unintentionally. The Gorongosa elephant study published in 2021 linked intense ivory poaching to increased tusklessness among surviving females and their descendants. Poaching selected among heritable variants; elephants did not deliberately stop growing tusks. The inheritance evidence supported a sex-linked model, not a claim that every tuskless elephant everywhere has the same cause.

Artificial selection deliberately chooses breeders. Repeated use of a few parents can reduce genetic diversity and increase shared vulnerability to disease or environmental change. This is a risk of breeding design, not proof that every breeding programme must lose every useful allele. Maintain varied parental lines, wild relatives and suitable gene or seed collections. On isolated islands, limited colonisation and restricted gene flow can foster endemism; small ranges can also magnify vulnerability to a single introduced predator or disturbance.

AHL: Geological history and extinction evidence

Earth is about 4.5 billion years old. The geological hierarchy runs from eons to eras, periods and epochs. Fossils provide evidence of past organisms and changing communities; sedimentary context and dating constrain their ages. Preservation and sampling are uneven, so a fossil's last observed occurrence is not necessarily the exact day its species disappeared. Missing fossils do not establish that an organism never lived there.



Leg bones of the North Island giant moa (Auckland Museum): hunted to extinction within about two centuries of human arrival

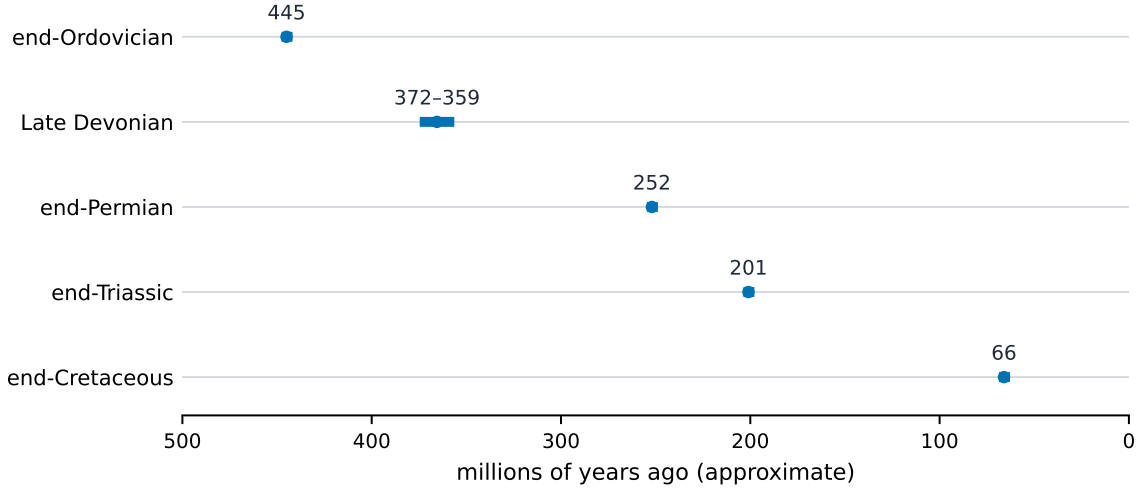
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Plate tectonics and biodiversity

The lithosphere consists of moving **tectonic plates** 构造板块. Plate movement can split populations, connect formerly separated faunas, build mountains and change climatic settings. Australian isolation helped shape its distinctive marsupial fauna, but Australia also has native placental mammals, including bats and rodents, and monotremes. Isolation is not a sufficient explanation for every trait or every extinction.

Mass extinctions

A **mass extinction** 大灭绝 removes a large share of species in a geologically short interval. The **background extinction rate** 背景灭绝速率 describes losses outside such exceptional intervals, with estimates depending on the organism group and time scale. The major extinction intervals are separated by long periods of evolutionary change. The end-Permian event was especially severe; the end-Cretaceous event removed non-avian dinosaurs, while birds survived. Volcanism, climate and ocean changes, sea-level changes and impact events contributed in different combinations. Estimates of losses depend on the organisms, time interval, fossil record and method: a list of precise-looking percentages without these definitions can mislead.



Geological intervals, not evenly spaced events or directly comparable species censuses

Survivors can diversify as ecological opportunities change, but recovery can take millions of years and need not restore the same species or functions. Present human-driven losses occur over much shorter management timescales. Calling the situation a sixth mass extinction expresses concern about the scale and trajectory; it does not make every current population decline a confirmed global extinction.

The Anthropocene describes profound human effects, but its status as a formal geological unit is a separate question. IUGS/ICS rejected the proposed formal epoch in 2024; the term remains useful outside the formal time scale. Candidate human signals include artificial radionuclides from nuclear testing, fly ash from combustion, plastics

or other novel materials in sediments, and changed sedimentation or fossil assemblages as species are redistributed. A useful boundary marker must be datable, widely correlatable and preservable; scientific evidence of human impacts is not cancelled by disagreement about a formal boundary.

AHL: Conservation priorities, rights and trade-offs

An **endemic species** 特有物种 occurs naturally only within a specified region. A **biodiversity hotspot** 生物多样性热点 has a specific terrestrial definition: at least 1500 endemic vascular plant species and loss of at least 70% of original natural vegetation. Conservation International describes 36 designated regions. A hotspot is not simply any species-rich site. Remaining natural vegetation covers much less area than the original region, so distinguish those two areas when quoting percentages.



Biodiversity at three levels: genetic, species, and habitat



Biodiversity at three levels: genetic, species, and habitat

Key biodiversity areas identify sites important for the global persistence of biodiversity using evidence about threatened species, ecosystems and other qualifying features. They are a prioritisation tool, not automatically a legal protection order. Two database examples make the site evidence concrete. Kakadu Savanna, Australia, is confirmed in an assessment dated 2018. Its savanna habitat and threatened or restricted-range biodiversity require attention to fire timing, frequency and introduced species. Tan-

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jung Puting, Indonesia, is a confirmed legacy site with an assessment dated 2001. Peat-swamp, heath and other forest habitats support birds and mammals, including orangutans; the historical factsheet identifies logging, conversion and fire pressures. Assess habitat condition and appropriate protection, while treating old records as dated evidence rather than current population counts. KBA recognition, a UNESCO biosphere reserve and legal protection are different designations.

Habitat clearing for oil-palm production can replace diverse tropical forest with a plantation, alter drainage and fragment populations. Income, employment and food demand are real benefits to analyse, while habitat loss, fire, emissions and unequal land access are costs. A plantation is not ecologically equivalent to the forest it replaces. Assess supply chains and displaced clearing elsewhere rather than assuming that banning one crop removes demand for vegetable oil.

At Kakadu, Bininj/Mungguy and Parks Australia describe cultural burning combined with contemporary management. Patchy burning under suitable conditions can reduce fuel continuity and the risk of extensive later fires. Loss of access, disrupted knowledge transfer, invasive grasses and changing climate can challenge such practices. This is a named, place-specific approach; Indigenous communities are diverse and no community should be assumed inherently sustainable or incapable of change.

Conservation also needs environmental justice: who decides, who loses access, who receives tourism income, and whose knowledge counts? UN experts' communications concerning Ngorongoro record allegations of pressure on Maasai people to leave their homelands. Treat the dated allegations and evidence explicitly; biodiversity gains cannot simply be presumed to justify displacement. Participation, land rights, fair benefit sharing, appropriate livelihoods and independent grievance procedures are part of assessing a project, alongside ecological monitoring.

Biosphere integrity concerns genetic diversity and ecosystem functioning. A planetary-boundary assessment signals elevated systemic risk; it is not an exact countdown or proof that one local species loss triggers a known global tipping date. Track abundance, distribution, interactions and functions as well as species counts.

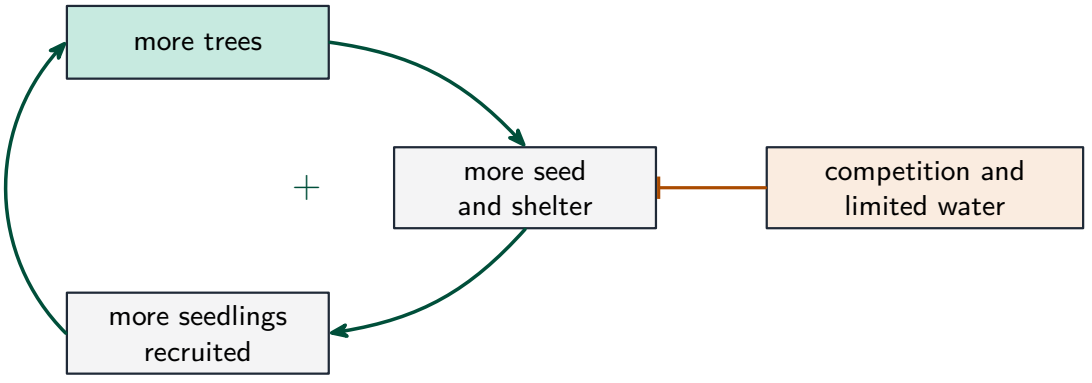
AHL: Restoring functions and evaluating success

National agencies can fund monitoring and enforce applicable rules; international bodies coordinate agreements and evidence. NGOs fund fieldwork, campaign and pursue legal challenges. UNEP does not enforce every national hunting law, and an NGO can influence legislation without enacting it. Compare named projects by funding, accountability, diplomacy, access, political influence, response time and results. Independence and speed vary; neither organisational label guarantees success.

Restoration can reinforce itself: more trees provide seed and shelter, increasing recruitment and supporting more trees. This is positive feedback because change is amplified, not because it is welcome. Competition and limited water constrain growth. Reinforcing processes can maintain alternative ecosystem states, but smooth growth alone

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does not demonstrate a tipping threshold.



Restoration as positive feedback: change is amplified, while competition and water set limits

Rewilding restores processes as well as selected species. Reconnecting habitat, restoring water regimes and allowing natural regeneration can be as important as reintroducing a predator. Land released from farming may lose food production or employment; moving production elsewhere can transfer environmental pressure. Assess animal welfare, neighbouring farms, invasive species, fire risk and funding continuity rather than assuming that management can simply stop.

Restoration comparison. A restored site records 40 breeding pairs before and 60 after the intervention; a comparable untreated site records 50 and 55. The restored site's increase is 20 pairs, but the comparison increased by 5, so a simple difference-in-changes is $(60 - 40) - (55 - 50) = 15$ pairs. This supports an additional increase associated with the intervention only under suitable comparison assumptions. It is not a randomised causal proof, and breeding pairs, occupancy, genetic variation and community acceptance measure different outcomes.

Evaluate success at three levels: was the promised activity completed, did ecological and social outcomes improve, and was this a defensible use of resources compared with alternatives? Planting 1000 trees measures an activity; survival after five years, native regeneration, habitat connectivity and community benefits measure outcomes. Record a baseline, comparable controls where possible, uncertainty and long enough monitoring to include bad years.

Ecotourism can fund rangers, restoration and local employment, while disturbing breeding animals, consuming water, producing waste or distributing profits unequally. Wuyishan's UNESCO account describes attempts to combine conservation with surrounding livelihoods. This is a management approach, not by itself a measured causal estimate of tourism's benefits. In a visitor budget, 8000 visits at 20 currency units

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generate 160000 gross revenue; operating costs of 110000 leave 50000, before any omitted costs. Specify how much actually funds conservation and local people, rather than calling gross receipts profit or equating visitor growth with ecological recovery.

Exam tips

- Define the measure, show index working, and judge conservation against ecological outcomes, feasibility and community rights.

Practice

1. (a) Define biodiversity and outline its three levels. (b) Distinguish between species richness and evenness.
2. Site X has species with 12, 4 and 4 individuals; site Y has 7, 7 and 6. Calculate Simpson's reciprocal index for each and state which is more diverse.
3. (a) Outline how natural selection leads to evolution. (b) Explain how geographical isolation can lead to the formation of a new species.
4. Explain two ways in which plate tectonics has affected biodiversity.
5. Describe what is meant by a mass extinction, and state two possible causes.
6. Outline four human causes of biodiversity loss, with an example of each.
7. Explain how habitat fragmentation reduces biodiversity, including edge effects.
8. State five characteristics that make a species vulnerable to extinction.
9. Outline the IUCN Red List categories and evaluate the usefulness of the Red List.
10. Explain why tropical rainforests are both important for and vulnerable to biodiversity loss.
11. Distinguish between the intrinsic and instrumental value of biodiversity, with an example.
12. Compare the roles of governmental and non-governmental organisations in conservation.
13. Evaluate captive breeding and reintroduction as a conservation strategy.
14. Explain four principles of protected-area design.

Answers.

1. (a) Biodiversity is the variety of life on Earth. Genetic diversity is inherited variation within a species; species diversity is the variety of species in an area; habitat diversity is the variety of habitats or ecosystems. (b) Richness is the number of species. Evenness is how equally individuals are shared among those species.
2. Both $N = 20$, $N(N-1) = 380$. X: $\sum n(n-1) = 132 + 12 + 12 = 156$, $D = 2.4$. Y: $\sum n(n-1) = 42 + 42 + 30 = 114$, $D = 3.3$. Y is more diverse because it is more even.
3. (a) Some variation is heritable. Overproduction and limited resources create competition; individuals differ in reproductive success. Inherited advantageous vari-

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ants can become more common across generations under the stated conditions. (b) A barrier can reduce gene flow; selection, mutation and drift may produce inherited differences. Reproductive isolation can develop, but a barrier alone does not guarantee speciation. Assess reproductive compatibility.

4. Land separation can reduce gene flow and allow divergence; continental connections can introduce competitors. Mountain building adds habitats and barriers; continental movement shifts climates. Australia also has native placentals and monotremes.
5. Mass extinction is a geologically rapid loss of a large share of species. Two possible causes are major volcanism and asteroid impact; mechanisms differed among events.
6. Any four, for example: habitat loss (rainforest cleared for oil palm); invasive species (cane toads in Australia); pollution (fertiliser runoff causing eutrophication); overharvesting (overfishing of cod); climate change (coral bleaching).
7. Fragmentation can increase edge exposure and restrict movement and gene flow. Interior specialists can lose suitable habitat; small populations face drift, inbreeding and shared hazards. Effects depend on species and surroundings.
8. Any five: small population, small range, narrow niche or specialised diet, low reproductive rate, large body or high trophic level, low genetic diversity, commercial value, migratory.
9. LC, NT, VU, EN, CR, EW and EX, plus DD and Not Evaluated. VU/EN/CR are threatened categories; DD is insufficient evidence, not low risk. Assessments guide priorities but do not themselves enforce protection.
10. Tropical forests can contain high richness and endemism. Clearing, fragmentation, fire and climate pressures threaten them; nutrient cycling, soils, seed sources and disturbance history affect recovery. Not every tropical soil is uniformly poor, and cleared forest does not universally fail to regrow.
11. Intrinsic value is the value of a species in itself, whatever its use (a right to exist). Instrumental value is its usefulness to people, such as medicines (artemisinin from sweet wormwood) or pollination.
12. National agencies can fund and enforce rules; international bodies coordinate agreements. NGOs fund fieldwork, campaign and pursue legal challenges. Powers, resources, speed and accountability vary; UNEP does not enforce all national wildlife law.
13. Strengths: can prevent loss and provide reintroduction stock (Przewalski's horse). Limits: costs, few species supported, and loss of genetic variation or wild behaviour. Success requires suitable habitat and control of original threats; combine with habitat protection.
14. Match area, shape, connectivity and buffers to species and threats. Compact shapes reduce relative edge; corridors aid movement but can transmit hazards. Several sites spread risk. Include local rights and monitoring; no layout is universally best.

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Water

International Baccalaureate · IB Diploma · Environmental Systems and Societies · HL

Scope and prerequisites

This handout teaches Topic 4, Water (4.1 Water systems, 4.2 Water access, use and security, 4.3 Aquatic food production systems, 4.4 Water pollution), for the course first assessed in 2026. Sections marked **AHL** are for Higher Level only. HL students also apply the three HL lenses (environmental law, environmental and ecological economics, and environmental ethics, units 9 to 11) to these ideas.

Prerequisites: Topic 1 (storages and flows, sustainability, natural income), Topic 2 (productivity, maximum sustainable yield, the nitrogen cycle, eutrophication) and Topic 3 (causes of biodiversity loss).

Water systems

Day Zero

In February 2018, Cape Town limited municipal water use to 50 litres per person per day during a severe drought. The city's 14 February notice reported dams at 24.7% and warned that stockpiling could bring the planned Day Zero supply restrictions closer. Day Zero was avoided through demand reductions and subsequent rainfall. A restriction is not the same as every tap actually running dry. Reservoir levels, household behaviour and governance interacted: water security is a social as well as a physical problem.

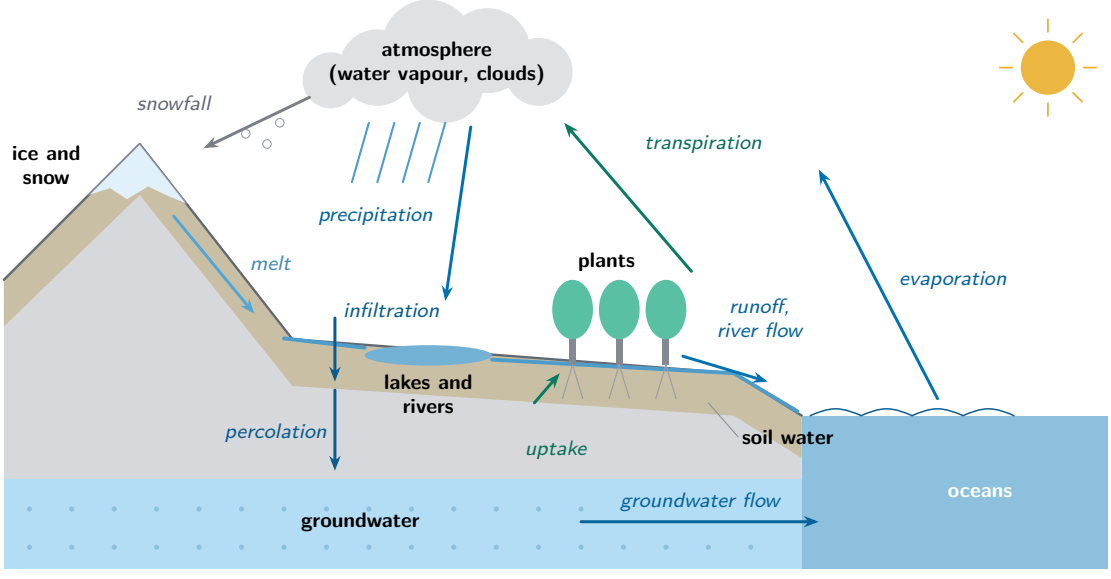
The hydrological cycle

The **hydrological cycle** 水循环 is the movement of water between storages, driven by energy from the Sun and by gravity. It is a closed system for matter (the amount of water on Earth stays almost the same) but an open system for energy.

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A waterfall in a river basin: a watershed is the land that drains into a stream or lake



Selected water storages (bold) and flows (italic); the diagram is not a complete numerical water budget.

Flows are of two kinds (Topic 1):

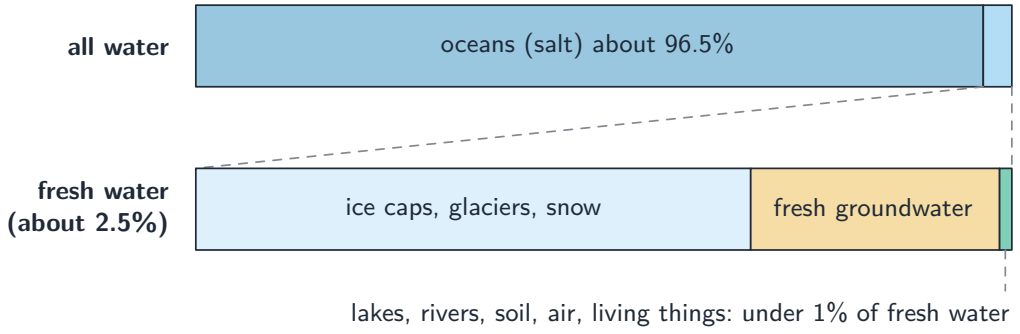
- **Transfers** move water without changing its state: runoff, river flow, **infiltration** 下渗 (water soaking into the soil), **percolation** 渗漏 (water moving through soil or porous rock), groundwater flow, and advection (horizontal transport of water vapour and cloud droplets).
- **Transformations** change its state: **evaporation** 蒸发 (liquid to gas), **transpiration** 蒸腾作用 (evaporation from plant leaves), **condensation** 凝结 (gas to liq-

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uid, forming clouds), freezing, melting, sublimation (ice to vapour) and deposition (vapour to ice). Evaporation and transpiration together are called **evapotranspiration** 蒸散.

Where the water is

Storage	Share of all water on Earth
Oceans	about 96.5 %
Ice caps, glaciers and permanent snow	about 1.7 %
Groundwater (about half of it fresh)	about 1.7 %
Lakes, rivers, soil, atmosphere and living things	about 0.02 %



Almost all water is salt; most fresh water is frozen or underground

Only about 2.5 % of the Earth's water is fresh, and most of that is frozen or deep underground. Less than 1% of fresh water is in lakes and rivers. These approximate rounded shares are not an exact inventory; accessible surface water still needs assessment and sometimes treatment before use.

The **residence time** 停留时间 of water is how long it stays in a storage on average. It varies greatly among rivers, lakes and aquifers: "a large lake" has no universal residence time. For an approximately steady storage with representative throughflow, use the following estimate. It is an average, not a claim that every molecule leaves on the same day; mixing and slow groundwater pathways matter.

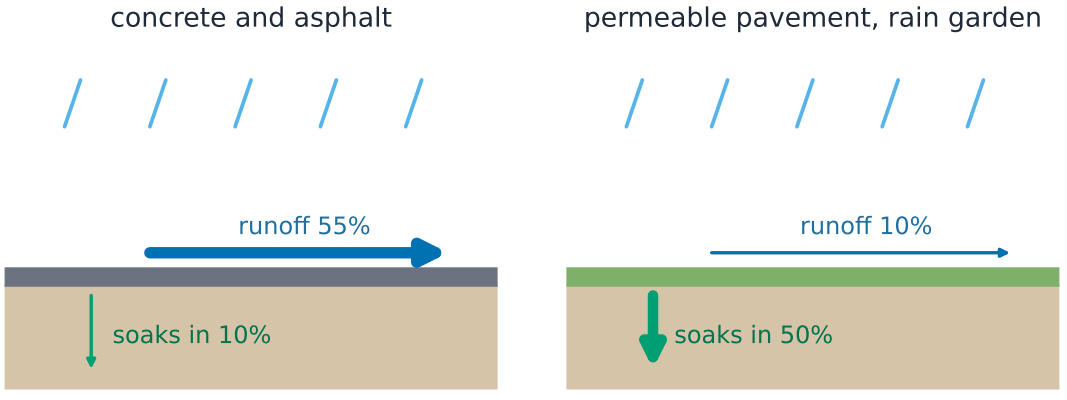
$$\text{residence time} = \frac{\text{size of storage}}{\text{rate of flow in or out}}$$

Worked example. A lake holds 2.0×10^9 m^3 of water, and 4.0×10^8 m^3 flows out each year. Residence time $= \frac{2.0\times10^9}{4.0\times10^8} = 5$ years.

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How people change the cycle

- **Withdrawing** water from rivers, lakes and **aquifers** 含水层 (rocks that store groundwater) for farms, industry and homes. If water is taken from an aquifer faster than it is recharged, the water table falls.
- **Urbanisation**: impermeable roofs and roads reduce infiltration and speed runoff. Drainage design, vegetation and storm intensity affect flood risk.
- **Deforestation** reduces transpiration; associated soil compaction and vegetation loss can reduce infiltration and increase erosion. Effects depend on soil, rainfall and subsequent land use.
- **Dams** store water and change river flow downstream.
- **Climate change** changes evaporation and precipitation patterns; drought and heavy-rainfall risks vary by region. Glacier loss can initially increase meltwater but eventually reduce this stored source of dry-season flow.

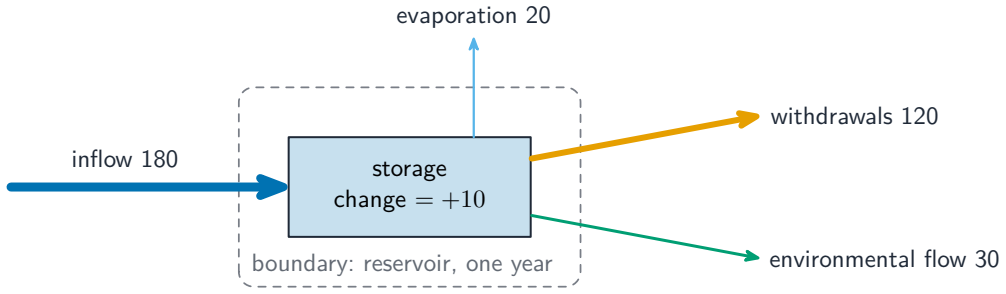


Impervious surfaces send rain into drains; permeable surfaces let it soak in

Balance a catchment budget

For a stated boundary and time period, change in storage = total inputs − total outputs. Rain is an input to a catchment; river discharge, evapotranspiration and water transferred out are outputs. A flow between two stores inside the boundary must not be counted as an external input twice.

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$180 - 120 - 20 - 30 = +10$ million m^3 per year (invented); arrow widths scale with flow

A reservoir budget: change in storage equals inputs minus outputs

Worked example, invented. A reservoir receives 180 million m^3 per year. Existing withdrawals are 120, evaporation 20 and a required downstream environmental flow 30 million m^3 per year. Storage change is $180 - 120 - 20 - 30 = 10$ million m^3 per year. An additional 10 would balance this simplified annual budget, not establish a safe drought-year allocation. Seasonal timing, water quality, ecological needs and recharge uncertainty still constrain use. Sustainable abstraction protects the stock and the services it supports, rather than merely matching one unusually wet year.

Water access, use and security

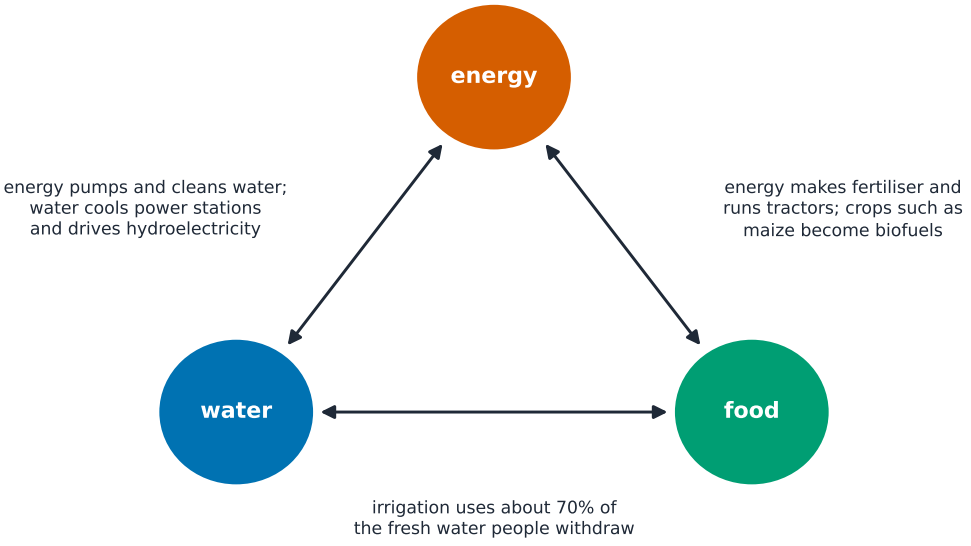
How we use water

FAO's SDG water-stress indicator reports 2023 global freshwater withdrawals as 72% agriculture, 15% industry and 13% services. These categories sum to 100%; "services" must not silently be relabelled as only household drinking water. Withdrawal is water removed from a source; consumption is the part not returned to the same system in the relevant period. Recycled water may reduce new withdrawals without eliminating all consumption.

Water security

Water security 水安全 means that people have reliable access to enough safe water at an affordable cost for health, livelihoods and the environment. In 2022 about 2.2 billion people still lacked safely managed drinking water, and about 3.5 billion lacked safely managed sanitation.

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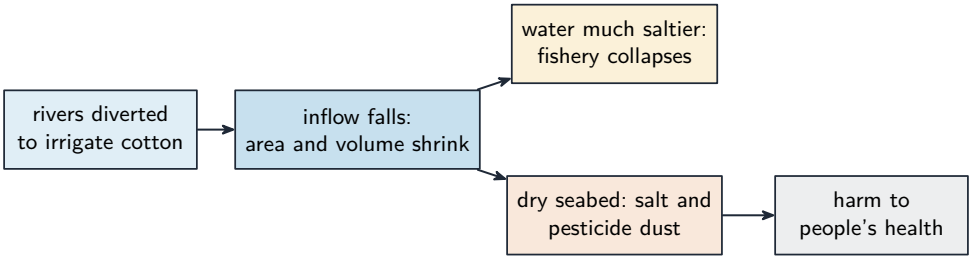


There are two kinds of water scarcity:

- **Physical water scarcity** 物理性缺水: there is not enough water, as in deserts and dry regions such as the Middle East.
- **Economic water scarcity** 经济性缺水: water is available but people lack the money, pipes or treatment to reach it, as in many parts of sub-Saharan Africa.

■ Case study: the Aral Sea

The Aral Sea in Central Asia was once the fourth-largest lake in the world. From the 1960s the two rivers that fed it were diverted to irrigate cotton fields. Its area and volume declined sharply, but percentages depend on the date, basin and quantity measured. Its water became much saltier, the fishing industry collapsed, and winds now blow salt and pesticide dust from the dry seabed, harming people's health. Since a dam was built in 2005, the small northern part has partly recovered, but most of the sea is gone. It shows how diversion changes a water budget and salinity. The partial northern recovery means this must not be presented as proof that every part crossed an irreversible tipping point.

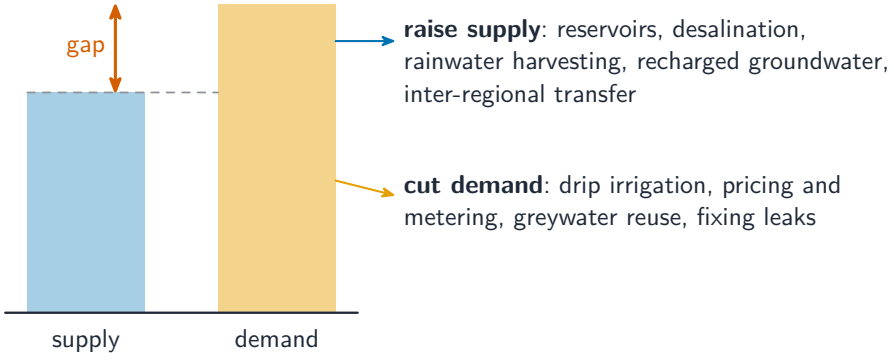


The Aral Sea: one diversion, a chain of consequences

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Increasing water supply and reducing demand

Increase supply	Reduce demand
Reservoirs and dams	Drip irrigation, which delivers water to the roots
Desalination 海水淡化 (removing salt from sea water; uses much energy)	Water pricing and metering
Rainwater harvesting	Recycling **greywater** 中水 (from washing) for toilets and gardens
Pumping groundwater, if it is recharged	Fixing leaking pipes
Transferring water between regions, such as China's South–North Water Transfer Project	Growing crops that need less water; eating less meat

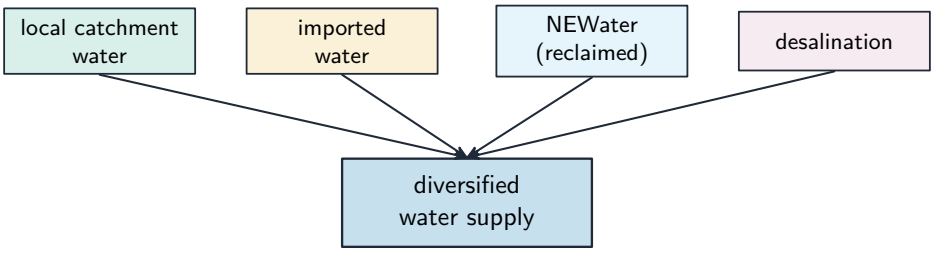


A water gap closes from either side: raise supply or cut demand

Supply measures often have environmental costs: dams flood land and block fish, desalination uses energy and produces salty waste, and transfers change two river systems. Compare lifetime costs, reliability, energy, ecological damage and affordability rather than assuming one measure is always cheapest. Reverse osmosis pushes water through a membrane under pressure; concentrated brine needs careful disposal. Greywater needs treatment appropriate to its reuse, not a direct connection to drinking water.

A named supply strategy: Singapore

Singapore's Four National Taps combine local catchment water, imported water, NEWater (high-grade reclaimed water) and desalination. Diversification reduces reliance on a single source, but treatment, energy, pipelines and maintenance cost money. Metering, leak reduction, low-flow fittings and suitable reuse complement supply. Emergency rationing needs arrangements for people unable to queue or store water; a high price alone can exclude low-income households.



Singapore's Four National Taps diversify supply

In farming, compare drip irrigation and drought-suited crops with their costs and possible rebound: saved water may enable expansion rather than lower total abstraction. Greenhouses can reduce exposure and improve control; aquaponics links recirculating fish water with plant production, but needs energy, nutrient balancing and hygiene. Industrial closed-loop cooling and process-water recycling need monitoring because salts and pollutants can accumulate. Choose a strategy using local rainfall, infrastructure, maintenance skills and environmental flows, not a universal technology ranking.

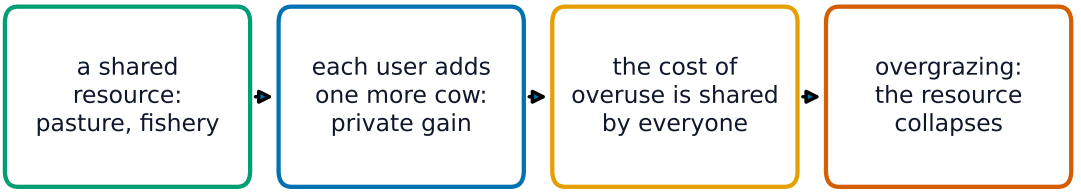
Aquatic food production

■ Fisheries under pressure

Fish and other aquatic foods supply a large share of the animal protein people eat, especially in coastal and island countries. Wild fish are a renewable resource when harvest and other losses do not exceed replacement over the relevant timescale (maximum sustainable yield, Topic 2). Stock percentages describe assessed stocks, not the same percentage of all individual fish or of global catch. State the assessment year and whether a figure is stock-counted or catch-weighted.

A **common resource** 公共资源 is shared and subtractable: one vessel's catch leaves fewer fish for others. The **tragedy of the commons** 公地悲剧 is a possible outcome when users gain individually while depletion costs are shared and effective rules are absent. It is not inevitable: community rights, monitoring and enforceable agreements can support sustainable use. Much fishing occurs under national or international regulation, not in an ocean that is everywhere ownerless and unregulated.

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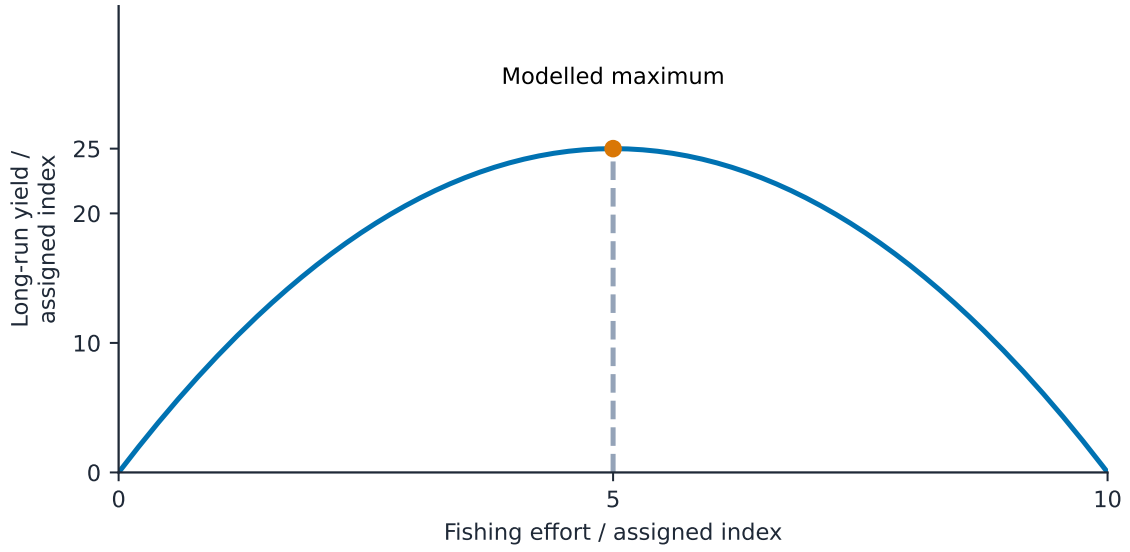
The tragedy of the commons: a possible outcome when private gain meets shared cost and effective rules are absent

Phytoplankton form the base of many aquatic food webs; rooted aquatic plants and larger algae also support consumers. People eat aquatic plants as well as animals: lotus rhizomes and carp are examples in Chinese food systems; kelp, mussels and marine fish enter wider markets. Demand reflects population, income, culture and trade. Harvesting high trophic levels can require substantial supporting production; no fixed 10% rule predicts every fishery's yield.

Sonar and large fleets can increase fishing pressure. **Bycatch** 兼捕 is catch additional to the intended target; it may be retained or discarded. Bottom trawling can damage seabed habitats; lost nets keep catching organisms. Explosives and poisons also harm non-target organisms and habitat. Warming changes ranges and thermal stress: heat-driven mass bleaching on the Great Barrier Reef illustrates climate damage to reef habitat. Ocean acidification is a distinct carbon-dioxide pathway that affects calcification, not another name for bleaching.

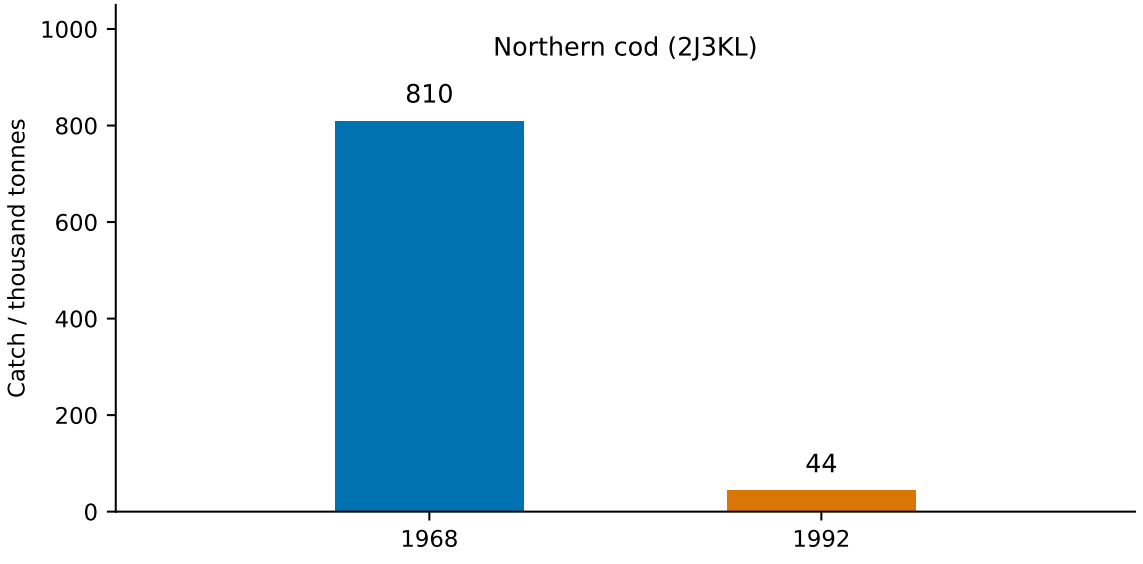
■ Maximum sustainable yield

Maximum sustainable yield (MSY) is the largest long-term harvest the modelled stock can replace under specified conditions. Replacement includes growth and recruitment, less natural mortality. At low effort, increasing effort can raise long-term yield; excessive effort reduces the breeding stock and can lower sustainable yield. A high catch in one year does not prove sustainability.



Equilibrium model: indices have no calibrated catch or vesse units. Real stocks have changing recruitment and uncertain estimates.

■ Case study: the Newfoundland cod



Northern cod (2J3KL), Newfoundland and Labrador: two dated catch observations, not a stock-biomass curve.

The Canadian historical report gives the 1968 peak as 810,000 tonnes and estimated 1992 catch as 44,000 tonnes. A commercial moratorium began in 1992 after severe depletion; it did not mean every form of cod fishing everywhere in Canada ceased. Overfishing, excessive confidence in stock estimates and ecosystem changes all matter. The 2025 DFO assessment records that the commercial fishery reopened in 2024.

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Reopening is a management decision, not proof of return to historical abundance. Distinguish catch, fishing mortality, recruitment and stock biomass when judging recovery.

Managing fisheries sustainably

- **Quotas** 捕捞配额: a total allowable catch for each species, based on scientific estimates of the stock.
- Limits on fishing gear, such as larger net **mesh sizes** so that young fish escape and can breed.
- Closed seasons and closed areas during breeding.
- **Marine protected areas** 海洋保护区, where fishing is banned or limited, can protect breeding areas and support recovery; outcomes depend on design, compliance and movement.
- Certification, such as the Marine Stewardship Council label, provides an assessed sourcing claim; certification and its auditing do not guarantee that every environmental effect is absent.
- International agreements, because fish do not stay within national waters.

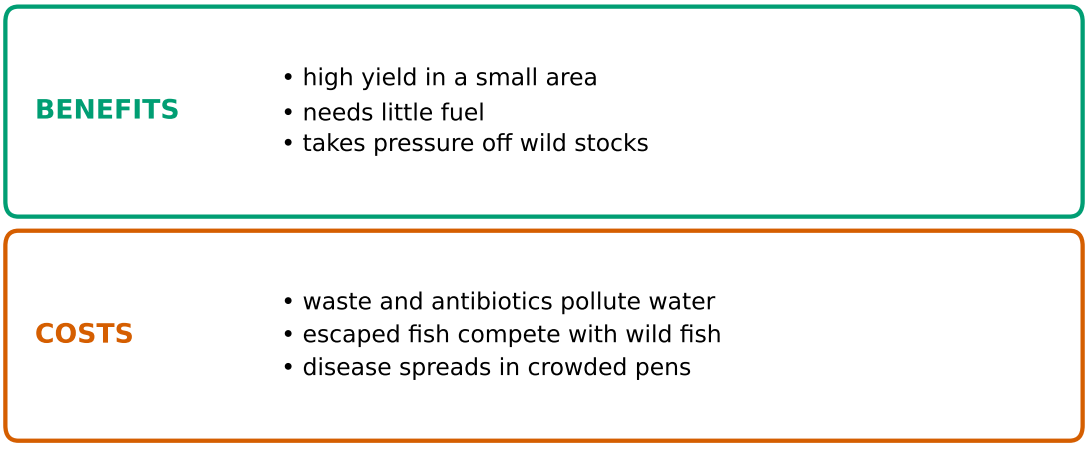
Aquaculture

Aquaculture 水产养殖 is the farming of fish, shellfish and seaweed. FAO's 2026 report reports aquaculture's share of aquatic animal production at 53% in 2024. Production, food supply and totals including algae have different denominators.



Salmon farm cages in a sheltered sound: aquaculture eases pressure on wild stocks but adds waste, parasites and escapes

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Benefits and costs of aquaculture

- **Advantages**: a more controllable supply; potentially reduced pressure on some wild stocks; efficient production in a small area; jobs in rural areas.
- **Disadvantages**: waste food and faeces cause eutrophication; disease and parasites can spread to wild fish; farmed fish escape and compete or breed with wild ones; antibiotics and chemicals pollute the water; mangrove forests have been cleared for shrimp ponds; carnivorous fish such as salmon are fed fishmeal made from wild fish.

More sustainable aquaculture can farm organisms lower in food webs (for example seaweed and filter-feeding shellfish), treats its waste, or combines species so that the waste of one feeds another. For example, seaweed takes up dissolved nutrients and filter-feeding shellfish remove suspended particles. These routes differ, and integrated farms still have capacity limits.

■ Aquaculture case: Norwegian salmon cages

Salmon farming in Norwegian coastal cages illustrates both food production and open-system costs. Feed inputs support growth, while uneaten feed and faeces add organic matter beneath cages. Sea lice and other disease pressures require coordinated management; escapees can interact with wild salmon. Site selection, stocking limits, fallowing, containment and independently monitored benthic conditions address different pathways. Fishmeal and oil sourcing affect wild fisheries; substituting plant feed shifts some impacts onto land. Do not claim that every cage has identical impacts or that all farmed species need fishmeal. A fair evaluation compares nutritional output and employment with whole-system feed, pollution, energy and ecological costs.

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Water pollution

Types of pollution

A **point source** 点源 of pollution is a single, identifiable place, such as a factory pipe or a sewage outfall. It is easier to monitor and control. A **non-point source** 面源 comes from many places spread over a wide area, such as fertiliser washed off farmland or oil washed off roads. It is much harder to control.



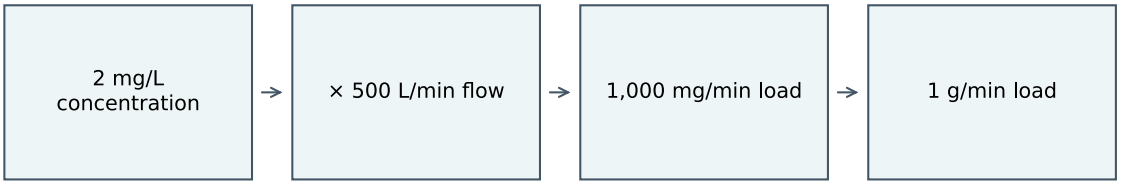
A pond choked by an algal bloom: extra nutrients let algae cover the whole surface. When they die and rot, the water loses its oxygen

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Pollutant	Sources	Effects
Organic matter	Sewage, food waste, animal slurry	Decomposers use up oxygen
Nitrates and phosphates	Fertilisers, sewage, detergents	Eutrophication
Toxic metals (mercury, lead)	Mining, industry	Toxic effects depend on chemical form and dose; methylmercury can biomagnify
Pathogens	Untreated sewage	Risk of infections such as cholera and typhoid, depending on the pathogen
Plastics	Litter, fishing gear	Animals trapped or eat it; microplastics in food chains
Heat (**thermal pollution** 热污染)	Cooling water from power stations	Less oxygen dissolves in warm water

The amount of pollution entering a river depends on both concentration and flow:

$$\text{load} = \text{concentration} \times \text{flow rate}$$



Load = concentration × flow = 2 mg/L × 500 L/min = 1,000 mg/min = 1 g/min

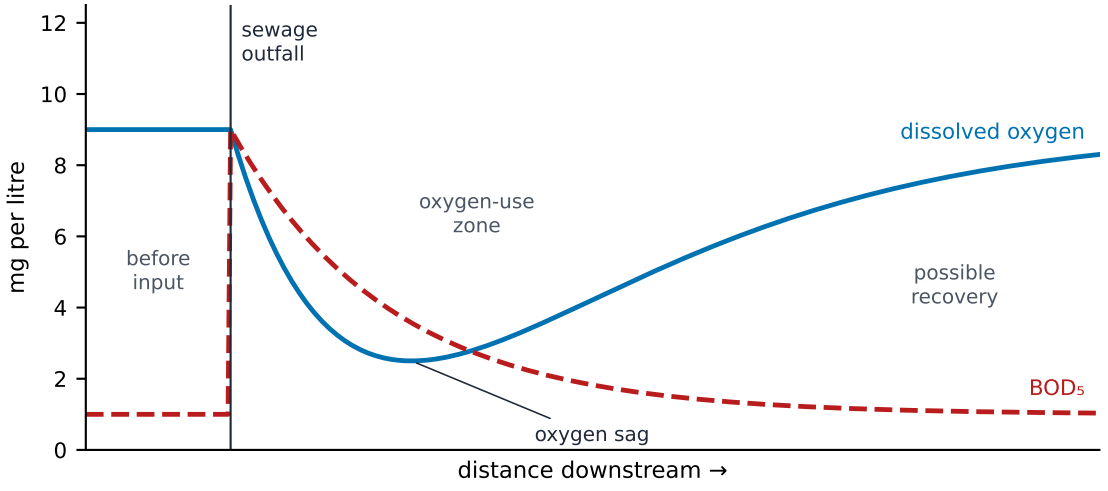
Adding clean water lowers concentration without removing pollutant mass if there are no other gains or losses. In the example, doubling flow to 1000 L/min while retaining a 1000 mg/min load halves concentration to 1 mg/L. For mixing streams, add their loads and flows separately, then divide total load by total flow; do not simply average concentrations.

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Measuring water quality

Direct measures of the water include dissolved oxygen, pH, temperature, nitrate and phosphate concentrations, turbidity (cloudiness) and the number of coliform bacteria (a sign of sewage).

Biochemical oxygen demand 生化需氧量 measures oxygen consumed by microorganisms under stated test conditions. BOD_5 commonly uses five days at 20 °C in darkness. An undiluted sample falls from 9.0 to 4.8 mg/L dissolved oxygen: BOD_5 is $9.0 - 4.8 = 4.2$ mg/L, assuming a valid test with any necessary controls. Real protocols may require dilution and blank corrections; a sample that exhausts its oxygen does not give an unrestricted reliable result by simple subtraction. High BOD suggests readily degradable material, not every possible pollutant.



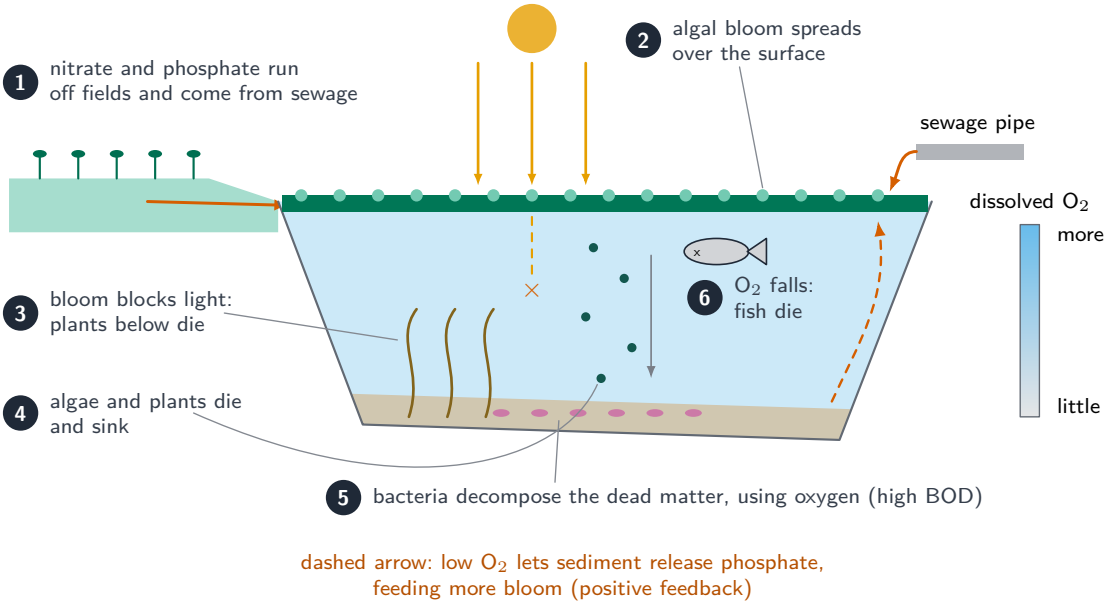
Schematic profiles, not measured distances. Temperature, flow, aeration and continuing inputs affect the response.

Use approved observations at matched sites, depths, seasons and times, with calibrated sensors and replicates. Report units, uncertainty and flow conditions. A one-off downstream–upstream difference can reflect tributaries or temperature as well as discharge. Clarity is not proof of drinking-water safety; microorganisms and dissolved pollutants may be invisible. Avoid contact with contaminated water and follow the approved sampling protocol.

Eutrophication

Eutrophication 富营养化 is the enrichment of water with nutrients, mainly nitrates and phosphates, which can stimulate producer growth and cause ecological changes, including oxygen depletion when respiration exceeds oxygen supply.

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Eutrophication: a chain with positive feedback

Algae themselves eventually die; decomposition does not require every submerged plant to die first. Daytime photosynthesis can temporarily raise surface oxygen while respiration continues at night and in deeper water. Decomposition and low oxygen can encourage sediment nutrient release, feeding further blooms: a positive feedback. **Dead zones** 死区 have oxygen too low for many oxygen-dependent organisms, not necessarily no living organisms at all.

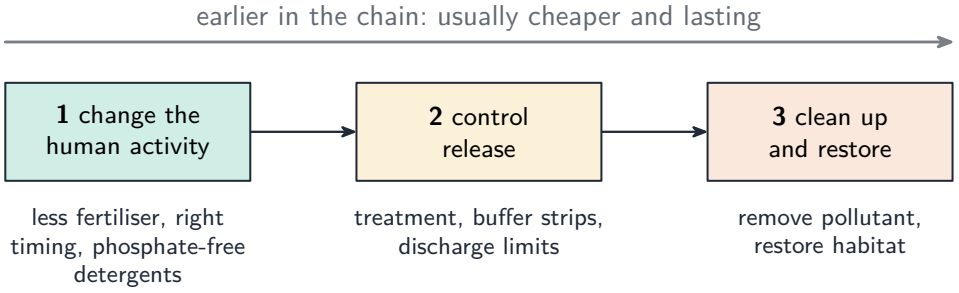
Some blooms make toxins; others mainly shade vegetation, alter food webs or consume oxygen after death. **Red tides** 赤潮 are marine harmful algal blooms that need not look red. NOAA identifies *Karenia brevis* on the Florida Gulf coast as a producer of brevetoxins. Not all blooms are toxic, and not all harmful blooms have the same nutrient cause.

A 2007 cyanobacterial bloom in **Lake Tai** 太湖, Jiangsu, contributed to severe odour and drinking-water supply disruption in Wuxi. Research on the crisis distinguishes malodorous compounds, bloom material and wider pollution: do not assume all reported harm came from one toxin. Sewage and agricultural nutrient control address inputs; sediment stores and circulation can delay improvement. Measure nutrient loads, bloom frequency and oxygen over time rather than judging success only by expenditure or a single clear day.

■ Managing pollution at three levels

Pollution can be managed at three levels, along the causal chain:

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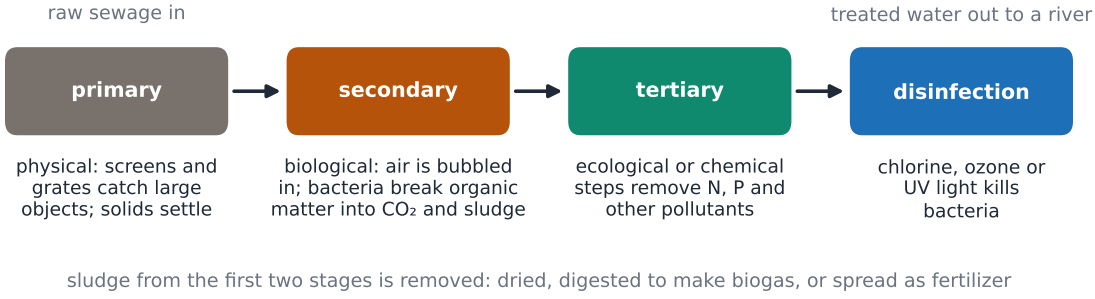
Pollution management at three levels; earlier in the chain is usually cheaper

1. **Change the human activity** that produces the pollutant: use less fertiliser, apply it at the right time, use phosphate-free detergents.
2. **Control its release** into the environment: use appropriate treatment to reduce organic matter and, where needed, nitrogen and phosphorus; plant **buffer strips** 缓冲带 of vegetation along rivers to absorb runoff; set legal limits for discharges.
3. **Clean up and restore** the damaged ecosystem: dredge nutrient-rich mud; pump oxygen into the water; remove algae; replant water plants; reintroduce fish.

Preventing pollution is usually cheaper and more effective than cleaning it up, but it needs farmers, industries and governments to change what they do.

■ Match treatment to the contaminant

Primary sewage treatment screens and settles solids. Secondary treatment uses biological processes to reduce biodegradable organic matter; nitrification converts ammonium to nitrate but is not itself removal of all nitrogen. Tertiary or advanced stages can target nutrients and fine particles. Disinfection targets pathogens and needs suitable conditions; it is not the same as removing every dissolved chemical. Treatment, pipe integrity, maintenance and affordable access all affect service quality.



Sewage treatment: primary (physical settling), secondary (aerated bacterial breakdown), tertiary (nutrient and pollutant removal) and disinfection

Prevention often avoids repeated damage, but compare feasible combinations. Buffer

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strips can intercept sediment and nutrients without stopping every dissolved input. Aeration may relieve low oxygen while leaving the nutrient source intact; dredging can disturb habitat and resuspend pollutants. Assign responsibility across farmers, households, utilities and regulators, and measure both ecological results and distribution of costs.

AHL: Water properties, oceans and evidence

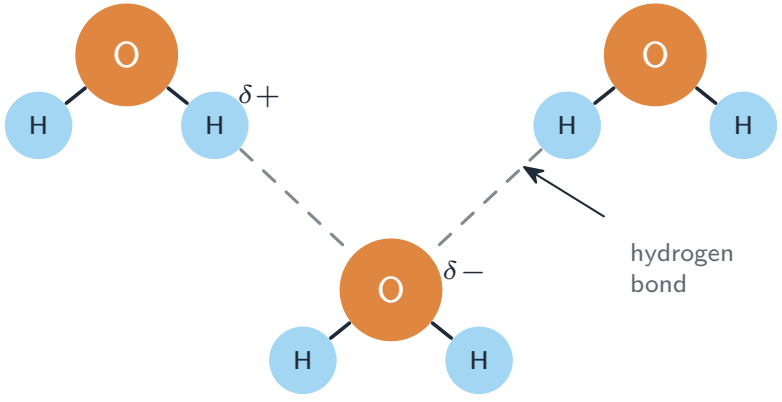
■ Link molecular properties to system behaviour

Water is polar: oxygen has a partial negative charge and hydrogen partial positive charges. Hydrogen bonds form between molecules. Cohesion helps maintain continuous water columns; adhesion to surfaces contributes to capillary movement. Water dissolves many ionic and polar substances, enabling nutrient transport and pollution pathways; it does not dissolve every substance equally. Transparency allows photosynthesis within a lit surface layer, but turbidity and wavelength affect penetration.



Ice floats on water because hydrogen bonding makes solid water less dense than liquid water

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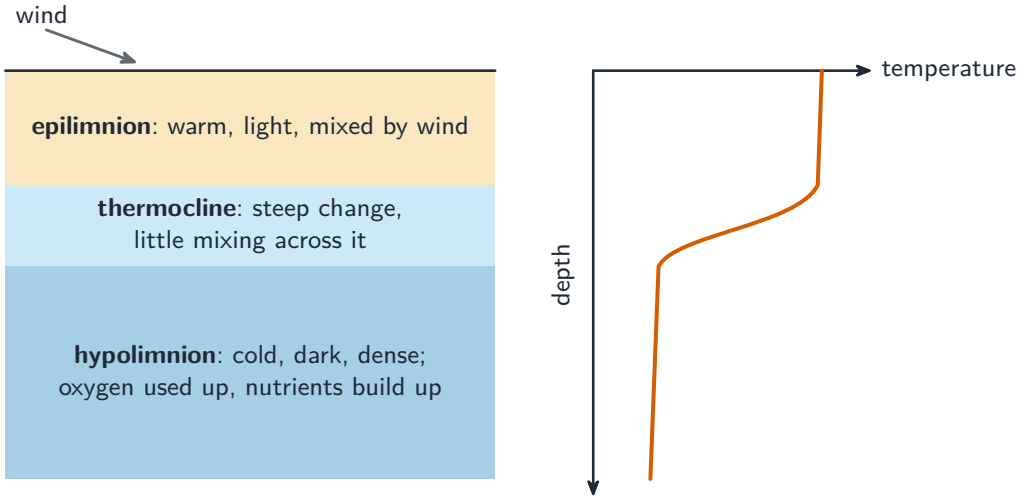
Water is polar (δ− oxygen, δ+ hydrogens), so its molecules attract each other by hydrogen bonds – the reason for all the properties above

High specific heat capacity buffers temperature change. **Example:** warming 200 kg of water by 3 °C, using $c = 4.18$ kJ per kilogram per degree Celsius, needs $Q = mc\Delta T = 200 \times 4.18 \times 3 = 2508$ kJ, ignoring losses. Evaporation also transfers latent heat. Fresh water is densest near 4 °C, so colder surface water can overlie it and freeze; do not apply that freshwater rule unchanged to seawater, where salinity affects density and freezing.

■ Stratification and circulation

Under comparable conditions, colder water can hold more dissolved oxygen; gas solubility also depends on pressure and salinity. Measured oxygen additionally reflects photosynthesis, respiration and mixing. A thermocline is a layer with a marked temperature gradient. Stable warm surface water may mix poorly with deeper water, limiting oxygen supply below and nutrient supply above. Seasonal cooling and wind can break stratification; lake depth and climate alter the pattern.

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Stratification: a thermocline separates warm surface water from cold deep water and limits mixing

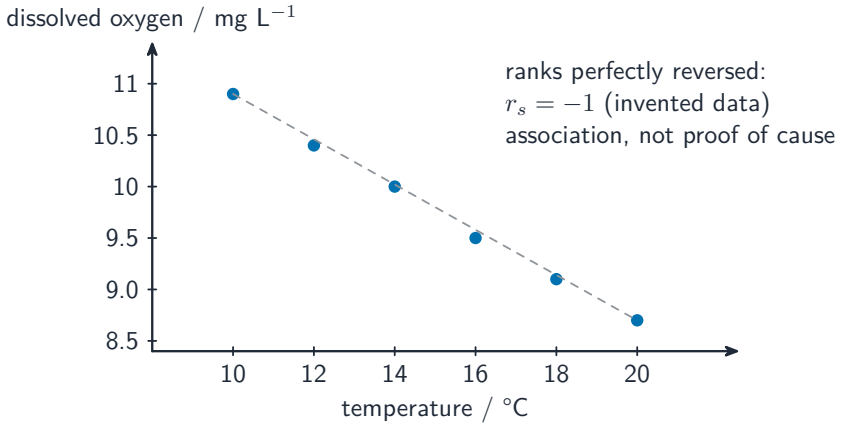
Thermohaline circulation 温盐环流 involves density contrasts from temperature and salinity. Cooling and greater salinity can promote sinking; freshwater input can reduce surface density. The global overturning circulation also depends on winds, basin geometry and mixing: an unbroken single conveyor arrow is a simplification. **Upwelling** 上升流 brings deeper water upward. When nutrients reach the lit zone, productivity can rise. During **El Niño** 厄尔尼诺, eastern equatorial Pacific winds and circulation change, often weakening nutrient supply; responses vary among coasts and events.

The ocean absorbs carbon dioxide through air–sea exchange. Cooling and circulation influence uptake; dissolved carbon chemistry and biological export move carbon among forms and depths. Absorption lowers pH and carbonate availability, affecting some calcifiers. Export to deep water is not automatically permanent burial: much organic matter is respired and carbon may return through circulation. Warming can reduce gas solubility and strengthen stratification, changing carbon and nutrient cycling.

■ Analyse paired data

Paired measurements from six independently selected comparable sites are:

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Six paired sites: a perfect negative rank correlation, not proof of cause

Temperature / °C	Dissolved oxygen / mg/L
10	10.9
12	10.4
14	10.0
16	9.5
18	9.1
20	8.7

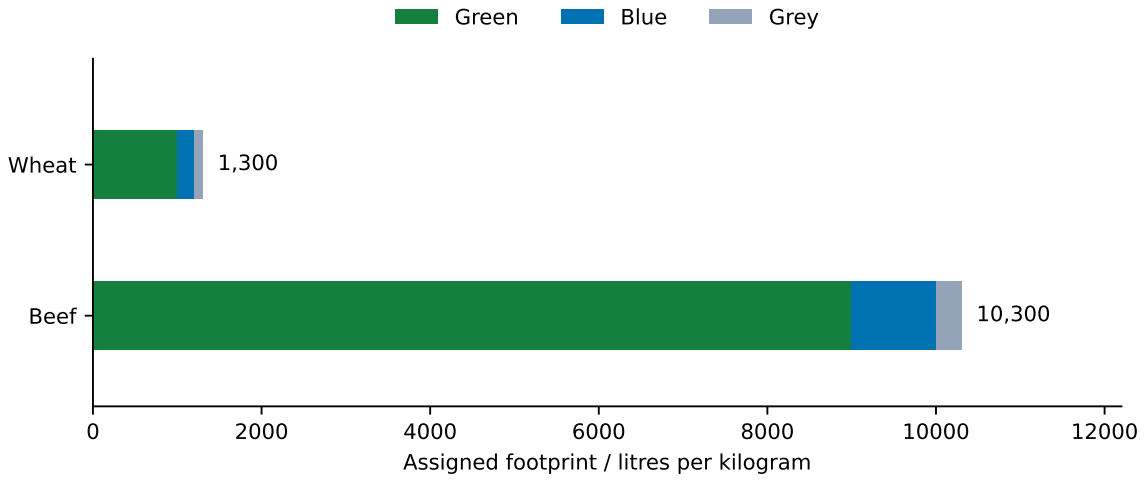
A scatter plot first checks the pattern and outliers. Spearman's rank correlation is suitable for testing a monotonic association with independent paired observations. Here the ranks are perfectly reversed: $\sum d^2 = 70$, so $r_s = 1 - 6(70)/(6(6^2 - 1)) = -1$. This constructed perfect association does not prove temperature caused every difference: salinity, shading, depth and respiration could confound it. Repeated readings at one site are not automatically six independent sites. Use the stated test assumptions and significance procedure, not correlation strength alone as proof.

AHL: Water footprints, scarcity and governance

■ Keep water-footprint components distinct

A **water footprint** 水足迹 measures freshwater appropriation linked to production or consumption. Green water is rainwater stored in soil and consumed by plants. Blue water is consumed surface water or groundwater. Grey water is the modelled volume needed to dilute a pollutant load to a specified water-quality standard under stated background conditions; it is not necessarily actual water withdrawn. Compare products using the same functional unit, method and boundary, and consider local scarcity and ecosystem needs as well as volume.

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Assigned teaching data, not measured global averages. Grey water is a dilution indicator; all bars use litres per kilogram of product.

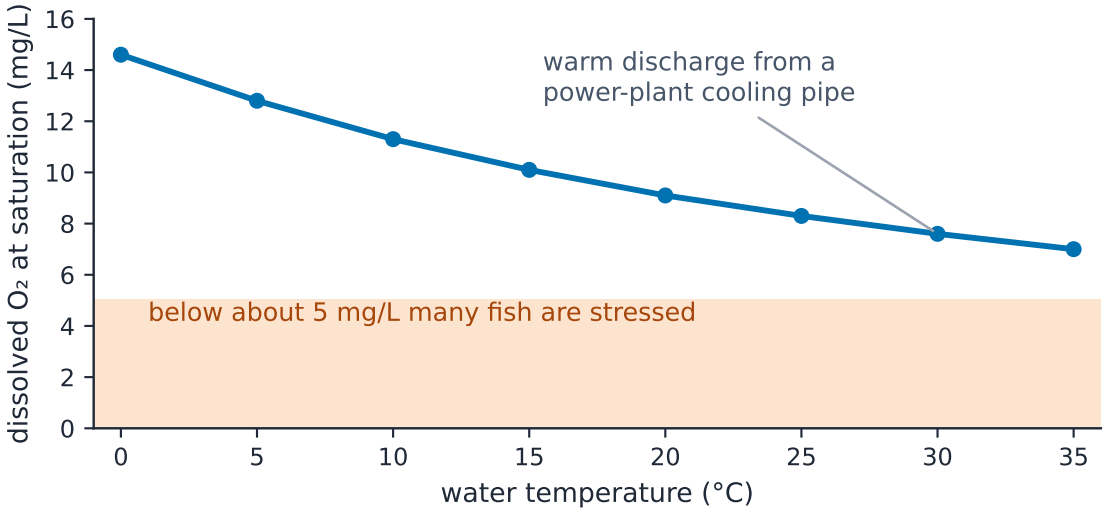
> **Worked example:** if an assigned cotton footprint is 10,000 L/kg and a shirt uses 0.25 kg, the attributed footprint is $10\,000 \times 0.25 = 2500$ L per shirt. A per-item value cannot be plotted against per-kilogram foods without a clear conversion. Cattle feed production, system efficiency, rainfall and feed sourcing affect beef footprints; energy-transfer percentages alone do not determine water use.

Virtual water 虚拟水 is water attributed to traded goods, not necessarily water physically shipped in pipes or contained in the final product. Trade can relieve local production demand but transfer impacts to a water-stressed exporter. "Exporting" does not prove a country is water-rich. Trace production location, seasonal water availability, pollution and who gains the income.

■ Compare indicators rather than mixing them

The Falkenmark indicator divides renewable freshwater resources by population. **Water stress** 水资源压力 is one label used with this availability measure:

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Warmer water holds less dissolved oxygen

Renewable water / m^3 per person per year	**Common availability category**
At least 1700	Above the stress threshold
1000 to less than 1700	Stress
500 to less than 1000	Scarcity
Less than 500	Absolute scarcity

A country with 120 km^3/year and 80 million people has $120 \times 10^9/(80 \times 10^6) = 1500$ m^3 per person per year: stress under this classification. A national average hides seasonality, distribution, quality, imports and affordability. Above 1700 is not a guarantee that every household has safe water.

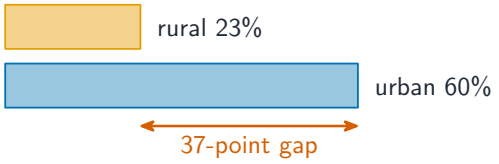
SDG indicator 6.4.2 instead compares freshwater withdrawals with renewable resources after reserving environmental flow requirements. With withdrawals of 30, renewable resources of 100 and environmental requirements of 40 million m^3/year, stress is $100 \times 30/(100 - 40) = 50\%$, not 30%. Name the indicator: the two measures have different quantities and units.

The freshwater-change planetary boundary assesses departures in blue-water streamflow and green-water root-zone soil moisture from baseline variability. It is not a national drinking-water-access threshold or the Falkenmark calculation. Global boundary transgression does not identify which local intervention is fairest without further evidence.

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Evaluate named contexts and inequalities

Jordan's National Water Strategy 2023–2040 reports about 61 m^3 of renewable freshwater per person per year. This dated resource estimate indicates severe scarcity; it is not a person's daily tap supply. Leak reduction, wastewater reuse and demand management face different finance and infrastructure constraints from Singapore's diversified, highly treated supply system. Compare two contexts without assuming technology alone removes unequal access.



Jordan: about 61 m^3 of renewable freshwater per person per year

a national resource estimate (severe scarcity), not a person's tap supply

WHO/UNICEF JMP 2023; Jordan National Water Strategy 2023–2040

Scarcity and unequal access in two named contexts

The WHO/UNICEF 2023 household WASH report gives 2022 safely managed drinking-water coverage in Peru as 23% rural and 60% urban, a 37-percentage-point gap. The category requires accessibility on premises, availability when needed and freedom from specified contamination. Rural location is an inequality dimension, not proof that all rural households share the same culture, income or service. Connect provision to maintenance, distance, affordability and representation; national averages can conceal excluded groups.

Governance and technology

Water governance includes laws, allocation rules, monitoring, accountability and participation. Local user agreements can share irrigation turns; basin agencies can set abstraction and discharge conditions; transboundary agreements can share drought data and release rules. On the Blue Nile, Ethiopia seeks power and development from the Grand Ethiopian Renaissance Dam; Egypt and Sudan have downstream flow and operational concerns. The UN Security Council's September 2021 statement encouraged negotiations towards agreement on filling and operation. This is a dated dispute example, not a claim that negotiations or dam status remained unchanged after 2021. A credible agreement needs drought contingencies, monitoring and a dispute process, not merely a promised annual average.

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A hydroelectric dam 大坝. The reservoir is held back behind the wall; water falls through the dam to spin turbines in the power house at its base

Managed aquifer recharge stores suitable water underground; recovery depends on aquifer properties, water quality and competing users. Solar desalination can reduce operational fossil-energy needs but still has land, material and brine costs. Dew collection depends on humidity and cooling conditions and supplies limited volumes. WMO's weather-modification statement explains that cloud seeding requires suitable existing cloud conditions; it cannot create a large rain-bearing weather system from nothing. Match claims to evidence and compare yield, energy, cost and ecological effects.

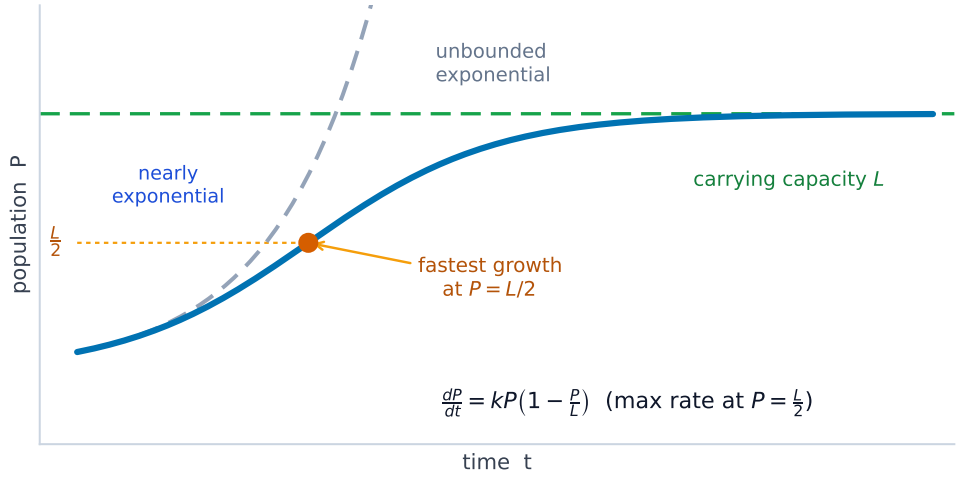
Citizen scientists can map leaks or monitor approved water-quality variables with shared methods, training, calibration and quality checks. Permissions, safe access and transparent reporting matter. Repeated comparable observations can expose unequal services; an unverified phone report or one reading should trigger investigation rather than serve as conclusive proof.

AHL: Fisheries assessment, rights and ethics

■ Use stock evidence cautiously

Assessment combines surveys, catch and effort records, size/age structure, tagging and models. Catch per unit effort may fall when abundance falls, but better technology or fish aggregation can hide depletion. Illegal or unreported removals create further uncertainty. Set monitoring requirements and conservative limits rather than treating an uncertain biomass estimate as exact.

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logistic: $dP/dt = kP(1 - P/L)$ · $P \to L$ as $t \to \infty$

The logistic model grows fastest at P=L/2 and levels off at the carrying capacity L

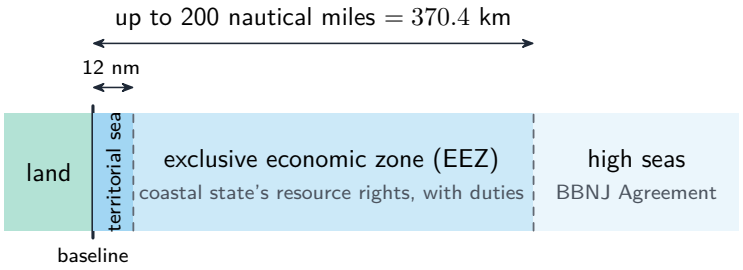
In a simple logistic model, annual net production is $rN(1 - N/K)$ and peaks at $N = K/2$. Invented $K = 1000$ tonnes and $r = 0.4$ per year give a maximum modelled replacement of $0.4(500)(1 - 0.5) = 100$ tonnes/year. Real recruitment, climate and food webs vary, so harvesting exactly this estimated maximum leaves little buffer for errors. Stakeholders may disagree over short-term jobs, food security, recovery time and the distribution of quota rights. Combine precaution, gear controls, transparent allocation and compensation or alternative livelihoods where needed.

Stratification links physical ocean change to fisheries: reduced mixing can restrict surface nutrient resupply; upwelling can support production but may also bring low-oxygen water. A productivity change does not immediately equal an identical catch change because food-web transfers, migration, effort and time lags intervene.

■ Compare jurisdiction and values

Under UNCLOS Article 57, an exclusive economic zone extends no further than 200 nautical miles from the relevant baselines: $200 \times 1.852 = 370.4$ km. Coastal resource rights come with obligations; an EEZ is not simply unrestricted sovereignty over every activity. Migrating stocks require cooperation. The BBNJ Agreement entered into force on 17 January 2026 and addresses biodiversity beyond national jurisdiction, including area-based measures, environmental assessment, genetic-resource benefit sharing and capacity building. It does not make national enforcement or existing fisheries organizations unnecessary.

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An EEZ gives resource rights with duties, out to at most 200 nautical miles; beyond it lie the high seas

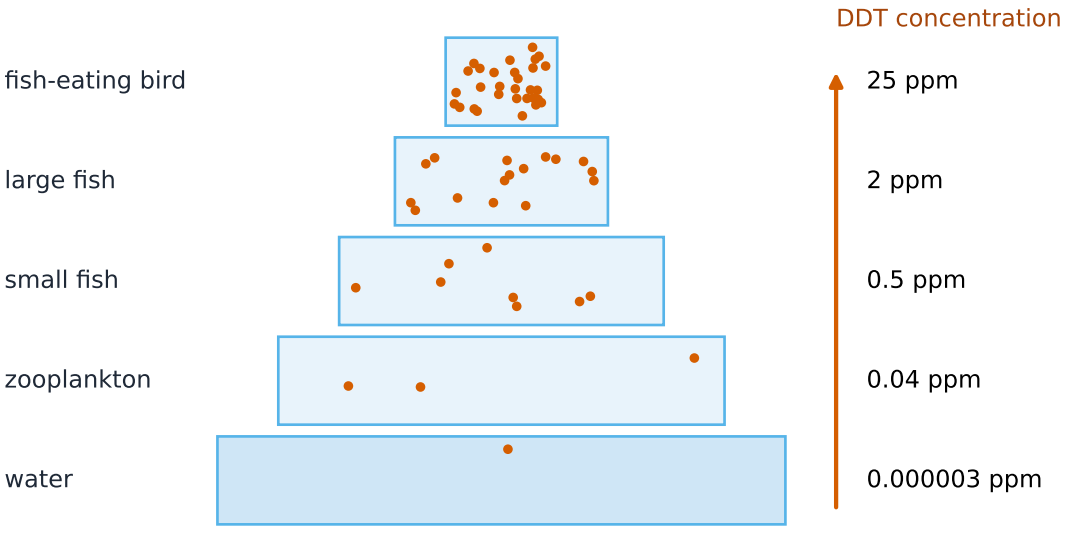
An Inuit narwhal hunt presents ethical questions about cultural continuity, food sovereignty, animal welfare, conservation evidence and who sets rules. An animal-rights argument may reject killing regardless of population effects; a sustainable-use argument may accept a regulated harvest if evidence supports it. Indigenous people and conservation groups do not each hold one uniform opinion. Evaluate decision-making rights, evidence, alternatives and the consequences of restrictions without inventing a universal quota or assuming cultural importance alone proves sustainability.

AHL: Pollution indices, treatment and accountability

■ Look beyond a single pollutant pathway

Tributyltin from historical antifouling paints can disrupt mollusc development; endocrine-active chemicals can alter hormonal signalling. PCBs persist and can accumulate through food webs, while methylmercury behaves differently from every other metal compound. Plastics can entangle organisms or be ingested; detection in a food chain is not by itself proof of increasing concentration at every trophic level. Thermal inputs can lower oxygen solubility and alter organisms' metabolic demand. Dose, exposure time, chemical form and species determine effects.

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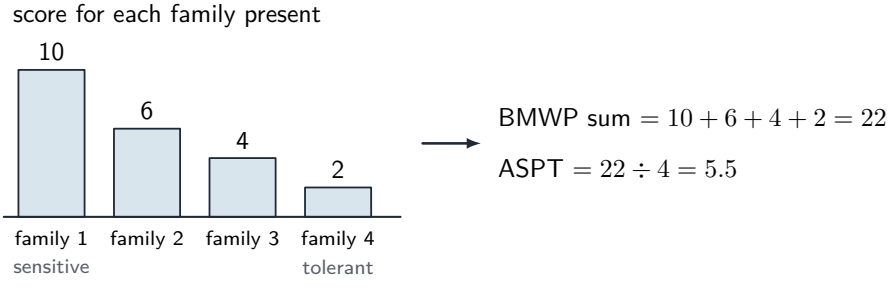


Biomagnification: DDT concentration rises at each trophic level

Freshwater cyanobacterial blooms at Lake Tai and marine *Karenia brevis* blooms illustrate different organisms and toxins. Warming and stable stratification can worsen hypoxia by lowering solubility, increasing respiration and restricting oxygen replacement. Measure depth profiles and time of day; a high afternoon surface oxygen value does not rule out night-time or bottom-water stress.

■ Interpret a biotic index correctly

An **indicator species** 指示物种 has a known response to conditions; its presence or absence is evidence with limits, not a universal purity certificate. Some mayfly and stonefly taxa are sensitive to low oxygen; tolerance differs, and their absence may reflect habitat or season. A **biotic index** 生物指数 combines biological observations using a stated scoring protocol. It can integrate conditions across organisms' lifetimes, but requires consistent sampling effort and suitable regional calibration.



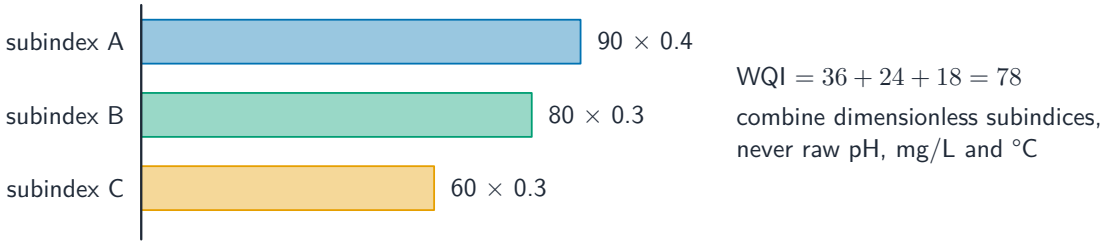
A BMWP-style index scores each family present, not each animal; ASPT averages over the scoring families

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The British BMWP approach assigns scores to recorded macroinvertebrate families and sums scores for families present; it is not a sum of all individual animals. Average score per taxon (ASPT) divides that sum by the number of scoring taxa. **Assigned teaching scores**, not an official family table: four families score 10, 6, 4 and 2. BMWP-style sum is 22 and ASPT is $22/4 = 5.5$. Do not compare this exercise with regulatory cut-offs or substitute a different region's family scores without justification. The Environment Agency's assessment report shows why family identification, sampling and reference conditions matter.

Combine chemistry with standards and action

A water-quality index (WQI) can combine measurements after converting them to defined dimensionless subindices. Subindices 90, 80 and 60 with weights 0.4, 0.3 and 0.3 give $0.4(90) + 0.3(80) + 0.3(60) = 78$. Adding raw pH, nitrate mg/L and temperature °C is meaningless. Aggregation may hide one hazardous contaminant; state the method, weights and intended use.



A weighted water-quality index combines dimensionless subindices

WHO drinking-water guidelines inform national standards; a guideline is not automatically binding domestic law. Meeting an ecological index does not certify drinking water. An environmental impact assessment for a bottling plant should examine seasonal abstraction, environmental flows, treatment, discharge, alternative sites and community access before authorization, then specify independent monitoring and enforceable conditions.

Citizens can contribute approved monitoring, ask regulators for discharge records, support research, comment on proposed permits and use lawful peaceful protest. Separate measured evidence from allegations, protect sensitive personal data and identify the authority with power to act. Evaluate enforcement, maintenance funding and equitable access as well as the existence of a policy document.

Exam tips

- State the boundary, time period and denominator. Distinguish a stock from a flow, withdrawal from consumption, catch from biomass and concentration from load.

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- Explain mechanisms before evaluating management; use a named case, dated evidence and limits. Show working and units, then interpret the result without claiming that an index proves safety or sustainability.

Practice

1. (a) Distinguish between a transfer and a transformation in the hydrological cycle, giving two examples of each. (b) State the share of the Earth's water that is fresh, and explain why only a small part of it is easy to use.
2. A reservoir holds 6.0×10^8 m^3 of water, and 1.5×10^8 m^3 flows out each year. Calculate its residence time.
3. Explain how urbanisation and deforestation change the hydrological cycle.
4. Explain how upwelling affects productivity and how an El Niño event can affect eastern Pacific conditions.
5. Explain why beef has a much larger water footprint than wheat.
6. A country has 45 km^3 of renewable fresh water a year and 60 million people. Calculate the water available per person and state its water-stress category.
7. (a) Distinguish between physical and economic water scarcity, with an example of each. (b) Outline the causes and effects of the shrinking of the Aral Sea.
8. Evaluate desalination as a way of increasing water supply.
9. Explain the tragedy of the commons, using fisheries as an example.
10. Outline three ways of managing a fishery sustainably.
11. Evaluate aquaculture as a way of meeting the demand for fish.
12. Distinguish between point and non-point sources of pollution, and explain which is easier to manage.
13. Explain the changes in dissolved oxygen and BOD downstream of a sewage outfall, and how indicator species show these changes.
14. Describe the process of eutrophication, and outline one way to manage it at each of the three levels.

Answers.

1. (a) Transfers: runoff and infiltration (no change of state). Transformations: evaporation and condensation (changes of state). (b) About 2.5% is fresh. Most is frozen or underground; less than 1% of fresh water is in lakes and rivers.
2. $\frac{6.0\times10^8}{1.5\times10^8} = 4$ years.
3. Impermeable surfaces reduce infiltration and speed runoff. Vegetation loss reduces transpiration; compaction can increase runoff and erosion. Effects vary with soil, rainfall and management.

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4. Wind-driven removal of surface water can bring nutrient-rich deeper water into the lit zone, supporting producers and food webs. El Niño can weaken eastern Pacific upwelling and alter productivity and catches; it does not stop all upwelling everywhere.
5. Beef production includes feed growth and animal conversion losses as well as drinking and servicing water. Footprints depend on feed source, climate and farming system. A fixed trophic-energy percentage cannot be used as a universal water multiplier.
6. $\frac{45\times10^9}{60\times10^6} = 750$ m^3 per person per year: water scarcity.
7. (a) Physical scarcity: not enough water exists, as in desert regions such as the Middle East. Economic scarcity: water exists but people lack money or infrastructure to reach it, as in parts of sub-Saharan Africa. (b) Irrigation diversions reduced inflow, shrinking the lake and raising salinity. Fisheries suffered and exposed sediments supplied dust. The 2005 northern dam supported partial recovery; basin trajectories differ.
8. Reverse osmosis can diversify coastal supply but needs energy, capital and brine management. Compare reliability, maintenance, carbon emissions, affordability and ecosystem effects with demand reduction and other supplies.
9. Extra catch benefits a user while depletion costs are shared. Ineffective rules can allow effort beyond replenishment. Collapse is possible, not inevitable: enforceable access rules and monitoring can change incentives.
10. Any three: quotas based on scientific stock estimates; larger mesh sizes so young fish escape; closed seasons or areas during breeding; marine protected areas; certification; international agreements.
11. Aquaculture supplies food and jobs but can impose feed, waste, disease, escape and energy costs. Evaluate species and system: suitable sites, stocking, feed sourcing and waste controls reduce particular impacts.
12. A point source has one identifiable outlet, such as a pipe. Diffuse inputs, such as farm runoff, need coordinated catchment controls rather than monitoring only one outlet.
13. Organic input raises microbial oxygen demand and can lower oxygen. Material depletion and aeration may allow recovery. Taxa differ in tolerance, but habitat, season and detection also affect the biotic index; none alone proves a source.
14. Nutrients stimulate producers; dead algae and shaded plants supply decay. Decomposer respiration consumes oxygen; deaths and nutrient recycling can reinforce change. Reduce unnecessary fertiliser (activity), intercept runoff/treat nutrients (release), and assess aeration or habitat repair (restoration).

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Land

International Baccalaureate · IB Diploma · Environmental Systems and Societies · HL

Scope and prerequisites

This handout teaches Topic 5, Land (5.1 Soil and 5.2 Agriculture and food), for the course first assessed in 2026. Sections marked **AHL** are for Higher Level only. HL students also apply the three HL lenses (environmental law, environmental and ecological economics, and environmental ethics, units 9 to 11) to these ideas.

Prerequisites: Topic 1 (systems, sustainability, natural capital), Topic 2 (energy flow between trophic levels, the nitrogen cycle, succession) and Topic 4 (water use, eutrophication).

Soil

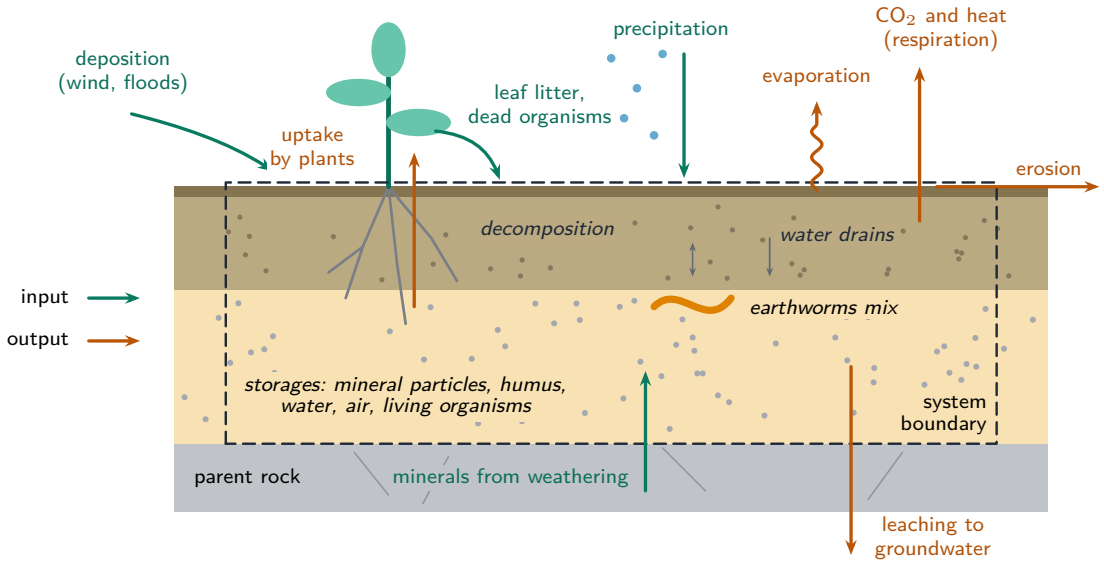
■ Saving the Loess Plateau

Loess is wind-deposited, often silt-rich material. On China's Loess Plateau, vegetation clearance, cultivation and grazing pressure exposed erodible slopes. A World Bank account of the 1994–2005 rehabilitation projects describes terraces, changed grazing and vegetation restoration in selected watersheds. Reducing sediment loss and improving livelihoods required an integrated programme, not planting trees alone. Surface cover, structure and organic matter can improve within years; rebuilding the full depth of lost soil may take much longer. A successful project site is not proof that every part of the plateau has recovered equally.

■ Soil as a system

Soil 土壤 is a mixture of mineral particles, **humus** 腐殖质 (relatively decomposed organic material), water, air and living organisms. It is a system with storages, inputs, outputs and processes.

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Soil as a system: inputs, internal processes and outputs

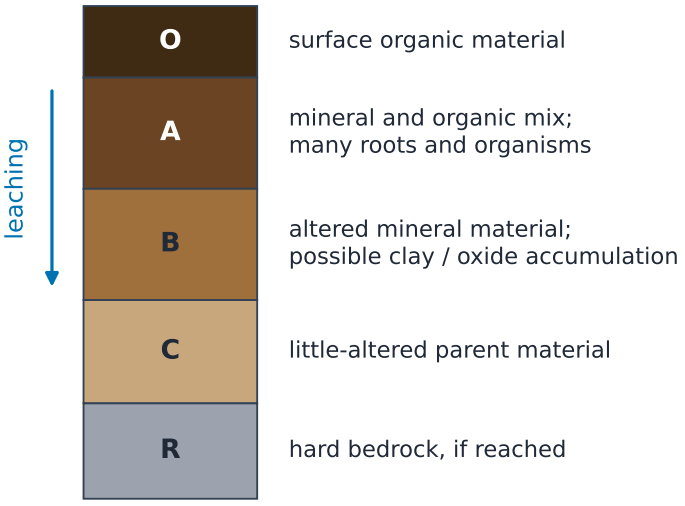
- **Inputs**: dead organic matter from plants and animals, precipitation, minerals from the **weathering** 风化 of parent rock, and material deposited by wind and water.
- **Transfers** inside the soil: water moving down; earthworms mixing organic matter into deeper layers.
- **Transformations**: decomposition and mineralisation of organic matter, plus chemical weathering of minerals. Physical weathering fragments material without necessarily changing its chemical composition.
- **Outputs**: carbon dioxide from respiration, heat from energy transfers, nutrients taken up by plants, **leaching** 淋溶 (nutrients washed downwards out of reach of roots), erosion, and evaporation.

Soil links the other systems of the Earth: it stores water (the hydrosphere), exchanges gases with the air (the atmosphere), forms from rock (the lithosphere) and is full of life (the biosphere). Soil is a major carbon store, but a store is not automatically a sink: inputs must exceed losses for its carbon stock to increase. An inventory depends on sampled depth, soil type and whether organic or inorganic carbon is counted. Plants obtain most of their carbon from atmospheric carbon dioxide, while soil supplies water and mineral nutrients such as nitrogen, phosphorus and potassium.

In warm, well-aerated tropical mineral soils, rapid decomposition and nutrient uptake can limit long-term organic accumulation. Cold tundra and oxygen-poor wetland conditions can slow decay; temperate grasslands can receive substantial root inputs. These are mechanisms, not universal stock rankings: tropical peatlands can store large amounts of carbon. Compare depth, drainage, inputs and losses instead of assuming every tropical soil is carbon-poor.

The soil profile

A vertical section can show layers called **horizons** 土层:



A simplified profile: real soils can lack a horizon or include additional horizons; colours and thicknesses vary.

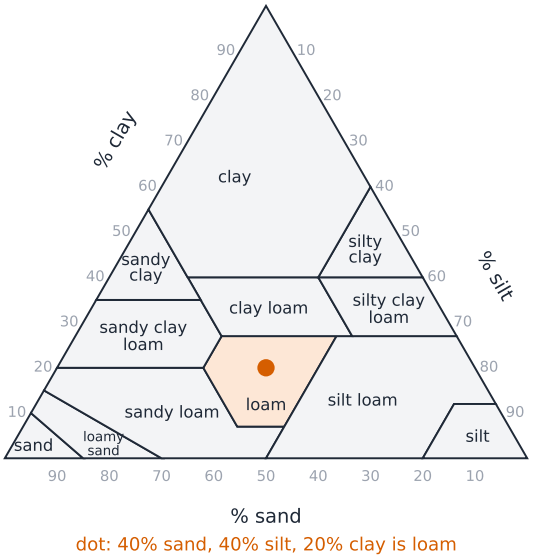
- **O horizon**: fresh leaf litter and humus at the surface.
- **A horizon** (**topsoil** 表土): dark, rich in humus, with most roots and soil organisms. This is the layer that matters most for farming, and the first to be lost by erosion.
- **B horizon** (subsoil): altered mineral soil, sometimes with accumulation of clay or iron compounds from above. It is not always lighter than the A horizon.
- **C horizon**: relatively little-altered parent material, which may be weathered rock or transported sediment.
- **R**: underlying hard bedrock where present; not every observed profile reaches it.

Soil forms very slowly: formation rates vary with climate, parent material, organisms and landscape. A centimetre can require centuries in some settings, but no single rate applies everywhere. On a human timescale it is effectively a non-renewable resource, so losing it is very serious.

Soil texture

Soil texture 土壤质地 depends on the sizes of the mineral particles:

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The soil texture triangle: the dot at 40% sand, 40% silt and 20% clay falls in loam

Particle	Size	Properties of a soil rich in it
Sand	0.05 to 2 mm	Large air spaces; drains fast; dries out; holds few nutrients; easy to dig
Silt	0.002 to 0.05 mm	In between; fertile, but easily eroded
Clay	less than 0.002 mm	Holds water and nutrients well; drains slowly; can become waterlogged and hard to work

A **loam** 壤土 has a balanced range of sand, silt and clay proportions under the chosen textural classification; organic matter is a separate property. Loamy textures often balance water retention and drainage, but the best soil depends on the crop, climate, pH and management. Mineral texture is distinct from structure: structure concerns how particles form aggregates and pores. Organic matter can improve aggregation, water and nutrient retention; excessive or contaminated additions can also cause problems. Humus contributes to aggregation and retention; further decomposition can release nutrients. It is not identical to all fresh litter or all living soil biomass.

Soil is also a habitat. Soil organisms include bacteria, fungi, roots, worms, mites and insects; their abundance varies greatly. Detritivores fragment litter, and decomposers chemically break down organic matter. Mineralisation releases inorganic nutrients; uptake, immobilisation, leaching and gaseous losses move nutrients along different paths. Earthworms are useful ecosystem engineers in many soils but are not present or beneficial in every ecosystem.

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Soil degradation

Soil degradation 土壤退化 is a fall in the quality or quantity of soil. Measure the type, depth, area and severity before comparing degradation estimates. The main types are:



A fresh clearcut: every tree in the strip is taken at once, leaving bare soil that erodes and washes into streams

- **Erosion** 侵蚀: removal of topsoil by water (on bare slopes after heavy rain) or wind (on dry, bare, flat land).
- **Salinisation** 盐碱化: in dry places, irrigation water evaporates and leaves salts behind; high salinity makes water uptake harder by lowering soil-water potential, and particular ions can also be toxic.
- **Nutrient depletion**: crops take nutrients away and they are not replaced.
- **Compaction**: heavy machines and animals squeeze out air spaces, so water cannot soak in and roots cannot grow.
- **Pollution**: pesticides, heavy metals and plastic.
- **Desertification** 荒漠化: land degradation in arid, semi-arid and dry sub-humid areas, associated with climatic variations and human activities. It does not require sand dunes or conversion into a literal desert.

Human causes include **overgrazing** 过度放牧 (too many animals remove the plant cover), **deforestation**, **overcultivation** (cultivation that depletes nutrients or damages soil faster than recovery) and poor irrigation. Lack of cover increases risk, but slope, rainfall, wind, aggregation and drainage also matter. Fertiliser can replace some nutrients without replacing lost soil depth, structure or biodiversity.

Case study: the Dust Bowl. In the 1920s farmers on the Great Plains of the USA ploughed up millions of hectares of natural grassland to grow wheat. When a

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long drought came in the 1930s, the crops failed, and strong winds blew the dry, bare topsoil away in huge "black blizzards". Hundreds of thousands of people had to leave their farms. The government then established the Soil Conservation Service in 1935, paid farmers to plant windbreaks and use contour ploughing, and returned some land to grass.



A dust storm in the Texas Panhandle, 1936: dry, bare, ploughed topsoil blown away by wind.

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Soil conservation

Method	How it protects the soil
Terracing 梯田	Flat steps cut into slopes slow runoff and trap soil
Contour ploughing 等高耕作	Ploughing across the slope along contours; furrows can slow runoff
Windbreaks (shelter belts)	Lines of trees reduce wind speed across fields
Cover crops 覆盖作物	Plants grown between main crops keep the soil covered and add organic matter
Crop rotation 轮作	Changing crops each year, including legumes with nitrogen-fixing symbiotic bacteria, can improve nutrient cycling and interrupt some pest cycles
No-till farming	Planting without ploughing leaves roots and crop remains in place
Mulching and compost	A layer of organic matter protects the surface and adds humus
Controlled grazing	Limiting animal numbers keeps plant cover
Careful irrigation	Manage salt inputs, leaching and drainage; drip irrigation alone does not guarantee salt removal

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Terraces turn a steep slope into level steps, so runoff slows and soil stays on the hillside.

Conservation costs time and money now, while the benefits come slowly. Farmers need knowledge, secure ownership of their land and often government support to adopt it.

Agriculture and food

Farming systems

Farming is a system with inputs (land, water, seed, labour, fertiliser, machinery, energy), processes (ploughing, sowing, harvesting) and outputs (food, fibre, waste and pollution). Farming systems are often classified as:

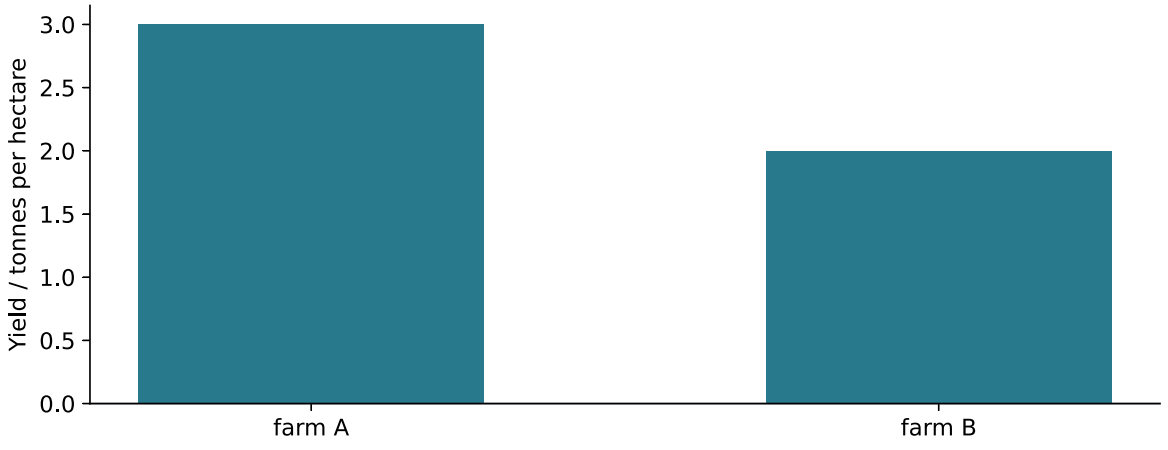


Aerial pesticide spraying: chemical pest control can protect yields but also harm non-target species and create resistant pests

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Type	Features
Subsistence farming 自给农业	Produces food mainly for the farmer's family; small scale; few bought inputs
Commercial farming 商业农业	Produces food to sell; often large scale
Intensive farming 集约农业	Large inputs of labour or money per hectare; high yields per hectare
Extensive farming 粗放农业	Small inputs per hectare over large areas; lower yields per hectare
Arable, pastoral, mixed	Growing crops; raising animals; both

Distinguish total harvest from **yield** 产量 per unit area. Also state crop, edible fraction, moisture basis and period: tonnes per hectare per harvest differs from tonnes per hectare per year. A larger farm can harvest more while having lower land productivity.



Compare yield per hectare, not total harvest: 18 t ÷ 6 ha = 3 t/ha against 20 t ÷ 10 ha = 2 t/ha

Farms can also be compared by energy efficiency:

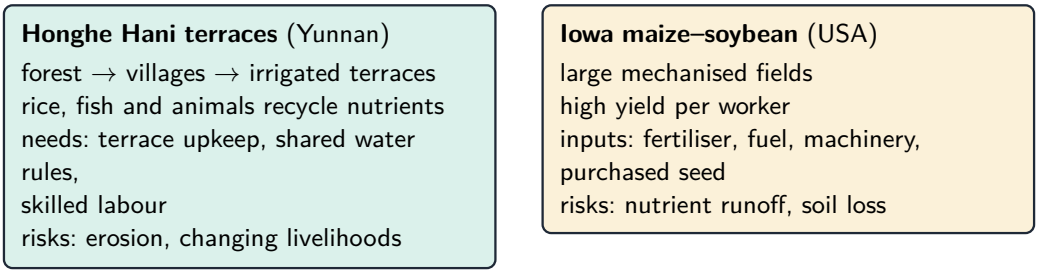
$$\text{energy efficiency} = \frac{\text{energy in food produced}}{\text{energy put in}}$$

Worked example, invented. Farm A uses 3000 MJ of counted non-solar energy per hectare and produces food containing 45,000 MJ: output/input ratio $= 45\,000/3000 = 15$. Farm B uses 20,000 MJ and produces 50,000 MJ: ratio $= 2.5$. Solar input is excluded from this accounting, so a ratio above 1 does not create energy or violate conservation. Include the same labour, fuel, fertiliser, machinery and boundary assumptions for both farms. Food-energy output is not the same measure as crop mass, protein quality, income or total lifecycle impact.

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Contrasting named systems

The Honghe Hani rice terraces in Yunnan integrate forest, villages, irrigated terraces and water management on mountain slopes. Rice, fish and domestic animals can provide different foods and recycle nutrients. Terrace maintenance, shared water rules and skilled labour matter; erosion, changing livelihoods and market pressures still require management. "Traditional" does not mean every input is free or every impact absent.



Two named food systems compared on inputs, outputs and risks

In Iowa, USA, a commercial maize–soybean rotation illustrates mechanised temperate row cropping. USDA field experiments near Ames compare tillage, fixed nitrogen application, no-till and cover-crop systems. Machinery, purchased inputs, drainage and market infrastructure can support large output, while nutrient loss and soil disturbance need controls. Soybean rotation does not make maize nitrogen requirements disappear. Not every Iowa farm uses an identical system.

Compare terrain and climate, water source, labour and machinery, nutrient inputs, marketed and household outputs, and off-farm effects. Use the same nutritional or energy output and time boundary for numerical comparison. The farm-type labels are independent dimensions: commercial farms can be small, organic, intensive or extensive; subsistence farmers may also sell surplus.

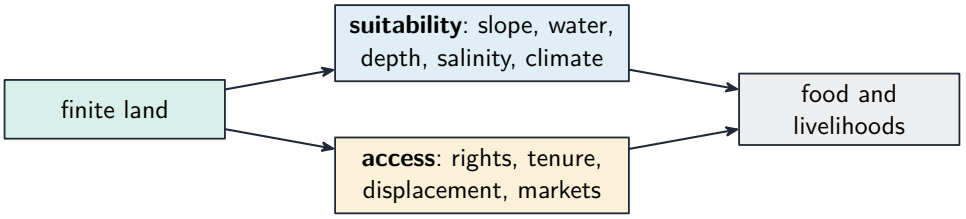
Mobility, fallows and recovery

Nomadic pastoralism can follow seasonal forage and water, spreading pressure where access remains flexible. Settling people permanently or restricting routes can concentrate animals and change viability. Shifting cultivation with long fallows can allow soil and vegetation recovery; shortened fallows under land pressure can prevent it. The relevant causes are land access, recovery periods and extraction rates, not a simple equation between cultural change and inevitable degradation.

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Land rights affect food systems

Land is finite, but not every hectare can grow the same crop: slopes, water, depth, salinity and climate constrain choices. Grazing can use some land unsuitable for arable farming, although this does not make every grazing system impact-free. Who can access land matters as well as its area.

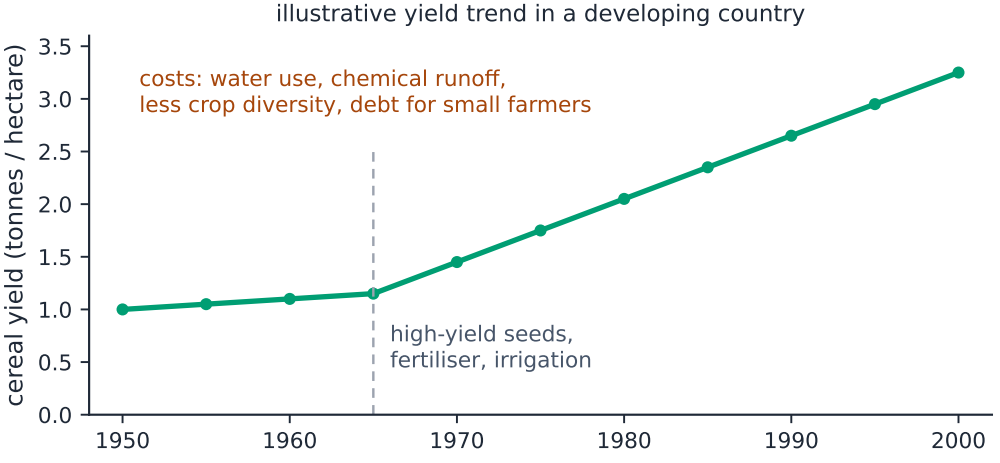


Food from land depends on suitability and on who has access

The Endorois community's displacement from land around Lake Bogoria in Kenya affected pastoral livelihoods and access to culturally important places. The African Commission's Communication 276/03 found violations of rights and recommended remedies. A decision and its implementation are different: do not assume the ruling itself returned every hectare or resolved every subsequent conflict. Evaluate consent, secure rights, compensation, participation and access to grazing and water when assessing a conservation or commercial land-use plan.

The Green Revolution

The **Green Revolution** 绿色革命 spread **high-yielding varieties** 高产品种, especially wheat and rice, alongside irrigation, fertiliser and pest control from the mid-20th century. Responses differed among regions and farmers. Improved harvests can support food availability and reduce pressure for additional land, but neither famine reduction nor land sparing follows automatically from yield alone.



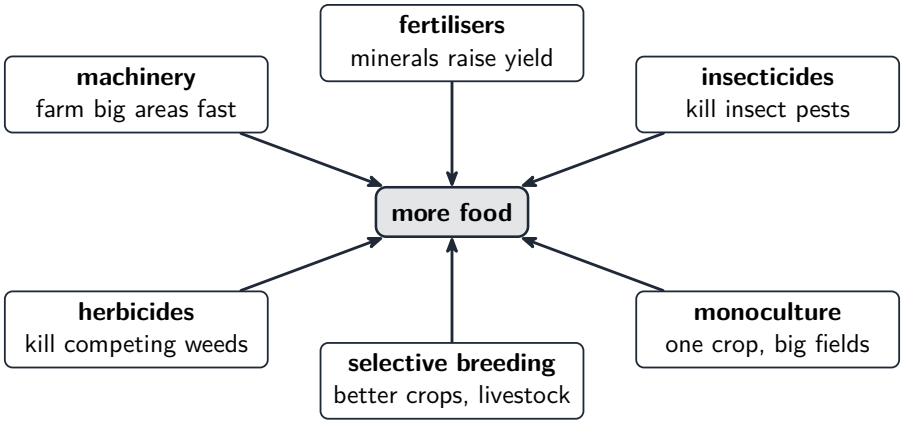
The Green Revolution raised yields, with environmental and social costs

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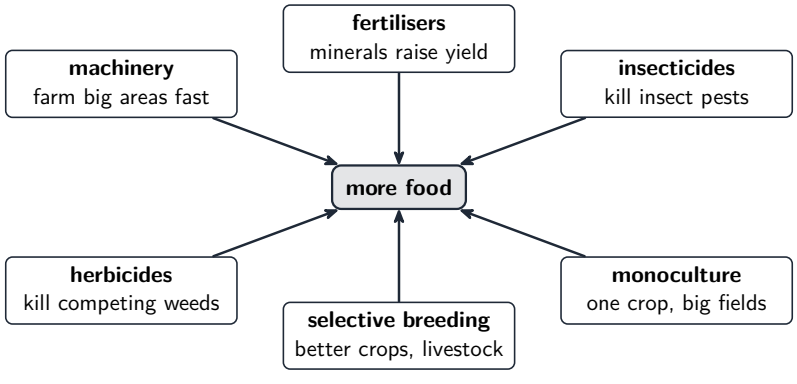
Costs include water demand, nutrient losses, pesticide exposure, salinisation and reduced crop diversity in some systems. Farmers need access to finance, seed, irrigation and markets; unequal access can widen income differences. Conventional synthetic nitrogen production often uses fossil energy, but this is a production pathway, not a law that all future fertiliser must be fossil-derived. Mycorrhizal fungi can supply nutrients to plant roots in exchange for organic carbon. Organic manures, compost, legume rotations, fallows and these root–fungus associations can support fertility, subject to nutrient budgets, safety and land constraints. Untreated human waste is not a classroom recommendation for fertiliser.

Food security

Food security 粮食安全 exists when all people, at all times, can get enough safe, nutritious food for an active, healthy life. It has four parts: **availability** (enough food is produced), **access** (people can afford or obtain it), **utilisation** (the body can use it: clean water, sanitation, a varied diet) and **stability** (all of these last through bad years).



Ways farmers increase food production



Ways farmers increase food production

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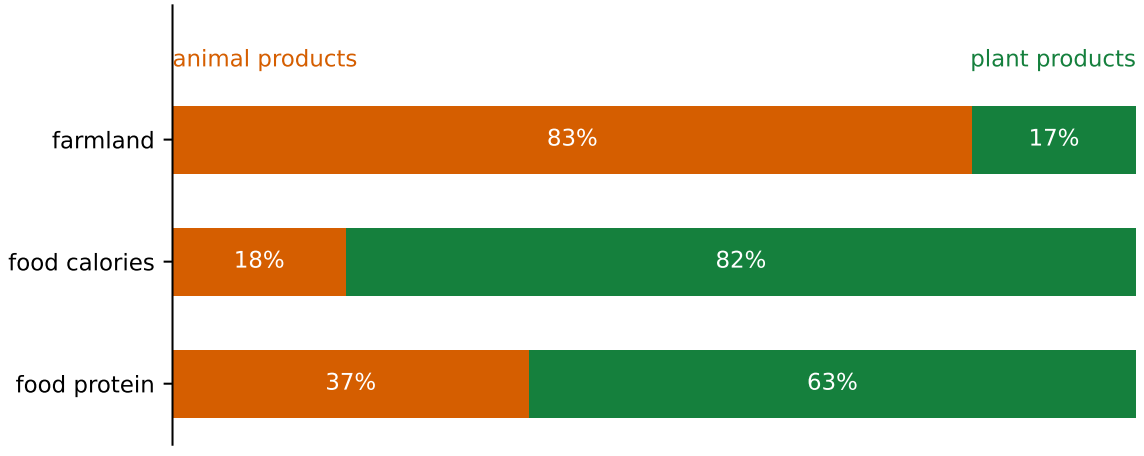
The 2025 State of Food Security and Nutrition report estimated about 673 million people experienced hunger in 2024; regional trends differed. This is a dated estimate, not a count of everyone lacking a healthy diet. WHO's 2022 adult estimates include 2.5 billion with overweight, of whom about 890 million were living with obesity. The second group is included in the first, not an additional population. Malnutrition includes deficiencies, imbalances and excesses, sometimes within the same society or household.

UNEP's 2024 Food Waste Index estimates that 19% of food available at retail, food service and household stages was wasted in 2022, alongside losses before retail. Supply-chain loss and consumer-stage waste have different denominators, so do not simply add their percentages. Household waste occurs across income groups; poor storage, purchasing practices, portion sizes and unreliable infrastructure can matter in different settings.

SDG target 12.3 aims by 2030 to halve per-capita global food waste at retail and consumer levels and reduce losses along production and supply chains. If a chain loses 10% of a 100-tonne harvest before retail and wastes 20% of the remaining 90 tonnes later, 72 tonnes remain: total loss/waste is 28%, not 30%. Reducing waste conserves embedded land, water and energy, but food redistribution still requires suitable quality, logistics and equitable access. Global availability does not ensure local affordability or stability during conflict, drought or price shocks.

■ Environmental impacts of food production

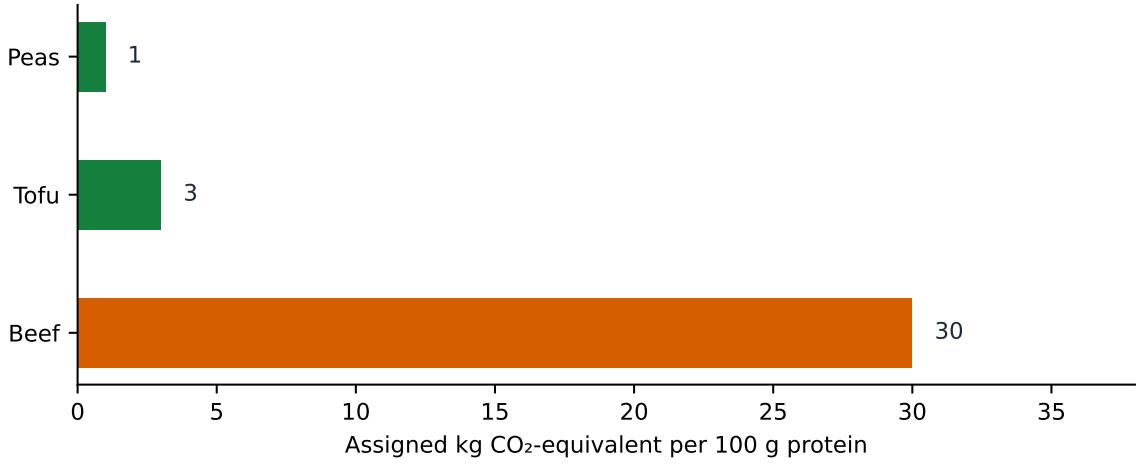
Food systems affect land conversion, water demand, nutrients, biodiversity and climate. State whether a footprint includes farming alone or processing, transport, storage and waste. Topic 4's dated FAO withdrawal categories assign 72% to agriculture in 2023; a different year or definition can give a different share.



Poore and Nemecek's 2018 analysis, described by their Oxford research group: approximate attributed shares, not a current land census. Farmland is not all Earth's land.

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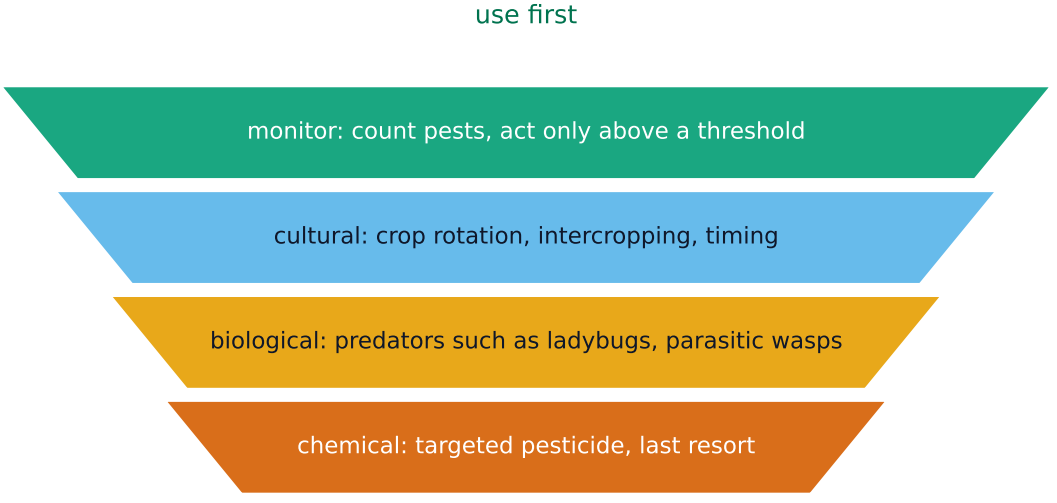
The reason is the energy loss between trophic levels (Topic 2). Animals use most of the energy in their feed for respiration, which helps explain why many animal products have greater impacts per comparable nutritional output than plant alternatives. Feed type, production system, co-products and the chosen nutritional unit affect the comparison; not all feed could be eaten by humans. Cattle also release methane, a strong greenhouse gas, as they digest grass.



Matched-unit comparison, not global median measurements. Under these assigned values, replacing 30 with 3 reduces emissions by $(30-3)/30 \times 100 = 90\%$.

More sustainable food systems

Ways to produce enough food with less harm include:



Integrated pest management: monitor first, chemicals last

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- **Eating lower in the food chain** 降低食物链营养级: replacing some meat, especially beef and lamb, with plant protein.
- **Reducing food loss and waste**: better storage and transport; buying, storing and using food carefully.
- **Sustainable intensification** 可持续集约化: growing more food on existing farmland with fewer harmful inputs, so that forests and grasslands are not cleared.
- **Integrated pest management** 病虫害综合治理 (IPM): using natural predators, crop rotation and resistant varieties, with pesticides only when needed.
- **Agroforestry** 农林复合: growing trees with crops or animals, which protects soil, stores carbon and provides extra products.
- **Polyculture** 混作 instead of **monoculture** 单一栽培: growing several crops together can diversify habitat and interrupt some pest transmission; competition, harvesting and management can be more complex.
- **Precision farming**: using satellite data and sensors to apply water and fertiliser only where needed.
- **Local food and seasonal food**: can reduce transport emissions, though transport is usually a small part of food's footprint compared with how it is produced.

Comparison	Certified organic systems	Other conventional systems
Nutrients	Approved composts, manures and rotations; nutrient budgets still matter	Can use synthetic and organic sources; timing and dose affect losses
Pest control	Cultural and biological methods plus permitted products under the relevant standard	Integrated methods and permitted pesticides; not necessarily spraying without monitoring
Yield	Depends on crop, site and management; may be lower	Depends on crop, site and management; high inputs do not guarantee high yield
Pollution	Organic nutrient losses and permitted pesticides can still cause harm	Nutrient and pesticide losses need controls; conservation practices can reduce them
Land	At lower yield, more area is needed for the same output unless other factors change	Compare actual yield, habitat conversion and off-farm inputs

Land-demand example: yield falls from 5 to 4 tonnes/ha while output must remain 100 tonnes. Required area rises from 20 to 25 ha: 20% lower yield needs 25% more land in this model, not 20% more. Whether that causes habitat loss depends on where land comes from and wider demand. "Organic" and "commercial" are not opposites. The best choice depends on values (Topic 1). Ecocentric arguments may stress ecolog-

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ical limits and relationships; technocentric arguments may stress innovation. People can combine these values, and a label does not determine every policy preference. Judge a particular technology or practice by evidence, nutrition, costs, access and whole-system impacts.

AHL: Soil formation, classification and exchange

■ Explain a profile rather than memorising one picture

Soil formation reflects climate, organisms, landscape, parent material and time. Warm, moist conditions can accelerate chemical weathering and decomposition; intense rainfall can also promote leaching. Cold or waterlogged conditions can slow decay, allowing organic matter to accumulate. Slope affects erosion and deposition, aspect affects energy and moisture, and drainage changes aeration and redox conditions. Calcareous parent material can supply bases and buffer acidity; volcanic materials can produce distinctive mineralogy and nutrient behaviour. Neither rock type nor climate alone determines the complete profile.



A pit dug through soil shows its horizons: dark organic topsoil on top, then paler mineral layers, over broken rock (tape for scale)

A temperate woodland brown earth often has a biologically mixed surface and active litter cycling. Strongly weathered tropical soils such as oxisols can contain abundant iron and aluminium oxides and relatively few readily weatherable minerals. Many are acidic with nutrient constraints, but tropical peatlands, young volcanic soils and floodplain soils do not follow one universal "all rainforest soils are poor" rule. Classification uses the whole profile and defined diagnostic properties, not colour alone.

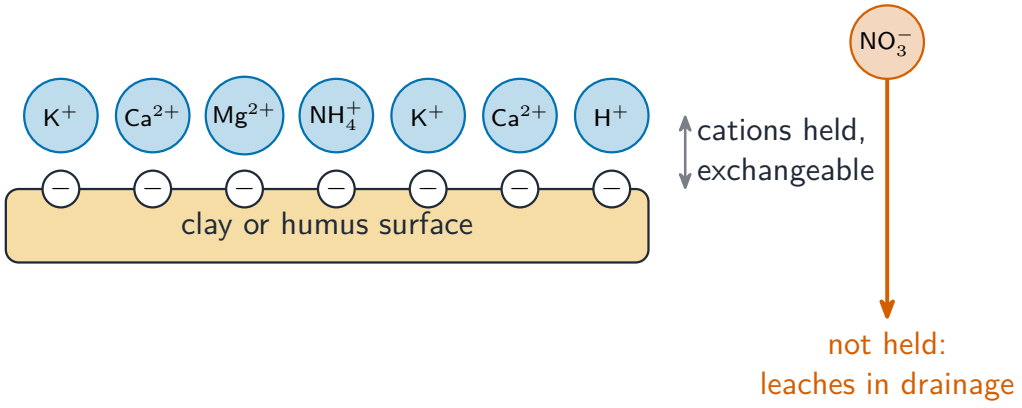
Cultivation mixes horizons and can expose soil to erosion, but intensive agriculture does not automatically remove every O and A horizon. An absent litter layer is not proof that topsoil has vanished. Compare actual depth, structure, organic matter

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and erosion evidence. Loss of the A horizon can remove roots, organisms, nutrient stores and favourable pore structure; replacing mineral nutrients with fertiliser does not replace those functions.

■ Relate mineral chemistry to retention

Cation-exchange capacity describes a soil's capacity to retain and exchange positively charged ions on surfaces. Many clay minerals and organic matter have negatively charged sites that retain potassium, calcium, magnesium and ammonium. Nitrate is negatively charged and is not retained by ordinary cation-exchange sites in the same way. Clay mineral types differ greatly; sand and silt can contain minerals other than quartz, so particle size alone does not determine chemistry.



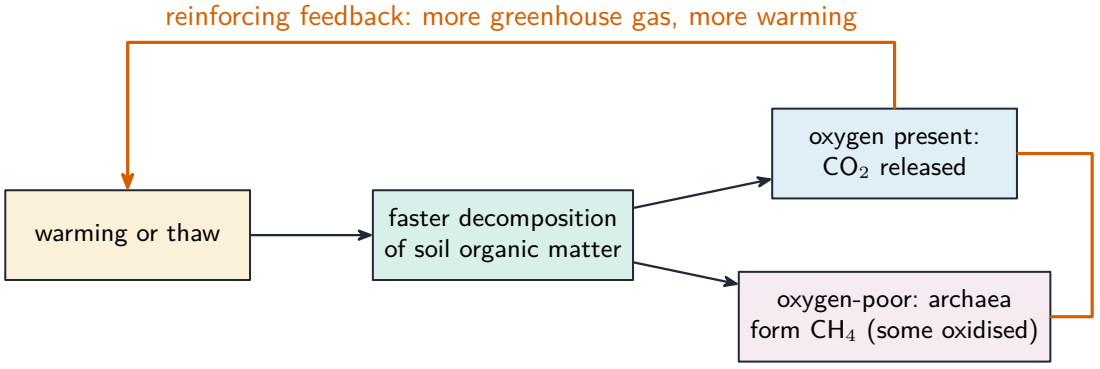
Cation exchange: negative sites hold cations, but nitrate leaches

Soil pH influences nutrient availability, microbial activity and potential toxicity. Liming an acidic soil can change pH and supply calcium, but is not a substitute for nitrogen or a universal remedy for all soils. Water retention is also not equivalent to plant availability: fine pores can retain some water too strongly for roots. Aggregates, macropores, organic matter and compaction modify the response expected from texture alone.

■ Distinguish soil feedbacks from hydrate claims

Aerobic decomposition releases carbon dioxide. Under oxygen-poor conditions, methanogenic archaea can form methane; oxidation and transport affect how much reaches the atmosphere. Warming or thaw can increase decomposition and release, reinforcing warming. Drainage may reduce some methane production while increasing carbon-dioxide losses from formerly wet soils, so one gas alone does not describe the net climate outcome.

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Oxygen decides the gas; both gases can reinforce warming

Methane clathrates are methane trapped in water-molecule cages in geological deposits under suitable pressure and temperature. They are distinct from the bulk organic carbon in permafrost soils. Warming can alter hydrate stability, but release, oxidation, transport and timescale must be assessed before claiming an immediate atmospheric effect. IPCC AR6's technical summary assesses permafrost carbon release as a feedback while finding a detectable departure from this century's emissions trajectory due to deeper terrestrial/subsea clathrates very unlikely. Local abrupt thaw or threshold behaviour is not proof of an inevitable instant global methane release.

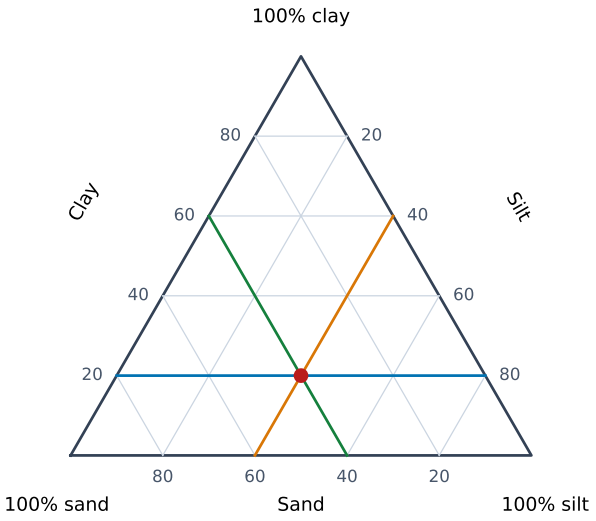
AHL: Measure soil properties and interpret data

■ Read composition without mixing denominators

Use an approved method to disperse and analyse the mineral fraction. A settling jar gives a rough comparison; particle shape, aggregation and settling time can bias it. A feel key is useful in the field but needs practice and consistent moisture. Laboratory particle-size methods have specified pretreatment and size boundaries. State the classification system: the USDA boundaries used here distinguish sand 0.05–2 mm, silt 0.002–less-than-0.05 mm and clay below 0.002 mm.

An 20 g mineral sample contains 8 g sand, 8 g silt and 4 g clay: 40%, 40% and 20%, summing to 100%. Organic matter and gravel should not quietly enter the same denominator. The USDA texture system classifies this composition as loam. Texture describes the mineral proportions, while organic matter strongly affects structure and retention without becoming a fourth mineral-size fraction.

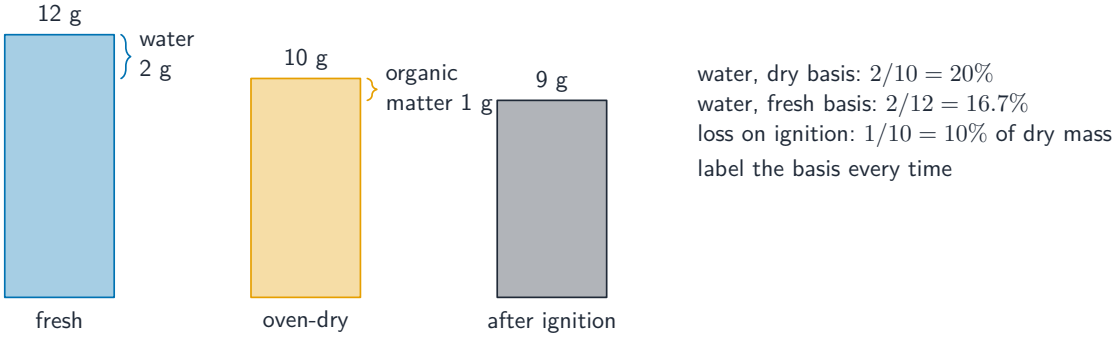
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Reading composition in three components; the named class requires the chosen classification key, not an arbitrary nearest corner.

Separate water content, organic matter and carbon

Use secondary data or a teacher-approved supervised protocol; do not improvise heating soil or handle unknown contaminated samples. Suppose a fresh sample has mass 12 g, oven-dry mass 10 g and post-ignition residue 9 g. Water content on a dry-mass basis is $(12 - 10)/10 \times 100 = 20\%$; on a fresh-mass basis it is $2/12 \times 100 = 16.7\%$. Both calculations can be valid if clearly labelled.



Masses before and after drying and ignition: always label the basis

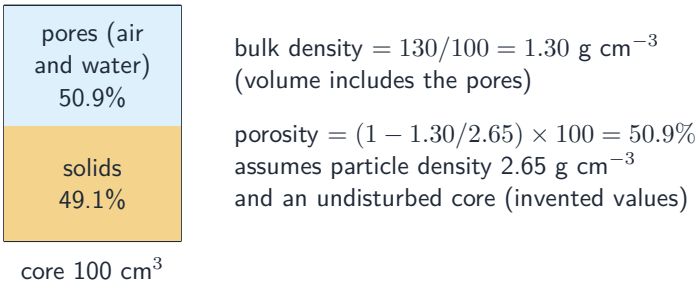
Loss on ignition is $(10 - 9)/10 \times 100 = 10\%$ of dry mass. This estimates organic-matter loss under the stated protocol, not a direct measurement of 10% elemental carbon. Bound water loss and carbonate decomposition can contribute, depending on method and soil. Converting organic matter to carbon requires a justified calibration;

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a universal factor should not be assumed.

■ Compare physical properties fairly

An intact 100 cm^3 core has dry mass 130 g. Bulk density is $130/100 = 1.30$ g/cm^3: the sampled volume includes pores. Particle density describes solids alone. With an assigned particle density of 2.65 g/cm^3, **porosity** 孔隙度 is $(1 - 1.30/2.65) \times 100 = 50.9\%$. This inference depends on the density assumption and a representative, undisturbed core; it does not measure the exact air-filled pore space at the sampling time.



Bulk density and porosity from one core

In an infiltration comparison, 50 cm^3 entering 100 cm^2 of soil in five minutes represents a depth of 0.5 cm, giving 0.1 cm/min, or 1 mm/min. Keep initial moisture, surface area, water head, disturbance and timing comparable. Replicate across sites rather than treating successive readings from one core as independent soils. Retention and drainage describe different properties from infiltration rate.

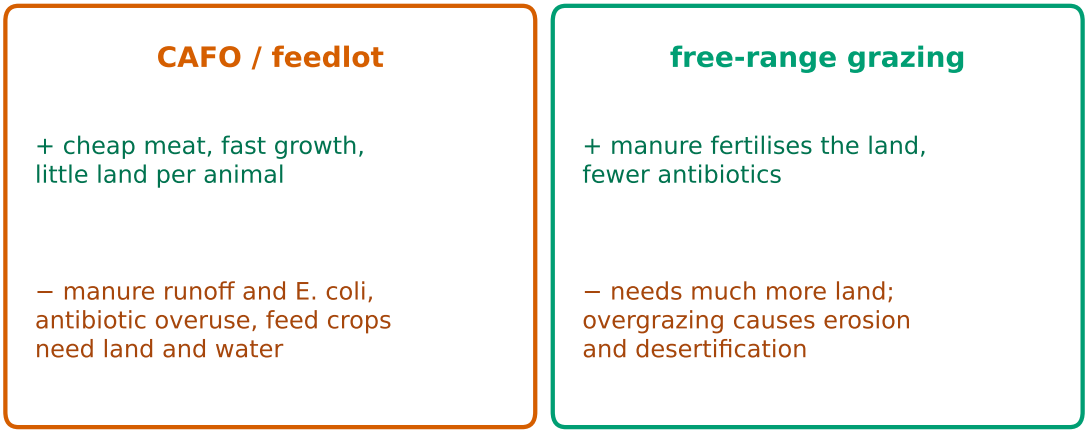
NPK tests, pH, colour, texture and density provide complementary evidence. A dark soil may contain organic matter, but colour alone is not a quantitative carbon assay. Compare garden and natural soils from matched depth or horizon and season; report site history, uncertainty and sample size before attributing differences to farming alone.

AHL: Compare regeneration, grazing and high technology

■ Match choices to biome and land capability

Within a temperate-grassland setting, deep, workable mollisol soils can support cereal cultivation, while shallower, stonier or drier sites may favour pasture. This is a land-capability comparison, not a claim that every prairie hectare has identical rainfall or can be converted to crops. Cropping may provide high edible yield but expose soil and need nutrient replacement; grazing can use non-arable vegetation but still needs stocking and erosion controls. Compare income, nutrition, soil losses and habitat, not only tonnes of one product.

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Feedlots and free-range grazing: benefits and costs

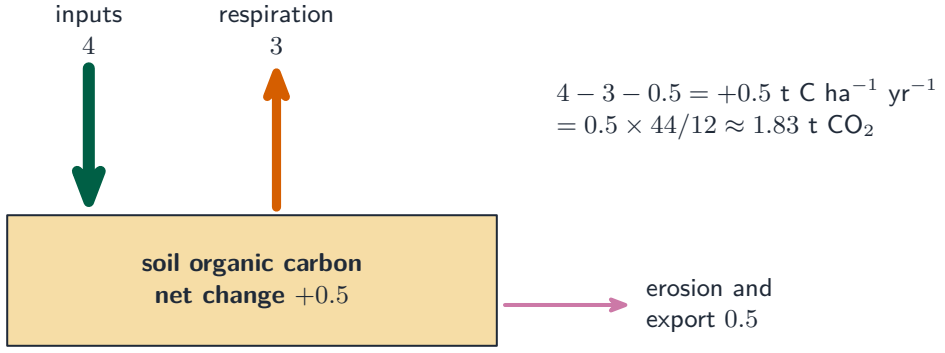
Regenerative approaches aim to improve functions such as aggregation, water regulation, nutrient cycling and biodiversity. "Regenerative" is not one universally identical method or proof that a product has no footprint. Permaculture uses design principles and diverse, interacting components; mixed leys, agroforestry, rotations and returning suitable organic materials can close some nutrient loops. Removing harvested food still exports nutrients, so a nutrient budget remains necessary.

Using pigs or chickens to disturb vegetation can prepare areas and cycle nutrients, but excessive disturbance can expose soil and concentrate wastes. Short-duration, high-density grazing with rest periods may suit some systems, yet outcomes depend on total stocking, recovery time, rainfall and initial condition. Do not assume mob grazing always increases carbon, eliminates methane or restores every dryland. Rewilding some marginal land can support biodiversity while shifting food production elsewhere; account for that displacement and who loses access or employment.

■ Evaluate net outcomes with a budget

Annual organic-carbon inputs are 4 tonnes C/ha; respiration removes 3 and erosion/export removes 0.5. Net stock change is $4 - 3 - 0.5 = +0.5$ tonnes C/ha/year. That corresponds to $0.5 \times 44/12 = 1.83$ tonnes CO_2 in carbon-mass equivalence. It is not automatically the farm's net climate benefit: nitrous oxide, methane, off-farm emissions, permanence, measurement depth and leakage also matter. A large starting stock can still be declining.

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A carbon budget: net change is inputs minus all outputs over the same area and year

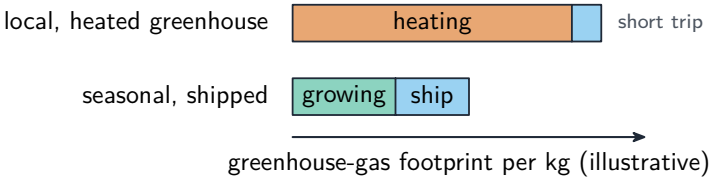
High-tech greenhouses and vertical farms can control water, light and temperature and produce selected crops on small land areas. They require capital, skills and energy; LEDs and climate control can be substantial inputs. Hydroponics removes soil as the growth medium but not the need for nutrients, water quality or waste management. Neither hydroponics nor genetic modification is intrinsically sustainable or unsustainable without a specified system and comparison.

Energy example: a vertical farm uses 8 kWh per kg edible crop. An electricity factor of 0.4 kg CO_2-equivalent/kWh gives $8 \times 0.4 = 3.2$ kg CO_2-equivalent/kg from electricity. At 0.05, it gives 0.4 kg/kg. Other inputs and infrastructure remain uncounted. Compare the same edible product and complete boundary before claiming lower total impact than a field-grown alternative. High-value leafy vegetables do not demonstrate that every staple grain can be produced economically in a tower.

AHL: Supply chains, food choices and wider needs

■ Evaluate diets and distribution

A shorter distance does not guarantee a lower footprint. Production method, storage, heating, transport mode, spoilage and nutritional output all matter: air freight differs from shipping, while a locally heated greenhouse may use more energy than seasonal production farther away. Local markets can still support livelihoods, trust and access; social benefits are not the same unit as greenhouse emissions.



Distance is not the footprint - heating a local greenhouse can outweigh shipping a seasonal crop

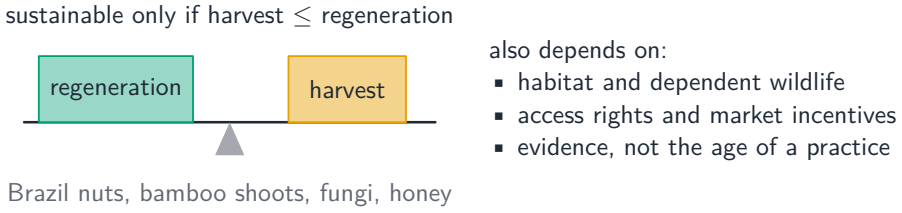
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Plant-rich dietary patterns can reduce some resource pressures, especially when replacing high-impact animal products, but nutrition, affordability, culture and livelihoods affect feasibility. The EAT–Lancet planetary health diet is a proposed dietary framework linking health and environmental goals, not one compulsory menu suitable unchanged for every individual or community. Distinguish nutritional adequacy, environmental comparison and ethical views about animals; they need different evidence.

Food quality and access can vary within a city: cheap calorie-dense products may be widely available while diverse nutritious foods are expensive or perishable. Undernourishment, micronutrient deficiencies and excess energy intake are distinct problems and can coexist. A national food surplus or high supermarket sales do not establish that every household can obtain a suitable diet throughout the year.

Compare traditional harvest and global demand

Collecting Brazil nuts, bamboo shoots, fungi or honey can provide food and income while retaining forest cover. Sustainability depends on harvest rate, regeneration, habitat, access rights, market incentives and effects on dependent wildlife. Not every traditional harvest is sustainable; endangered wildlife trade can deplete populations even where a practice has a long history. Compare evidence without assuming all communities hold identical views or have identical bargaining power.



A forest harvest is sustainable only while regeneration keeps pace

Small-scale or low-input systems can protect valuable functions and livelihoods while still having limits to total supply, labour or land. High-output systems can feed markets while shifting costs onto ecosystems or vulnerable groups. Evaluate combinations against local food needs and wider demand rather than declaring either category the universal solution.

Design a defensible food-preference survey

Use informed consent, voluntary participation, neutral questions and appropriate privacy. Ask about actual foods, access constraints and stated priorities rather than leading participants with "Do you support destructive farming?" Distinguish a preference from a purchasing ability, and self-reported intentions from observed behaviour. Sample different groups fairly, state response rates and avoid presenting a convenience sample as everyone's view. Survey findings can inform dialogue; they do not authorize speaking for a whole culture or predict every future dietary choice.

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Exam tips

- Define the soil or farm boundary, functional unit and time period; distinguish texture from structure, carbon stock from net sink, total harvest from area yield and energy ratio from complete thermodynamic efficiency.
- Connect every management proposal to a mechanism, named context, measurable outcome and limitation. Consider nutrition, livelihoods and rights as well as output, and show denominators and units in calculations.

Practice

1. (a) Outline the inputs, outputs, transfers and transformations of the soil system. (b) Describe the horizons of a typical soil profile.
2. Explain why soil can be considered a non-renewable resource.
3. **AHL:** Compare sandy and clay-rich soils, and explain why loamy texture may suit many crops without being universally best. An 100 cm^3 core has dry mass 130 g. Find bulk density and explain why loss on ignition is not a direct carbon assay.
4. Outline four types of soil degradation.
5. Explain how overgrazing and deforestation lead to soil erosion.
6. (a) Describe three soil conservation methods and how each works. (b) Using the Dust Bowl or the Loess Plateau, explain how human activity can degrade and restore soil.
7. Distinguish between intensive and extensive farming, and between subsistence and commercial farming.
8. Farm X harvests 35 t of maize from 7 ha; farm Y harvests 48 t from 16 ha. Calculate the yield of each.
9. **AHL:** A farm uses 12 000 MJ of energy per hectare and produces food containing 36 000 MJ per hectare. Calculate its energy efficiency, and explain why mechanised farms often have low energy efficiency. A vertical farm uses an assigned 8 kWh/kg at 0.4 kg CO_2-equivalent/kWh. Calculate its electricity-related emissions.
10. Evaluate the Green Revolution.
11. Outline the four parts of food security, and explain why hunger exists although enough food is produced.
12. Explain why producing beef has a larger environmental impact than producing peas.
13. Compare organic and conventional farming.
14. Evaluate two strategies for making food production more sustainable.

Answers.

1. (a) Inputs: litter, water, minerals and deposition. Transfers: percolation and biological mixing. Transformations: decomposition and chemical weathering. Outputs: uptake, leaching, erosion, evaporation, respiratory carbon dioxide and heat;

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classify against the stated boundary. (b) A simplified O horizon has surface organic matter; A mixes minerals and organic material; B has altered or accumulated mineral material; C is relatively little-altered parent material; R is hard bedrock if reached. Real profiles vary.

2. It forms very slowly (a centimetre may take hundreds of years) but can be lost by erosion in a few years, so on a human timescale it cannot be replaced.
3. **AHL:** Sand-rich soils often drain quickly and retain fewer nutrients; clay-rich soils retain more water but can drain slowly. Aggregation, organic matter, pH and climate modify the response. Loam often balances properties; suitability depends on crop and management. Bulk density = $130/100 = 1.30$ g/cm^3. Loss on ignition is an organic-matter proxy affected by method and soil composition, not a direct elemental-carbon assay.
4. Any four: erosion, salinisation, nutrient depletion, compaction, pollution, desertification.
5. Both remove the plant cover. Without roots to bind it and leaves to protect it, the bare soil is washed away by rain or blown away by wind. Trampling by too many animals also compacts the soil, so more water runs off.
6. (a) Terraces shorten slopes and slow runoff; contour cultivation runs across slopes; cover crops protect the surface. Alternatives include windbreaks, suitable rotations, mulches and managed grazing. State the mechanism and a local limitation. (b) Dust Bowl: grassland was ploughed for wheat; in drought the bare, dry soil was blown away. Restored with windbreaks, contour ploughing and grass. Loess Plateau: clearing and overgrazing left bare slopes that eroded; terraces, a grazing ban and planting reduced erosion and raised yields.
7. Intensive farming uses large inputs per hectare for high yields; extensive farming uses small inputs over large areas. Subsistence farming feeds the farmer's family; commercial farming produces food to sell.
8. X: $35 \div 7 = 5$ t/ha. Y: $48 \div 16 = 3$ t/ha. X has the higher yield although Y harvests more in total.
9. **AHL:** $36\,000 \div 12\,000 = 3$. Mechanised farms use large amounts of fossil fuel energy in machines, fertiliser, pesticides and transport, so the energy put in is large compared with the energy in the food. Electricity-related emissions = $8 \times 0.4 = 3.2$ kg CO_2-equivalent/kg; other lifecycle inputs remain uncounted.
10. Improved varieties with water, nutrients and pest control raised yields in many settings. Benefits depended on access and management; costs can include water depletion, nutrient loss, pesticide harm and reduced crop diversity. Higher yield alone does not guarantee equitable food security or habitat protection.
11. Availability, access, utilisation and stability. Hunger exists because poor people cannot afford food (access), food is lost and wasted, and conflict and climate shocks disrupt supply (stability).

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12. Respiration and other conversion losses help explain greater inputs for many animal products. Cattle emit methane; impacts vary with feed, system, co-products and nutritional unit. Peas associate with nitrogen-fixing bacteria; the plants do not perform the fixation themselves.
13. Organic systems follow specified input standards but may still lose nutrients or use permitted pesticides. Conventional systems can also use organic inputs and conservation methods. Compare measured yield, biodiversity, pollution, energy and land demand for the same edible output.
14. For example: eating less meat cuts land use and emissions greatly, but depends on changing habits and culture. Reducing food waste saves land, water and energy already used, but needs action by many people and better storage in poorer countries. (Accept other strategies with strengths and limits.)

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Atmosphere and climate change

International Baccalaureate · IB Diploma · Environmental Systems and Societies · HL

Scope and prerequisites

This handout teaches Topic 6, Atmosphere and climate change (6.1–6.4), for first assessment in 2026. Sections marked **AHL** are for Higher Level only. Numerical datasets explicitly called are teaching examples, not measurements from real papers. Prerequisites: energy and feedback (Topic 1), carbon cycling (Topic 2), oceans (Topic 4) and land use (Topic 5).

Introduction to the atmosphere

One warm year and a long-term target

The **Paris Agreement** 巴黎协定 was adopted in December 2015; signing opened in April 2016. Its temperature goal is to hold warming well below 2 °C and pursue efforts to limit it to 1.5 °C above pre-industrial levels. WMO's report on 2024 estimated that calendar year at 1.55 ± 0.13 °C above 1850–1900. A single year and long-term warming are different statistics: one annual value above 1.5 °C does not by itself establish that the long-term Paris limit has been exceeded. Natural variability is superimposed on human-caused warming. A cold day at one station cannot overturn a global multi-decade trend either.

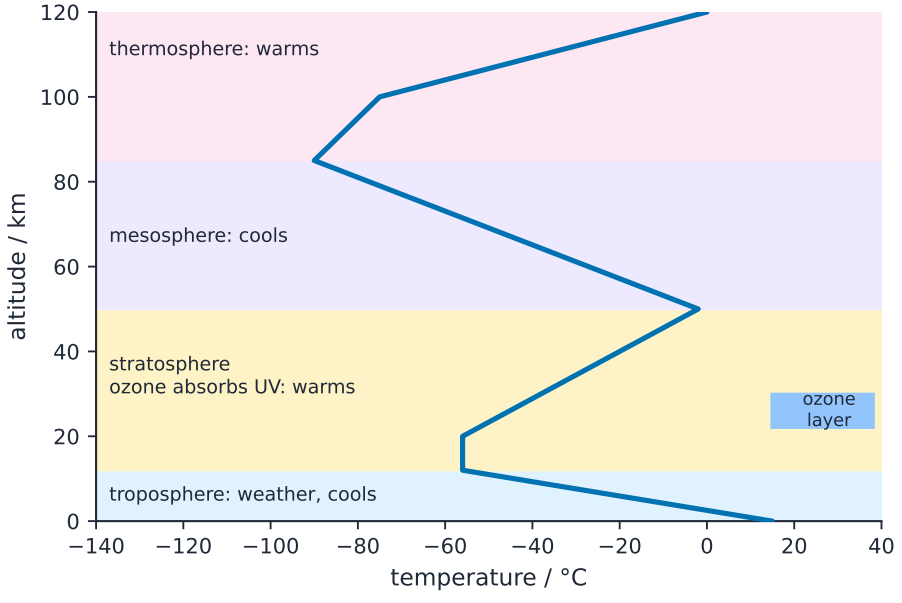
Composition, layers and exchanges

The **atmosphere** 大气层 is gas held around Earth by gravity. Dry air is about 78% nitrogen, 21% oxygen and 0.9% argon, with carbon dioxide and other trace gases making up the remainder. Water vapour is excluded from "dry air"; its concentration varies greatly with place and conditions. A trace concentration can matter because absorption depends on molecular properties, wavelength and amount, not simply which gas is most abundant.

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Earth's atmosphere seen edge-on from the ISS: a thin blue layer, with the Moon beyond



Temperature against altitude defines the layers of the atmosphere

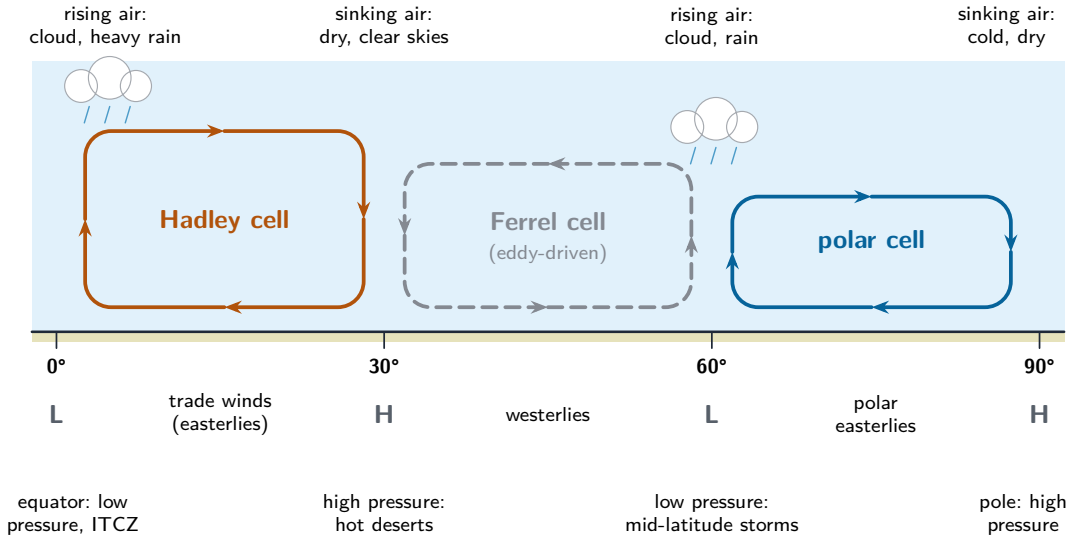
For a dated comparison, NOAA's global annual record gives about 422.8 ppm CO_2 in 2024, or 0.04228%. One ppm means one part per million, not one percent. This global average differs from a particular station's annual mean or seasonal maximum.

The **troposphere** 对流层 contains most atmospheric mass and weather. Its top varies, roughly 8–18 km, higher in the tropics. Temperature usually falls upwards, but inversions occur. The **stratosphere** 平流层 extends to about 50 km and contains the **ozone layer** 臭氧层; absorption of ultraviolet radiation helps temperature rise with

height. Pressure and density generally fall upwards. Above lie the mesosphere and thermosphere; these layers describe temperature behaviour, not sealed compartments. Water, gases and energy exchange with oceans, organisms and rocks.

■ Redistributing heat: three circulation cells

Unequal solar heating helps drive atmospheric circulation. In a simplified hemisphere, strongly heated air rises near the equator, producing low surface pressure and frequent rainfall. Air moves polewards aloft, cools and sinks around 30°, giving subtropical high pressure and often dry climates. Surface return flow completes the **Hadley cell**. Between about 30° and 60°, the **Ferrel cell** is an indirect, eddy-driven circulation coupled to neighbouring cells and mid-latitude weather systems. Air tends to rise around 60° and sink near the pole in the **polar cell**.



one hemisphere, idealised zonal mean; heights not to scale

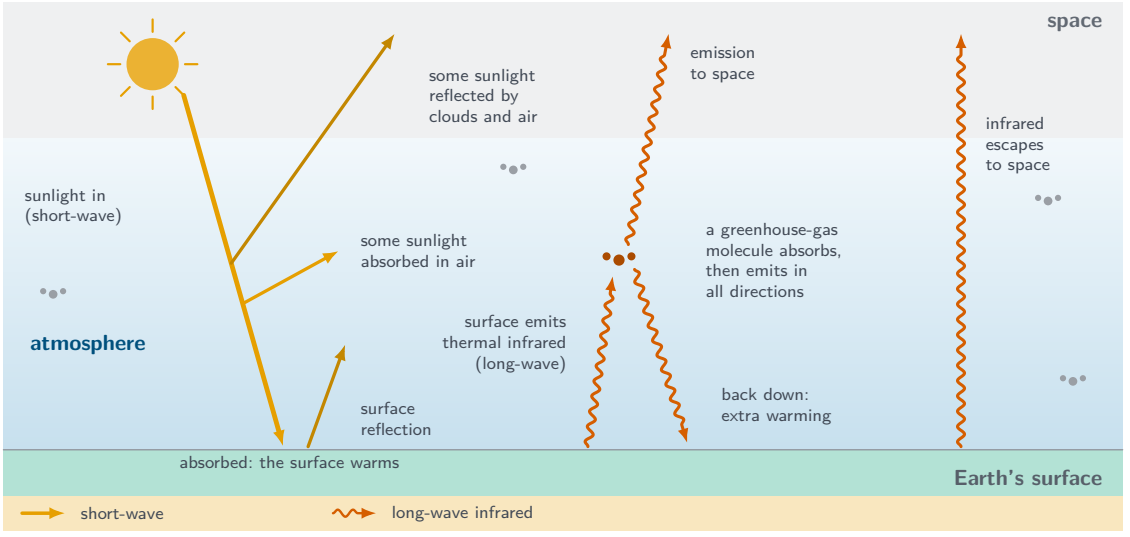
An idealised zonal-mean model, not a prediction of daily winds at every place. The other hemisphere has corresponding cells.

Earth's rotation deflects moving air to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. Surface trade winds are easterlies in the tropics, westerlies dominate mid-latitudes, and polar easterlies occur at high latitudes. "Easterly" names the direction a wind comes **from**. The cells redistribute heat but do not remove the equator-to-pole energy contrast. Seasons, continents, oceans and mountains shift or interrupt the idealised belts; a desert does not have to lie precisely at 30°.

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Radiation, reflection and the greenhouse effect

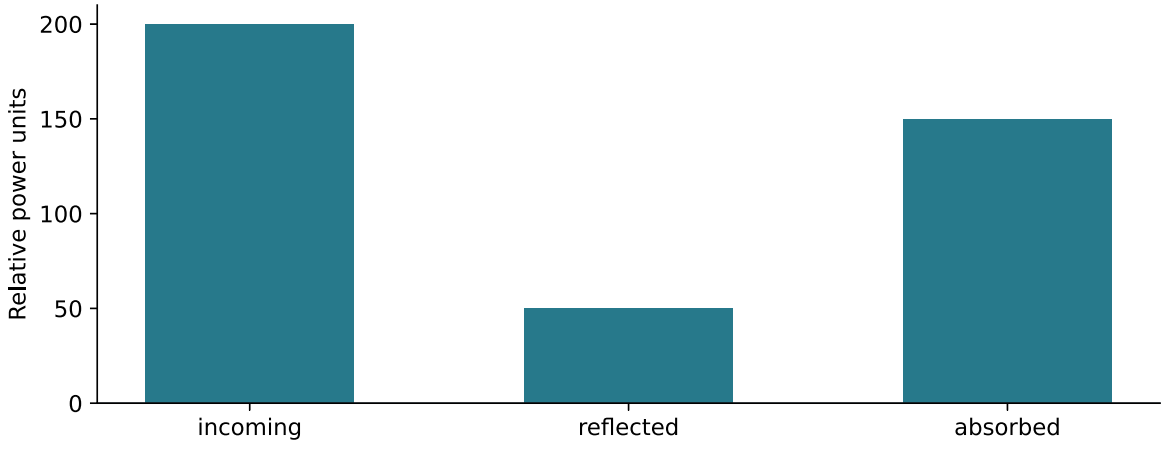
The Sun supplies relatively **short-wave radiation** 短波辐射, including visible light, near-infrared and ultraviolet. Clouds, air and surfaces reflect some sunlight; the atmosphere and surface absorb the rest. The global average reflected fraction, **albedo** 反照率, is approximately 0.30, but local values vary. It is wrong to allocate all the remaining 70% to surface absorption alone.



Selected energy pathways, not a complete measured budget. Greenhouse gases occur through atmospheric volumes, not only in a thin pictured band.

The surface thermalises absorbed energy and emits **long-wave radiation** 长波辐射, mainly thermal infrared. These are newly emitted photons, not incoming photons stretched into longer ones. **Greenhouse gases** 温室气体 absorb and emit infrared at particular wavelengths in all directions. Downward emission contributes to surface heating, while some infrared escapes to space. The natural **greenhouse effect** 温室效应 supports a warm surface. About 15 °C versus −18 °C is a useful simplified comparison with Earth's effective radiating temperature at fixed albedo; it is not an exact prediction of a real Earth with its atmosphere removed.

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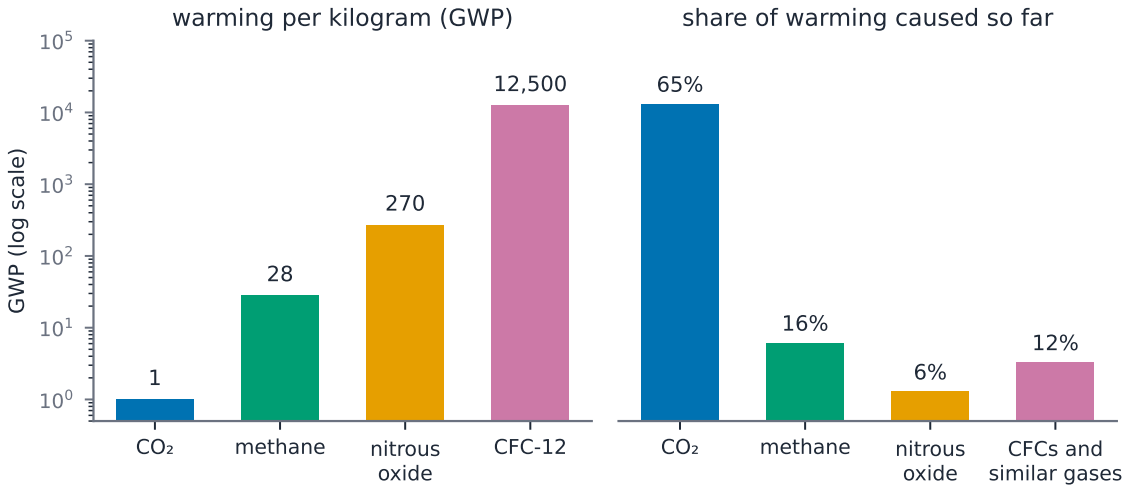
At this surface boundary, incoming minus reflected equals absorbed; atmospheric absorption is outside the model.

Worked example, invented: incoming 200 units and reflected 50 give albedo $\alpha = 50/200 = 0.25$ and absorption $200 - 50 = 150$ units. At fixed incoming 340 W/m^2 and albedo 0.30, reflected power is $340 \times 0.30 = 102$ W/m^2 and absorbed power is $340 - 102 = 238$ W/m^2. Absorbed solar power alone is not a full surface heat budget: infrared, latent heat and sensible heat also matter. Snow is usually more reflective than open ocean, but angle, cloud, grain size and impurities change measured albedo.

Gases, aerosols and warming metrics

- **CO_2:** combustion, cement and land-use change add emissions alongside natural cycling. There is no single lifetime: removal acts on several timescales, with a fraction persisting for centuries to millennia.
- **CH_4:** fossil leakage, ruminants, rice, wastes and wetlands. A concentration perturbation decays over roughly a decade, not on one fixed expiry date; ongoing emissions matter.
- **N_2O:** microbial processes affected by fertiliser and manure; long atmospheric lifetime makes nitrogen management important.
- **Halocarbons:** refrigerants and industrial compounds differ in warming strength and ozone effects; judge the particular chemical.
- **Water vapour:** evaporation and circulation supply it. Warming permits more vapour under suitable conditions, amplifying warming; it is included in climate models.

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Left: global warming potential on a log scale, from carbon dioxide (1) to CFC-12 (about 12,500). Right: carbon dioxide still causes about two-thirds of the warming because so much more of it is emitted

Aerosols are suspended particles or droplets. Some scatter sunlight and cool; black carbon absorbs sunlight and can warm air or darken snow. They are not all greenhouse-gas molecules and do not all have the same effect. Short-lived air pollutants can change rapidly when emissions change.

Global warming potential compares the time-integrated radiative effect of a pulse emission with an equal mass of CO_2 over a stated horizon. It is not instantaneous heat trapped or the gas's lifetime. Values depend on the assessment, time horizon and treatment of indirect effects. **Calculation:** assign a 100-year methane factor of 28; then 2 tonnes CH_4 correspond to $2 \times 28 = 56$ tonnes CO_2-equivalent under that assigned metric. This equivalence does not make the gases' time profiles identical. Cutting ongoing methane emissions can reduce near-term warming pressure without making CO_2 reductions unnecessary.

Climate change: causes and impacts

■ Forcing and measured evidence

The **enhanced greenhouse effect** 增强的温室效应 is additional warming caused by increased greenhouse-gas concentrations. Adding these gases initially reduces outgoing radiation at a given temperature; an energy imbalance builds until the climate responds. Human emissions exceed net removal, so atmospheric CO_2 has risen from roughly 280 ppm before industrialisation. The Mauna Loa annual series gives 316.91 ppm in 1960 and 424.61 ppm in 2024. These are station annual means, distinct from the global 422.8 ppm value.

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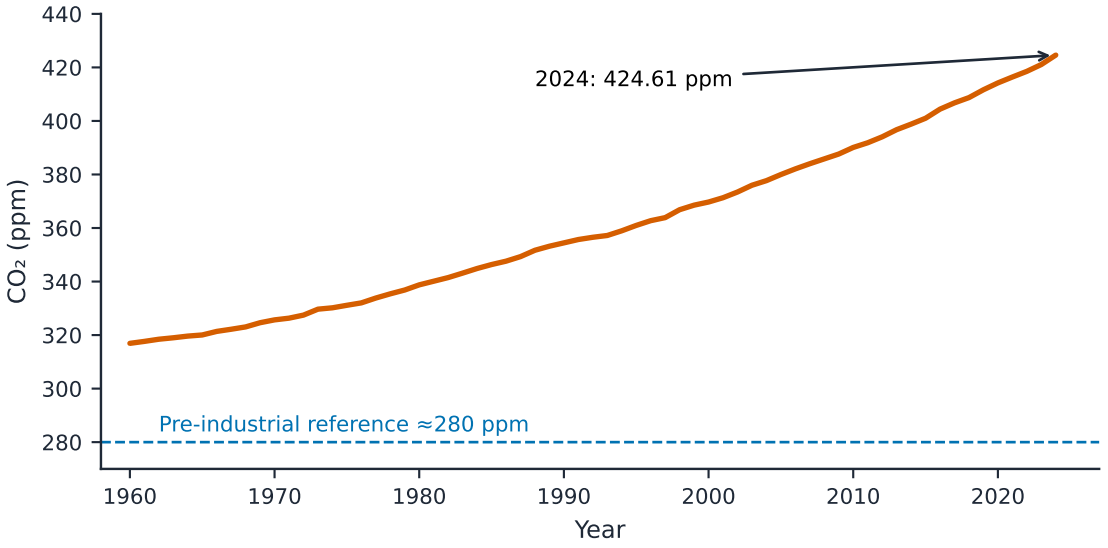


A bleached coral colony: warmer water made it expel its colourful algae, revealing the white skeleton through the still-living, transparent tissue. If the heat lasts, the coral dies



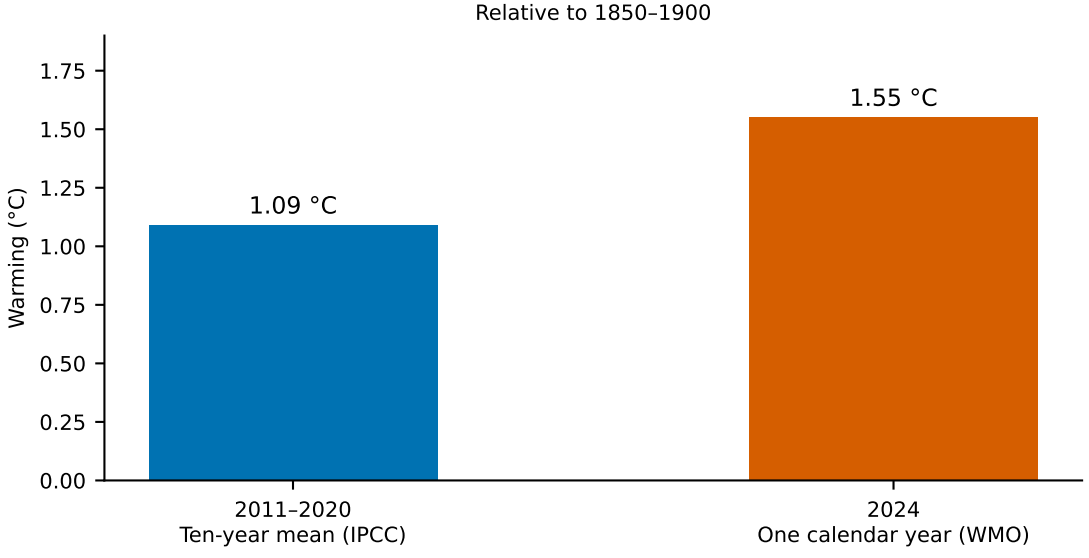
A glacier breaking apart into the sea: warming melts land ice, which adds water to the oceans and raises sea level

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Actual annual data, not interpolated observations. A multi-decade concentration trend is distinct from emissions in one year.

Evidence comes from independent measurements and proxies. Thermometers, ocean measurements and satellites track different parts of the warming system. Shrinking glaciers and ice sheets, changes in sea ice and biological timing provide additional evidence, though not every place changes identically. Sea level rises through ocean thermal expansion and loss of **land** ice; floating sea-ice melt has little direct effect on water level. Atmospheric CO_2 and ocean acidity are linked through chemistry, not because warming itself is the only cause of acidification.

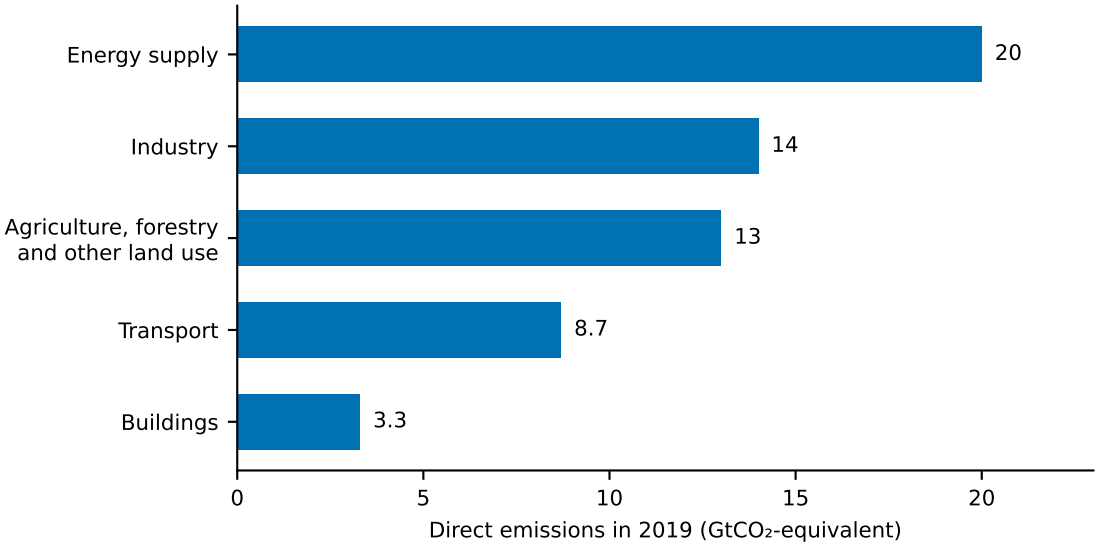


Different averaging periods: IPCC's 2011–2020 estimate and WMO's 2024 estimate. These two bars are not a complete time series or a calculated recent warming rate.

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Ice-core bubbles preserve samples of ancient air, supporting direct measurements of past greenhouse-gas composition. Isotopes in ice provide temperature-related **proxy** evidence requiring interpretation. Tree-ring widths and densities, pollen and sediments can reconstruct aspects of past climate; they do not all directly measure ancient atmospheric CO_2. Dating, calibration, preservation and spatial coverage affect uncertainty. Correlation between past CO_2 and temperature supports study of linked processes, but attribution also uses radiation physics, other forcings and model comparisons. Natural changes in the past do not establish a natural cause for the present trend.

Emissions and the climate boundary



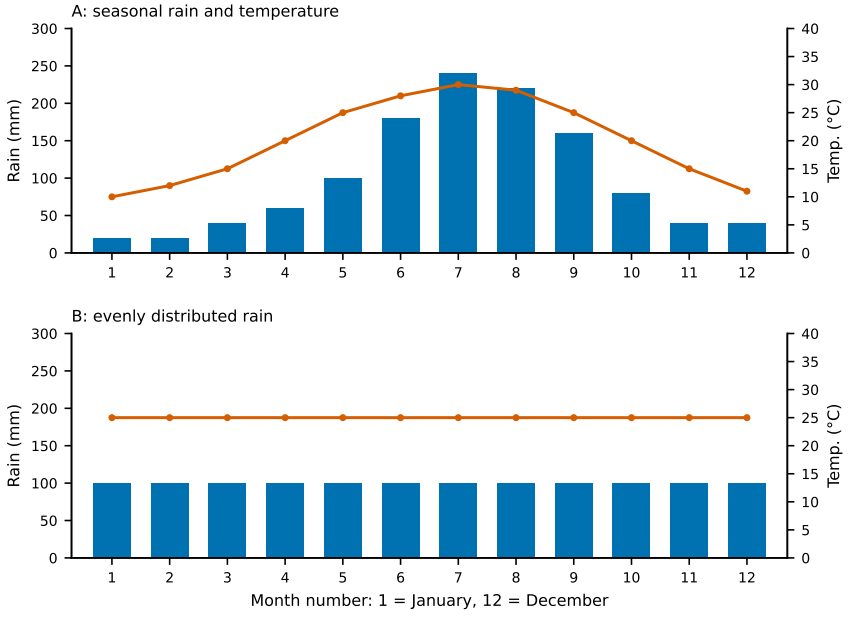
IPCC's 2019 sector estimates, in $GtCO_2$-equivalent: total of these rounded values is 59. Electricity is allocated to energy supply here; reallocating it to users changes sector shares.

Energy systems, industrial processes, land-use change, transport and food production offer different mitigation opportunities. Choose a gas, accounting boundary and year before comparing countries. Territorial emissions occur within borders; consumption accounting reallocates emissions embodied in trade. Annual totals, cumulative emissions and per-person values answer different fairness questions.

The climate-change **planetary boundary** is a precautionary Earth-system risk framework, not a country's legal emissions allowance. Its commonly used CO_2 concentration control value is 350 ppm, with radiative forcing another control variable. The dated 2024 global concentration exceeds that value. This does not mean the 1.5 °C Paris goal is the same numerical boundary, nor that every proposed tipping point has already been crossed. A boundary signals rising systemic risk rather than a precise date of universal collapse.

Read climate and impacts at the right scale

Climate includes temperature and precipitation distributions, seasonality and extremes. Construct a climate graph with months in chronological order, rainfall as bars and mean temperature as a line; label each vertical axis and its units. Do not read millimetres from a temperature scale.



Sites An and B, not real weather stations. Blue bars use the left rainfall axis; orange lines use the right temperature axis.

For A, January–December rainfall values in mm are 20, 20, 40, 60, 100, 180, 240, 220, 160, 80, 40 and 40: total 1200 mm. Monthly mean temperatures in °C are 10, 12, 15, 20, 25, 28, 30, 29, 25, 20, 15 and 11: their sum is 240, giving an equally weighted monthly mean of 20 °C and range $30 - 10 = 20$ °C. A daily-weighted annual mean would need month lengths and the underlying data. B has 100 mm and 25 °C every month: also 1200 mm/year, mean 25 °C, temperature range 0 °C. Equal annual rainfall does not imply equal dry-season stress, runoff or crop suitability. Compare monthly values, variability and extremes over matching periods, with location and units stated. One storm is weather; its changing probability belongs to climate analysis.

Heat extremes, heavy rainfall, drought and tropical cyclone risks vary among regions and processes. Warmer air can support heavier rainfall, and stronger cyclone rainfall or intensity does not imply every ocean basin must have more storms. Glacier retreat can initially increase meltwater but later reduce dependable dry-season supply. Heat, water stress, disease and infrastructure damage can affect food, health, livelihoods and migration.

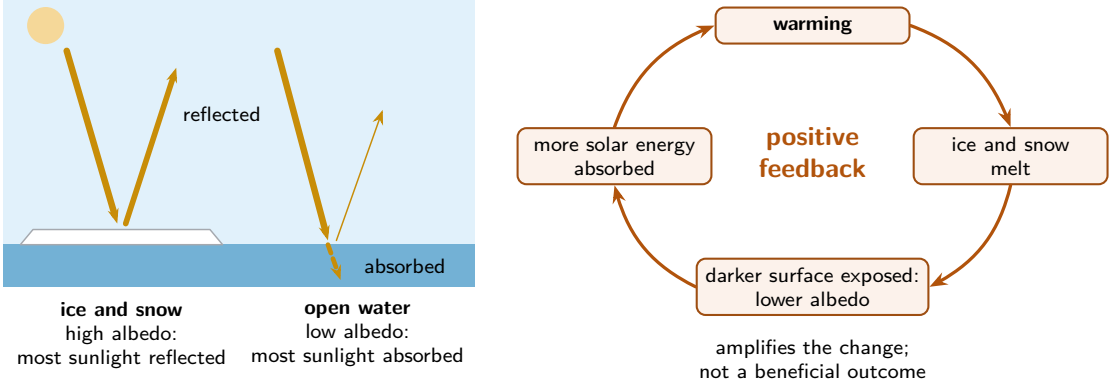
At ecosystem scale, warming can shift ranges and breeding or flowering times, disrupt food relationships and cause thermal stress. Some cooler regions may gain a longer growing season or productivity, but water, nutrients, pests and heat limits con-

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strain benefits. Species cannot all migrate fast enough or cross fragmented habitats. In the Great Barrier Reef's 2024 event, marine heat stress caused widespread **coral bleaching** 珊瑚白化. Loss of symbiotic algae reduces energy supply; bleaching is not automatically immediate death, but prolonged or repeated stress can kill coral and reduce habitat for other species. Local water-quality measures help resilience but cannot alone stop ocean warming.

Vulnerability combines exposure, sensitivity and capacity to adapt. Low-lying Tuvalu faces flooding, erosion, saltwater intrusion and infrastructure risks despite a small contribution to global emissions. A UNDP account dated October 2024 records the handover of 7.3 hectares of reclaimed land under its coastal adaptation project. Raised land and protection can reduce particular risks; maintenance, ecology, cost, access and future sea level still matter. This is evidence of an adaptation action, not proof that all islands are permanently safe or inevitably uninhabitable on one fixed date. Within any country, income, occupation, disability, housing and political access affect risk.

Feedbacks, thresholds and perspectives



Positive means amplification, not a beneficial outcome.

The **ice-albedo feedback** 冰反照率反馈 starts when warming reduces ice and snow, lowering albedo and increasing absorbed solar energy: a **positive feedback**. More water vapour can amplify warming; thawing **permafrost** 永久冻土 can add CO_2 and methane. Drought and fire can weaken forest carbon storage. A warmer emitting body generally radiates more, providing a stabilising response. CO_2 fertilisation may increase plant uptake, but nutrients, water, heat and disturbance limit this negative feedback; it cannot be assumed to cancel emissions.

A **tipping point** 临界点 is a threshold beyond which a system's change can become self-sustaining. Ice-sheet retreat, some ecosystem shifts and circulation changes are studied examples. Positive feedback alone does not demonstrate a particular threshold or an immediate, irreversible global collapse. State the component, mechanism, uncertainty and timescale. People weigh these risks differently because of livelihoods, evidence, trust, values and responsibilities. "Ecocentric" and "technocentric" describe

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emphases, not fixed beliefs shared by everyone in a group.

Climate change: mitigation and adaptation

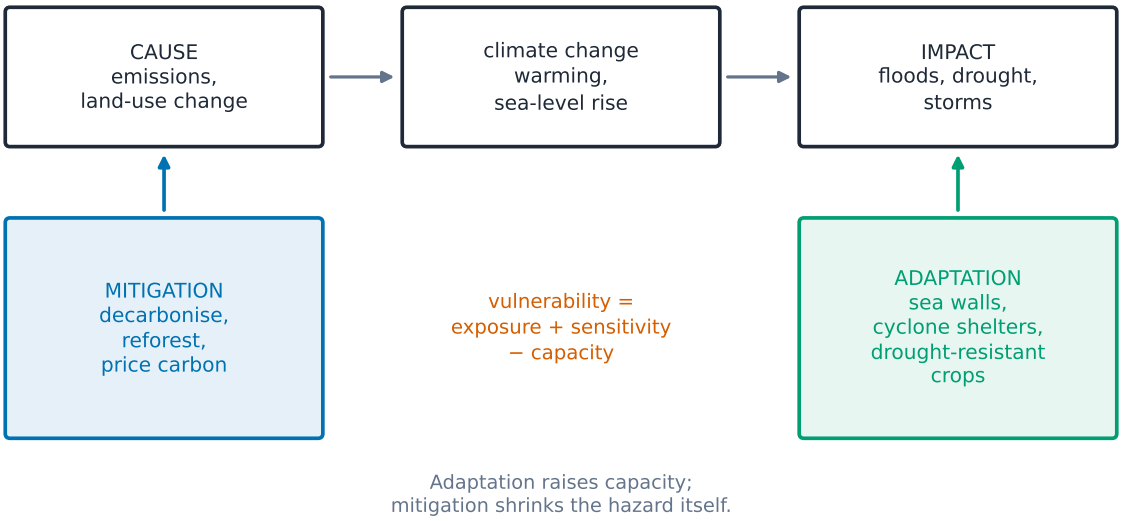
■ Choose the response by its mechanism

Mitigation 减缓 reduces greenhouse-gas emissions or increases removals. **Adaptation** 适应 reduces harm or uses opportunities under changed climate conditions. Insulating a home may reduce energy demand and improve protection from heat: classify the actual mechanism, since an action can do both. Mitigation limits future change; adaptation addresses exposure and vulnerability, with limits at high warming. Reaching **net zero** 净零排放 for CO_2 does not instantly restore former sea levels or remove all greenhouse gases.



A solar farm: rows of photovoltaic panels tilted toward the sun generate electricity without burning fuel

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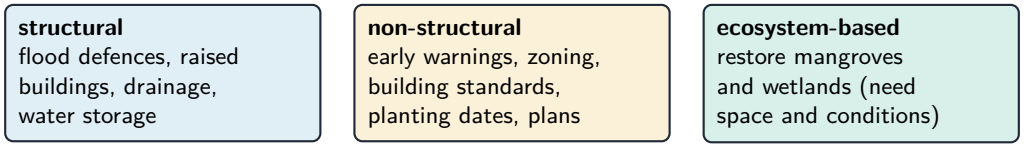


Response	Examples	Main conditions and limits
Reduce emissions	Renewable electricity replacing fossil generation; efficient buildings and transport; protect existing forests; cut methane leaks	Lifecycle inputs, grid reliability, access, land rights and rebound effects
Remove atmospheric CO_2	Reforestation or suitable soil-carbon gains; direct air capture with durable storage; biomass capture/storage under a favourable net balance	Permanence, land and energy demand, monitoring, additionality and leakage
Alter incoming solar energy	Proposed stratospheric aerosol intervention; more reflective selected surfaces	Scale, rainfall effects and governance differ; no direct solution to CO_2-driven acidification

Carbon capture and storage 碳捕集与封存 at a fossil-fuel plant or cement kiln can prevent some new CO_2 reaching the air. It is not automatically removal of existing atmospheric carbon. Account for capture fraction, energy penalty, upstream emissions, transport and verified storage. Direct air capture removes ambient CO_2 only if the complete process and storage deliver a net removal. Trees and soil can store carbon but face saturation, fire and reversal; a temporary store is not equivalent to permanent avoidance of fossil emissions.

Adaptation from infrastructure to institutions

Structural measures include flood defences, raised buildings, drainage and water-storage infrastructure. Non-structural measures include early warnings, land-use zoning, building standards, changed planting dates and emergency planning. Restoring mangroves or wetlands is ecosystem-based adaptation; living systems need space and suitable conditions. A seawall may protect one shoreline while shifting erosion elsewhere; desalination can improve supply while requiring energy and brine management. Compare lifecycle cost, beneficiaries, residual risk and maintenance rather than claiming a measure "prevents climate change".



Three kinds of adaptation, compared on cost, beneficiaries and shifted harm

A **sponge city** 海绵城市 approach combines permeable paving, green roofs, planted storage areas and wetlands to retain or slow runoff. They can reduce peak flows within design conditions; extreme rainfall, saturated soil, blocked outlets or poor maintenance can exceed capacity. Shade and vegetation can also reduce heat, with water and land trade-offs. Managed retreat may reduce exposure but requires rights, consultation, compensation and viable livelihoods.

National adaptation plans organise medium- and long-term risk assessment, priorities, funding, implementation and monitoring. Earlier National Adaptation Programmes of Action (NAPAs) focused on urgent needs of least-developed countries. Neither is the same as an emissions inventory or an NDC. Local knowledge and participation help identify who benefits or loses; budgets and institutional capacity affect delivery. For an attitude survey, use neutral questions, voluntary participation and privacy, describe sampling and non-response, and distinguish preference from ability to pay or actual behaviour.

International cooperation and accountability

The UN Framework Convention on Climate Change (1992) provides a negotiating framework. The Kyoto Protocol (1997) set binding commitments for participating developed-country Parties listed in its Annex B; it did not impose identical targets on every rich state. Paris uses nationally determined contributions (NDCs), successive updates, transparency and global assessment. Parties have procedural duties, but stating a target does not guarantee achievement or create a simple global enforcement police. A conditional IPCC pathway reaching net-zero global CO_2 around the early 2050s is not a treaty rule that all countries must achieve net-zero **all gases** by 2050.

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The climate regime from the UNFCCC to COP30

A **carbon tax** 碳税 sets an emissions price; the resulting quantity depends on responses. An absolute-cap **emissions trading scheme** 碳排放交易 limits covered emissions and permits trading; allowance prices can vary. Coverage, monitoring, free allocations, offsets and enforcement determine results. Revenue can fund public investment or protect low-income households. Carbon-border measures can address imported embodied emissions but raise questions about measurement, development and trade fairness. International finance, technology and capacity-building can support action; announced funds must be distinguished from money delivered and measurable outcomes.

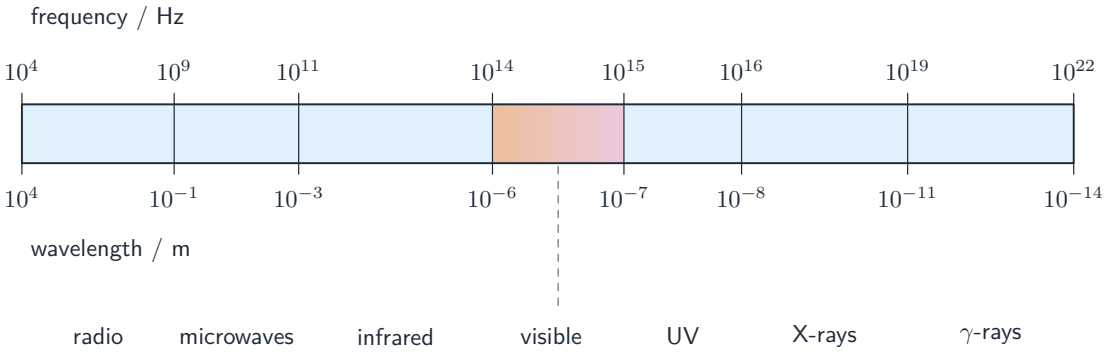
State sovereignty makes international action depend on negotiated obligations and domestic institutions. Governments set laws and infrastructure; industries invest and change processes; NGOs, communities and individuals influence monitoring, demand and politics. Responsibility is shared but unequal in resources and influence. Lower consumption, clean technology and institutional change can complement each other. Evaluate effectiveness, cost, distribution, rights and feasibility rather than assuming one value label supplies an answer.

Stratospheric ozone

■ Radiation and a protective dynamic balance

Infrared, visible and **ultraviolet** 紫外线 belong to the electromagnetic spectrum. Shorter wavelength means higher frequency and photon energy. O_2 and **ozone** 臭氧 absorb essentially all solar UV-C and much UV-B before it reaches the ground; much UV-A penetrates. Excess UV-B can damage DNA, increase skin-cancer and cataract risks, harm crops and affect phytoplankton and aquatic food webs. The ozone shield does not block all solar radiation or make unlimited sun exposure safe.

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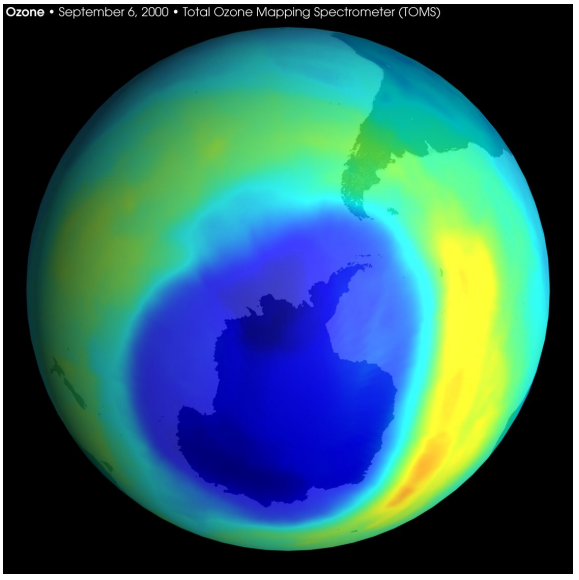
The electromagnetic spectrum

Ozone is continually formed and destroyed in a **dynamic equilibrium** 动态平衡: balanced average rates can maintain a concentration while individual molecules change. Sunlight supports both formation and destruction. Ozone absorbs UV and contributes to stratospheric heating. The same O_3 molecule near ground level is a harmful secondary pollutant formed through sunlight-driven reactions involving nitrogen oxides and volatile organic compounds; it also acts as a greenhouse gas. Location and chemistry distinguish these problems.

■ Ozone-depleting substances and recovery

Ozone-depleting substances 消耗臭氧层物质 include **chlorofluorocarbons** 氯氟烃 (CFCs), formerly used in cooling, foams and propellants. Their tropospheric stability lets them reach the stratosphere, where ultraviolet radiation releases reactive chlorine. Chlorine and bromine participate in catalytic destruction; a catalyst is regenerated, so one atom can participate in many cycles. They are atoms or radicals in this explanation, not chloride ions. Very cold polar conditions, confinement and returning spring sunlight help explain severe seasonal Antarctic depletion, the **ozone hole** 臭氧空洞, rather than a literal empty opening in the atmosphere.

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The ozone hole 臭氧洞 *over Antarctica (dark blue) on a NASA map: this is where the ozone layer has thinned the most*

The **Montreal Protocol** 蒙特利尔议定书 (1987) controls production and consumption of ozone-depleting substances through agreed phase-out schedules. Universal ratification, scientific assessment, monitoring, financial support and available alternatives helped action. Ratification alone is not the physical mechanism of recovery: reduced emissions and declining atmospheric burdens matter. Long atmospheric lifetimes cause delayed recovery, while annual ozone-hole size also varies with weather.

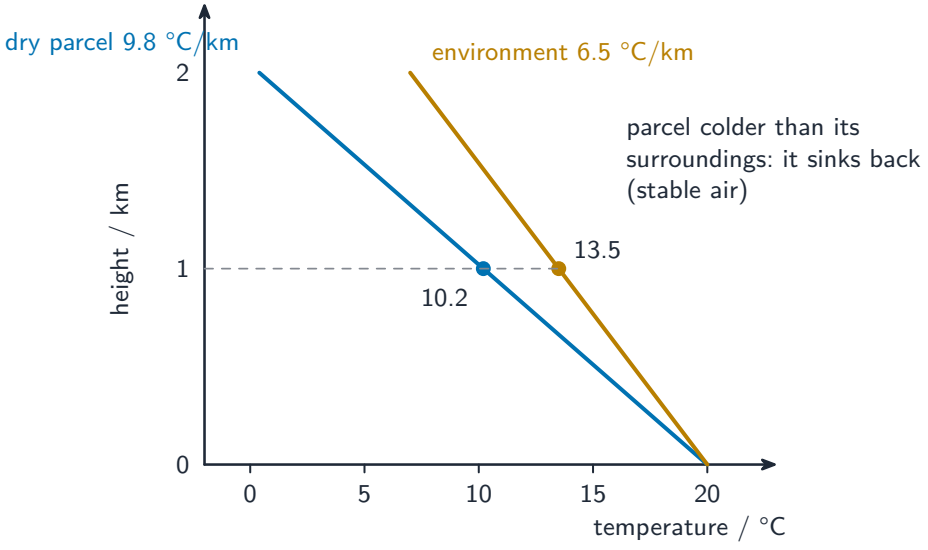
The 2022 scientific assessment projected return to 1980 ozone values around 2040 for the near-global belt, 2045 for the Arctic and 2066 for Antarctica under continued compliance and stated scenarios. These are conditional projections with ranges, not exact guaranteed dates. The stratospheric-ozone planetary boundary concerns a global control measure; serious regional Antarctic depletion does not mean its global threshold is necessarily transgressed. Conversely, a global measure within its boundary does not imply the absence of regional damage.

HFC substitutes generally contain no chlorine or bromine and have negligible ozone-depletion potential, but particular HFCs can be strong greenhouse gases. The Kigali Amendment (2016) phases down controlled HFCs. It is not the separate phase-out of HCFCs, which still contain chlorine. Ozone protection and climate protection overlap but are not interchangeable: less CO_2 does not directly remove stratospheric chlorine. Montreal's narrower set of industrial chemicals and practical replacements aided agreement; decarbonisation reaches energy, transport, food and other systems. This comparison does not mean climate cooperation is impossible or ozone protection complete.

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Pressure, temperature and a rising parcel

Most atmospheric mass lies near the surface because gravity acts on gas and the overlying column creates pressure. Gravity decreases with the square of distance from Earth's centre, not simply inverse distance, although it changes relatively little across the lower atmosphere. Falling pressure allows rising air to expand. If a parcel exchanges little heat with its surroundings, expansion lowers its temperature: **adiabatic cooling**. Condensation releases latent heat, so a saturated parcel generally cools more slowly than a dry one. Environmental lapse rate describes the surrounding air and need not equal either parcel rate; a temperature inversion can suppress vertical mixing and trap pollutants.



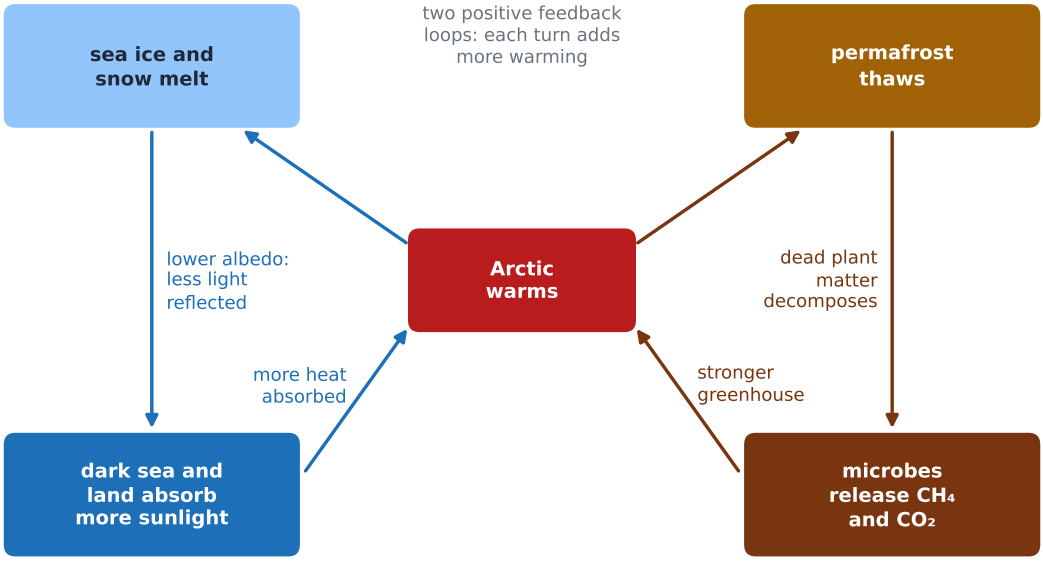
Compare the parcel with its surroundings: a parcel colder than the air around it sinks back

Comparison: a dry parcel and its environment start at 20 °C. Assign dry-parcel cooling 9.8 °C/km and environmental cooling 6.5 °C/km. At 1 km, the parcel is 10.2 °C and the environment 13.5 °C; the parcel is colder and tends to sink back without continued forcing. At 2 km they are 0.4 °C and 7.0 °C. These assigned linear profiles are not a universal atmosphere or the saturated rate. Stability also depends on moisture, lifting and the actual profile. A warming stratosphere inhibits the kind of convection typical of the troposphere.

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Orbital forcing and life change the atmosphere

Milankovitch cycles include changes in eccentricity, obliquity and precession on tens to hundreds of thousands of years. They alter seasonal and latitudinal insolation and help pace Quaternary glacial–interglacial cycles, amplified by ice and carbon feedbacks. The Quaternary began about 2.58 million years ago. These slow changes do not explain the rapid recent warming pattern; distinguish a forcing's existence from evidence that it caused a particular event.



Two positive feedback loops in the Arctic: melting ice exposes dark surfaces that absorb more sunlight, and thawing permafrost releases methane and carbon dioxide; both cause more warming

Photosynthetic organisms changed atmospheric composition by producing oxygen, initially partly consumed by reactions with reduced minerals. Later oxygen accumulation enabled an ozone shield and supported aerobic life; organisms also modified carbon stores and soils. Atmosphere and life co-evolved through feedbacks, not a single instantaneous switch. "Anthropocene" is widely used for human influence, but its proposal as a formal geological epoch was rejected in 2024; do not label it an officially adopted successor to the Holocene.

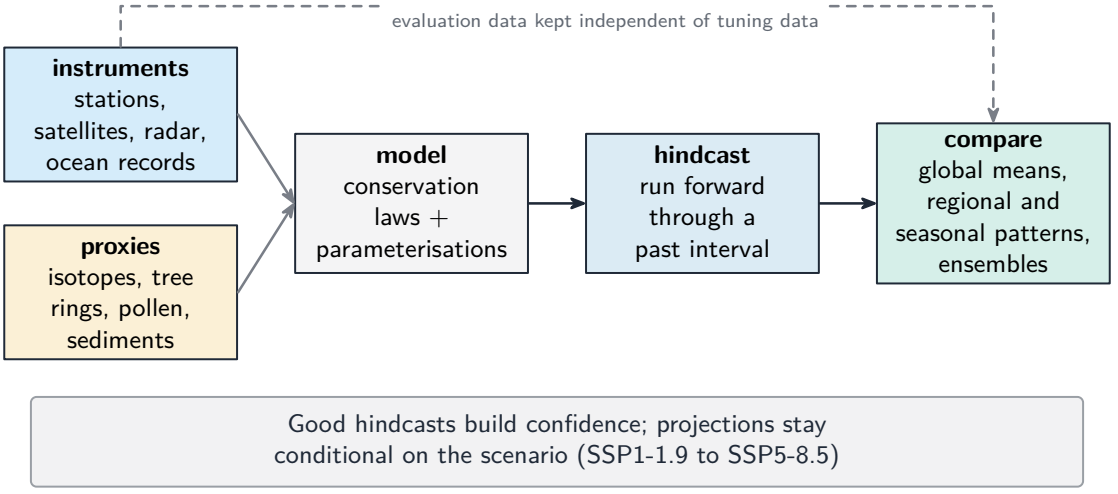
A small albedo investigation can compare equal-area light and dark surfaces under the same lamp or incoming sunlight. Measure reflected/incoming radiation with suitable calibrated sensors, or compare heating while controlling distance, material, initial temperature and airflow. Replicate independent samples and randomise positions; colour may covary with emissivity or conductivity, so heating alone is not an exact albedo measurement. A lamp model lacks real clouds, spectral distributions, atmospheric circulation and ocean heat storage. It tests a mechanism under conditions, not an entire climate projection.

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AHL: Evaluate evidence, models and responsibility

Observations, proxies and hindcasting

Weather stations give local instrument records; satellites infer quantities through calibrated remote sensing; radar helps measure precipitation and storm structure. Coverage, station moves, urban effects, instrument changes and retrieval assumptions require correction and uncertainty estimates. Independent networks and ocean records test whether conclusions depend on one method. Isotope ratios, tree growth, pollen assemblages and sediment layers extend records, each with its own response, dating and calibration limits. Several independent proxies agreeing is stronger evidence than one uncalibrated series.



Hindcasting tests a model against an independent past; projections stay conditional on the scenario

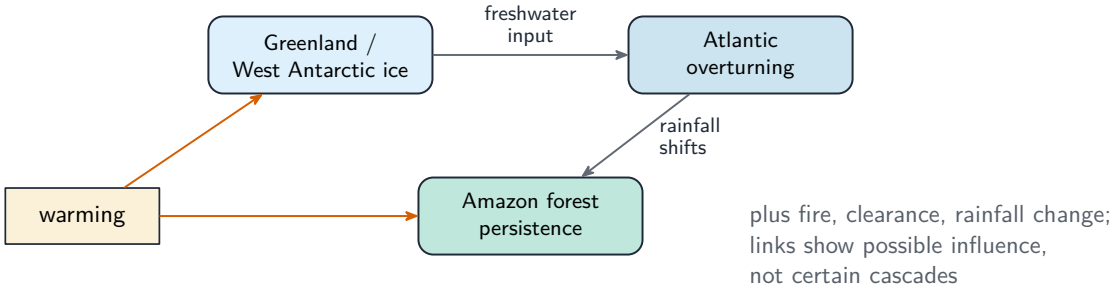
A climate model represents energy, mass and momentum conservation, radiation, fluids and interacting atmosphere, oceans, ice, land and biology. Finite grid resolution requires parameterisations for unresolved processes. In **hindcasting**, researchers simulate a past interval and compare output against observations; this normally runs the model forward through historical conditions, not time-reversed physics. Keep evaluation data sufficiently independent from tuning data, test spatial and seasonal patterns as well as global means, and compare ensembles. Good past performance supports confidence but cannot prove every future regional outcome. Uncertainty includes observations, model structure, internal variability and future human choices.

The five illustrative AR6 pathways–SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5–span contrasting emissions and development assumptions. Their numbers refer to approximate radiative forcing levels in 2100, not probabilities or degrees of warming. They are not the only possible futures. Scenario projections are conditional; a range is not evidence that models "say nothing". Assess whether a proposed policy changes emissions, vulnerability, or an assumption behind the projection.

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Tipping elements and connected risks

An ice sheet may retreat as lower surface elevation exposes it to warmer air and geometry changes ice flow. Atlantic overturning can respond to freshwater input and density changes, affecting heat transport. Parts of the Amazon could shift towards a more open, drier state if warming, rainfall change, fire and clearance undermine forest persistence; the Amazon–Cerrado transition is not a single uniform switch across all South America. Local coral-dominated systems can also change state after repeated disturbances.



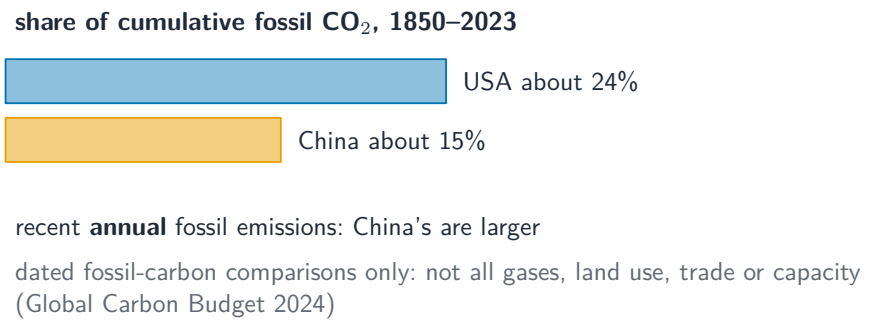
Tipping elements can be connected, but a link is not a certain cascade

A **tipping cascade** means change in one component alters conditions for another, potentially increasing risk. Interactions may amplify or damp effects, thresholds differ among models, and ice-sheet response can unfold over centuries or longer. A possible cascade is a reason to manage risk, not evidence that all components will cross thresholds on one date. Irreversibility is relative to process and timescale: emissions cuts still matter even if some losses cannot quickly be reversed.

Who contributed and who can respond?

The Global Carbon Budget 2024 analysis distinguishes annual fossil CO_2, cumulative fossil CO_2 and land-use emissions. For 1850–2023 it assigns about 24% of cumulative fossil emissions to the USA and 15% to China; China's recent annual fossil emissions are larger. These are dated fossil-carbon comparisons, not complete all-gas climate responsibility. Historical borders, embodied trade, population, development needs and capacity complicate ethical conclusions. Do not mix tonnes of carbon with tonnes of CO_2 without the factor 44/12.

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Cumulative and annual emissions tell different stories (Global Carbon Budget 2024)

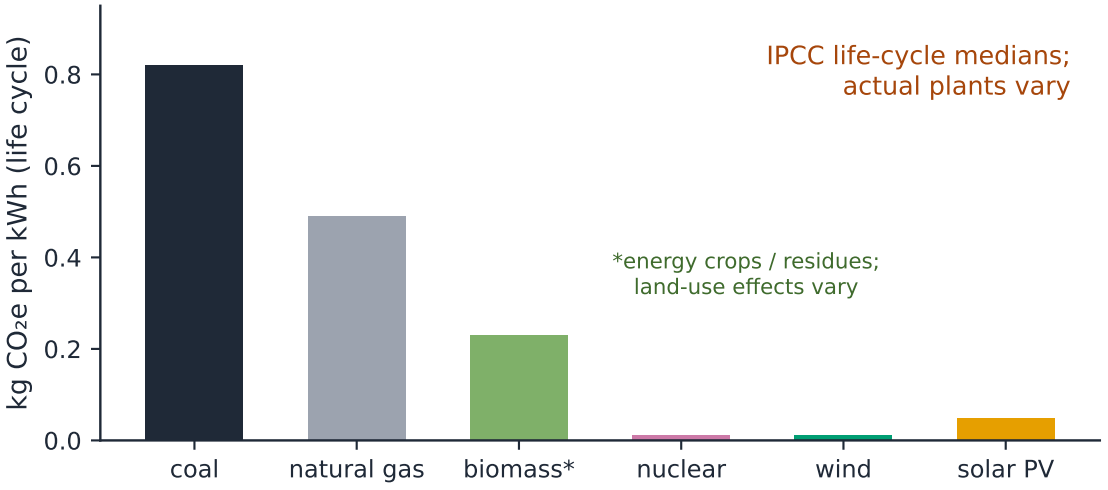
Country comparison: An emits 400 million tonnes CO_2/year with 40 million people: 10 tonnes/person/year. B emits 600 million tonnes with 200 million people: 3 tonnes/person/year. B has the larger annual total; A has the larger per-person value. Neither calculation supplies cumulative responsibility, household inequality or vulnerability. Climate justice combines distributive questions about costs and benefits, procedural questions about voice, and recognition of affected communities and future generations.

AHL: Compare climate policies and technologies

■ Law, incentives and industry in a shared system

Economic instruments include carbon taxes, allowance trading and carefully designed subsidies; legislation can set efficiency standards or phase-out requirements; industry can reduce methane leakage, electrify processes or change materials. These categories overlap: a law can create a market, and a subsidy can support an industrial change. Test additional reductions, enforcement, administrative cost, price effects and distribution. Efficiency can lower the cost of use and encourage greater consumption, so evaluate rebound rather than equating engineering savings with guaranteed total savings.

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Approximate life-cycle greenhouse gas emissions per unit of electricity; biomass depends on feedstock and land use

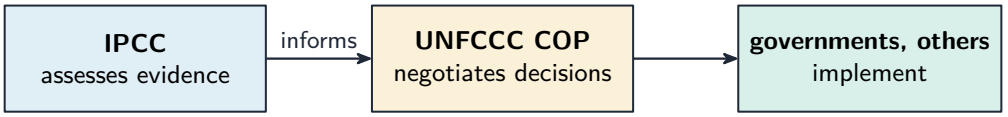
At Norway's Brevik cement works, a project announcement in June 2025 reported the first 1000 tonnes of CO_2 captured and liquefied during ramp-up. Design capacity was about 400,000 tonnes/year; design capacity is not a measured annual capture total. Cement's process emissions make capture a relevant option, but society must examine transport, storage verification, energy, cost, residual emissions and alternatives such as material efficiency. This point-source example avoids emissions; it is not automatically direct atmospheric removal.

Project accounting: a process generates 100 units of CO_2, captures 90 and has 15 units of upstream/energy emissions not included in that 100. If all captured carbon is durably stored, residual accounted emissions are $(100 - 90) + 15 = 25$ units, not 10. This simplified boundary excludes other lifecycle flows. Claiming "90% capture" does not establish "90% lower complete footprint".

Institutions and the latest completed COP

The IPCC assesses scientific evidence; it does not negotiate national targets or enforce climate law. UNFCCC Conferences of the Parties negotiate decisions, while governments and other actors implement them through different institutions. **As of October 2026**, the latest completed annual conference was COP30 in Belém, Brazil, in November 2025. The UNFCCC's outcome account describes the Mutirão decision's call for efforts to triple adaptation finance by 2035. A decision, a pledge, a funding transfer and a successful adaptation outcome are distinct evidence. Explain what was agreed, whose capacity it may improve, and what delivery information remains needed; a conference ending is not proof of solved warming.

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the IPCC sets no national targets and enforces no law

Who does what: assess, negotiate, implement

Climate stability has public-good features: many benefits of mitigation are shared beyond the payer. Individual actors may free-ride on others' reductions, while fossil-fuel infrastructure, short political horizons, finance, technology access and unequal bargaining power impede cooperation. Transparency, reliable finance, shared standards and just-transition support can change incentives. Sovereignty does not prevent cooperation, but commitments need credible domestic follow-through. Carbon markets also require safeguards against double counting and non-additional offsets.

■ Geoengineering, perspectives and barriers

Carbon dioxide removal addresses atmospheric CO_2 if its complete net balance is negative and storage lasts. **Geoengineering** 地球工程 includes large-scale deliberate interventions. Solar radiation modification aims to alter the energy balance; it does not directly remove CO_2 or prevent its chemical effect on oceans. Proposed stratospheric aerosol injection raises uncertainty about regional rain, unequal effects, termination after sustained deployment and who has authority to decide. Neither category has one uniform risk profile: compare specific scale, readiness, monitoring, reversibility and governance. Do not assume an unproven intervention safely replaces rapid emissions reduction.

carbon dioxide removal
lowers atmospheric CO_2 if the full net balance is negative and storage lasts
can reduce the CO_2 that acidifies oceans

solar radiation modification
alters the energy balance only
CO_2 and ocean acidification remain
risks: regional rain, unequal effects, termination shock, who decides

Removal and solar modification change different things

Governments shape grids, standards, public transport and investment; companies change products and supply chains; NGOs can scrutinise claims and support communities; personal choices influence demand and politics within real constraints. Education, trusted media and community involvement can change understanding, while misinformation, polarisation and affordability impede action. A survey should not assign one belief to all young, wealthy or religious respondents. Compare stated values with observed behaviour and structural opportunities. A defensible judgement weighs emissions outcomes, adaptation benefits, costs, justice and political feasibility

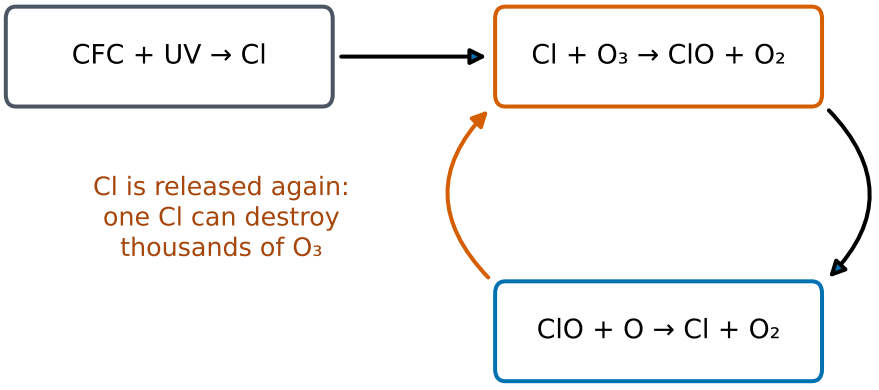
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together.

AHL: Ozone chemistry and cooling choices

Formation, destruction and polar conditions

A simplified Chapman sequence is:



the Montreal Protocol phased out CFCs; the ozone layer is slowly recovering

A chlorine atom from a CFC destroys ozone in a repeating cycle

$$O_2 + UV \rightarrow 2O, \qquad O + O_2 + M \rightarrow O_3 + M.$$

$$O_3 + UV \rightarrow O_2 + O.$$

M is a third collision partner carrying away energy; it is not consumed. Formation and loss rates depend on light, temperature, transport and chemical species. The ozone layer is a region of enhanced concentration, not a solid film.

One simplified catalytic chlorine cycle is:

$$Cl + O_3 \rightarrow ClO + O_2, \qquad ClO + O \rightarrow Cl + O_2.$$

Adding and cancelling intermediates gives $O_3 + O \rightarrow 2O_2$. Chlorine is regenerated. Chlorine and bromine drive major halogen-catalysed depletion; fluorine from CFCs is largely bound in stable HF and is not an equivalent major catalytic agent. Do not infer identical behaviour just because elements share a periodic-table group.

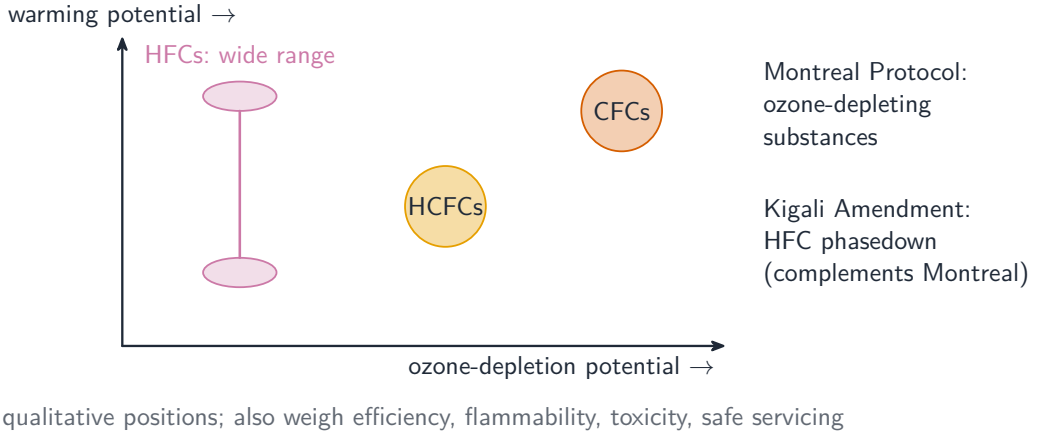
In the cold Antarctic winter, polar stratospheric clouds provide surfaces converting relatively inactive chlorine reservoirs into forms that sunlight can activate. The polar vortex confines cold air; returning spring sunlight supports rapid loss through cycles including ClO-dimer chemistry. That polar mechanism is not fully represented by the

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simple atomic-oxygen cycle above. Winter darkness alone does not cause the spring ozone hole, and the clouds are reaction surfaces rather than clouds physically scraping ozone away. Subsequent warming and mixing affect the hole's evolution; year-to-year weather variability must be separated from long-term recovery.

Air conditioning links energy and chemicals

Cooling systems can affect climate through refrigerant leakage and electricity generation. CFCs have ozone and climate effects; HCFCs have lower but non-zero ozone-depletion potential; HFCs generally avoid ozone depletion but vary greatly in warming potential. The Kigali HFC phasedown complements, rather than replaces, existing Montreal controls on ozone-depleting substances. New alternatives require assessment of efficiency, warming potential, flammability, toxicity and safe professional servicing; "natural refrigerant" does not mean risk-free.



Refrigerants trade ozone depletion against warming potential (qualitative)

Passive shading, insulation, ventilation where suitable, urban greening and efficient equipment can reduce cooling demand while protecting people from heat. Electricity decarbonisation reduces indirect emissions; leak prevention, recovery and appropriate end-of-life treatment reduce direct releases. Demand can rise as incomes and heat exposure grow, so efficiency alone may not reduce total use. Evaluate affordable access to safe cooling and worker safety as well as tonnes of emissions. Ozone and climate treaties show how science, law, finance, markets and ethics interact in a concrete technology choice.

Exam tips

- State the boundary, year, averaging period and unit. Separate station/global CO_2, annual/long-term warming, mass of carbon/CO_2, and capture fraction/net lifecycle reduction.

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- Trace mechanisms: radiation is not ozone chemistry, point-source capture is not automatically removal, and positive feedback is not proof of a specific tipping threshold.
- Evaluate named actions using measured outcomes, uncertainty, equity and implementation. Distinguish treaty adoption, targets, funding announcements and delivery.

Practice

1. **AHL:** (a) State the composition of dry air, and explain why gases with very low concentrations can matter greatly. (b) Describe the troposphere and the stratosphere. (c) In a profile, a 20 °C dry parcel cools 9.8 °C/km while its environment cools 6.5 °C/km. Find both at 1 km and predict the tendency.
2. Explain the natural greenhouse effect, using the terms short-wave radiation, long-wave radiation and albedo.
3. A surface receives 340 W m^{-2} of sunlight and has an albedo of 0.3. Calculate the radiation reflected and absorbed.
4. (a) Distinguish between the natural and the enhanced greenhouse effect. (b) Outline three pieces of evidence that the climate is warming.
5. Explain why methane has a strong but short-lived effect on warming.
6. Explain the ice-albedo feedback, and state whether it is positive or negative.
7. Outline what is meant by a tipping point in the climate system, with an example.
8. Describe three impacts of climate change, and explain why they fall unequally on different countries.
9. Distinguish between mitigation and adaptation, with two examples of each.
10. Evaluate carbon capture and storage as a mitigation strategy.
11. Outline the main features of the Paris Agreement, and evaluate its effectiveness.
12. Explain how sponge cities help people adapt to climate change.
13. **AHL:** Explain how CFCs destroy stratospheric ozone, and state two effects of increased UV radiation. (b) Show the net change after adding the two chlorine-cycle reactions. Explain why polar stratospheric clouds and returning sunlight matter.
14. Explain why the Montreal Protocol has been more successful than agreements on climate change.

Answers.

1. **AHL:** (a) Dry air is about 78% nitrogen, 21% oxygen, 0.9% argon and about 0.04% CO_2 plus traces; water vapour is variable and excluded from dry-air percentages. Absorption depends on molecular properties and wavelength, so trace gases can have large effects. (b) The troposphere contains most air and weather; its top varies roughly 8–18 km and temperature usually decreases upwards, with inversions possible. The stratosphere extends to about 50 km and warms upwards partly

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through ozone absorption of UV. (c) Parcel 10.2 °C, environment 13.5 °C: the colder parcel tends to sink back without continued forcing.

2. Solar short-wave radiation is reflected or absorbed by atmosphere and surface. The surface emits thermal infrared; greenhouse gases absorb and emit some of it in all directions, including downwards. Some infrared escapes. Albedo is reflected/incoming solar radiation; the approximately 30% global reflection does not mean all remaining sunlight warms only the surface.
3. Reflected $= 0.3 \times 340 = 102$ W m^{-2}; absorbed $= 340 - 102 = 238$ W m^{-2}.
4. (a) The natural greenhouse effect is caused by natural levels of greenhouse gases and keeps the Earth habitable. The enhanced greenhouse effect is the extra warming caused by the gases people have added, mainly by burning fossil fuels and clearing forests. (b) Rising multi-decade instrument temperatures, loss of glaciers/land ice and rising sea level are independent lines. Proxy records extend the baseline, with dating and calibration limits. Present high CO_2 alone is evidence of changed forcing, not a thermometer measurement.
5. Methane has a large time-integrated effect per mass on common stated-horizon metrics. Its perturbation lifetime is roughly a decade, not a fixed expiry date; ongoing emissions maintain concentrations. CO_2 has multiple removal timescales. Cutting methane helps near-term warming without replacing CO_2 reductions.
6. Warming melts ice and snow, exposing darker ocean and land with a lower albedo, which absorb more energy, causing more warming. It amplifies the change, so it is positive feedback.
7. A threshold beyond which component change can become self-sustaining, such as ice-sheet retreat aided by elevation and flow changes. Threshold and response time are uncertain; positive feedback does not alone prove an immediate global tipping cascade.
8. Examples: heat harms health; land-ice loss and thermal expansion raise sea level; marine heat stress bleaches coral. Regional effects differ. Exposure, sensitivity and adaptive capacity vary within and between countries; low emissions do not ensure low vulnerability.
9. Mitigation reduces emissions or adds atmospheric removals: replacing fossil electricity and reducing methane leaks. Adaptation reduces harm: flood defences and heat warnings. One action can have both roles; classify its mechanism.
10. Point-source capture can avoid some new emissions, especially process CO_2, but does not automatically remove existing atmospheric carbon. Evaluate complete net emissions, capture fraction, energy, upstream inputs, cost, transport, durable storage and monitoring. DAC with storage is a distinct potential removal route.
11. Adopted in 2015, Paris aims well below 2 °C and pursues 1.5 °C, with successive NDCs, transparency and global assessment. Long-term warming differs from one annual value. Broad participation supports cooperation; national implementation, ambition, finance and unequal capacity limit delivery. Procedural duties do not guarantee target achievement.

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12. Permeable surfaces, planted storage and wetlands retain or slow runoff and may reduce peak flooding. Capacity, saturation, maintenance and extreme rainfall limit protection; heat benefits are separate mechanisms. It is adaptation rather than direct removal of greenhouse gases.
13. **AHL:** Stable CFCs can reach the stratosphere, where UV releases chlorine that participates repeatedly in catalytic ozone destruction. More UV-B can increase skin-cancer/cataract risk and damage crops or phytoplankton. At HL, show chlorine regeneration in the reaction cycle and explain polar cloud/sunlight conditions. (b) Net $O_3+O \rightarrow 2O_2$; chlorine is regenerated. Cold cloud surfaces activate chlorine reservoirs; returning sunlight supports rapid spring loss. The polar dimer pathway is more complex than this simplified cycle.
14. Montreal targeted a narrower chemical group with alternatives, monitoring, finance and agreed controls, supporting reduced ODS burdens and conditional recovery. Climate emissions span many systems and unequal development needs. Universal ratification is not proof of complete recovery; climate agreements can still achieve reductions.

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Natural resources

International Baccalaureate · IB Diploma · Environmental Systems and Societies · HL

Scope and prerequisites

This handout teaches Topic 7, Natural resources (7.1 Natural resources: uses and management, 7.2 Energy sources: uses and management, 7.3 Solid waste), for the course first assessed in 2026. Sections marked **AHL** are for Higher Level only. Datasets are teaching examples, not observations from real papers. The HL extensions connect law, economics and ethics to resource decisions.

Prerequisites: Topic 1 (natural capital and natural income, sustainability, the circular economy, perspectives), Topic 5 (soil as a resource) and Topic 6 (greenhouse gases and mitigation).

Natural resources

The solar surge

The IEA's Renewables 2023 report, published in 2024, reported that China commissioned as much solar photovoltaic capacity in 2023 as the whole world did in 2022. This is a comparison of new capacity, not electricity generated or all energy consumed. A panel's rated power does not show how many hours it operates or whether output matches demand. Sunlight has supported agriculture, heating and other uses for much longer than modern panels have existed; technology, cost and policy change how it is used. This topic follows resources from natural stocks and flows through useful services to waste and recovery.

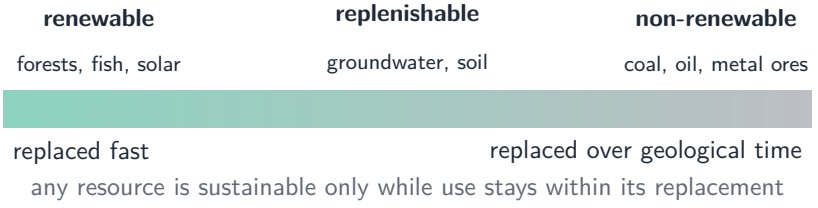
What is a natural resource?

A **natural resource** 自然资源 is any material, energy or service from the natural world that people use. In Topic 1 we called the stock **natural capital** 自然资本 and the flow of goods and services from it **natural income** 自然收入. Resources can be grouped by how quickly they are replaced:

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An open-pit mine: benches are cut ever wider and deeper to reach a non-renewable ore



Resources grouped by how quickly they are replaced

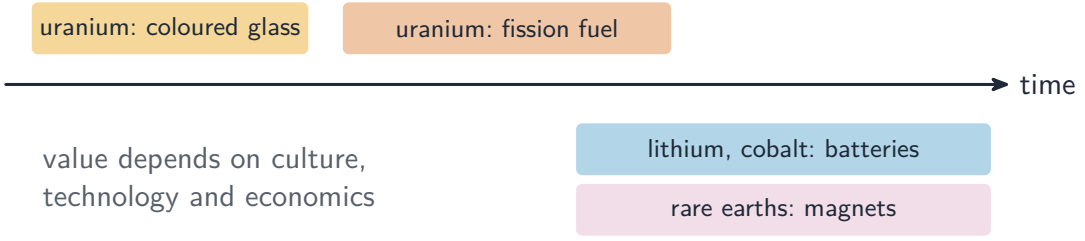
Type	Meaning	Examples
Renewable 可再生	Regenerated or supplied through recurring natural processes on relevant human timescales	Timber growth, reproducing fish stocks and renewable freshwater flows; solar and wind energy flows
Non-renewable 不可再生	Formed over geological time, so used much faster than they form	Coal, oil, natural gas, uranium, metal ores, minerals

A renewable stock can be depleted if use exceeds regeneration: overfishing can collapse a stock, while abstraction can exceed aquifer recharge. Some groundwater is effectively fossil water; full soil formation is often too slow for renewal on planning timescales (Topics 4 and 5). Sunlight and wind are recurring energy flows with finite available power, area and infrastructure constraints. Metals can be reused and recycled, but collection losses, contamination, energy and quality constrain repeated recovery; matter does not circulate perfectly forever.

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The value of resources changes

What counts as a resource depends on culture, technology and economics:



What counts as a resource changes with technology

- Uranium's energy and strategic value changed with fission technology; it also had earlier uses in coloured glass and ceramics.
- Lithium, cobalt and **rare earth elements** 稀土元素 illustrate changing technology demand. Lithium is not a rare earth, and these materials serve different battery, magnet and industrial roles; not every battery or turbine requires every one of them. Supply concentration depends on material, processing stage and year.
- Whale oil was once a major fuel for lamps; kerosene and then electricity replaced it.
- Some resources have values that markets do not show. A forest's timber has a price, but its carbon storage, flood control and spiritual value usually do not (Topic 1, ecosystem services).

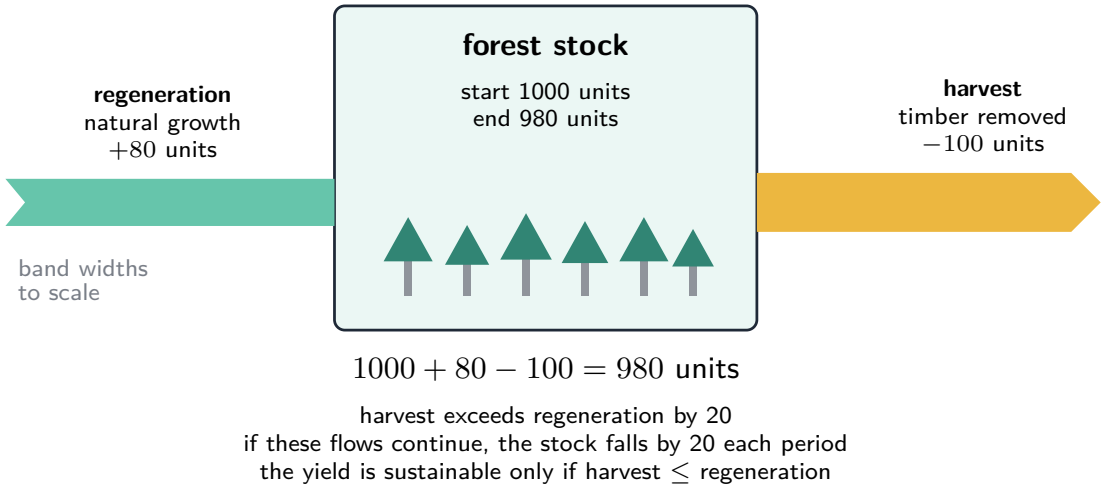
Managing resources sustainably

- **Reduce demand**: use resources more efficiently; design products that last longer and use less material.
- **Substitution** 替代: replace a scarce or harmful resource with another, such as aluminium for copper in cables, or renewable energy for fossil fuels.
- **Reuse, repair and recycling**, which keep materials in use (the circular economy, Topic 1).
- **Protect renewable stocks and ecological functions**: a harvest at estimated growth does not alone protect habitat, soil, age structure or other services.
- **Resource security** 资源安全: countries try to secure reliable supplies by diversifying sources, stockpiling and trade agreements. Concentration of supply in a few countries makes resources a political issue.

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Stocks, services and contrasting values

A standing forest, wetland and local river illustrate different natural capital. Timber or fish are goods; flood regulation, water replenishment, nutrient removal, erosion protection and carbon storage are services. A reed-bed buffer may take up nutrients but has limited capacity and can release pollutants under changed conditions; it is not a substitute for unlimited waste treatment. Sustainability requires both harvest within regeneration limits and pollution within rates and conditions that avoid harmful accumulation.



One-period model: $1000 + 80 - 100 = 980$ *units; use exceeds regeneration by 20. A sustained-yield calculation also needs uncertainty and protection of other ecosystem functions.*

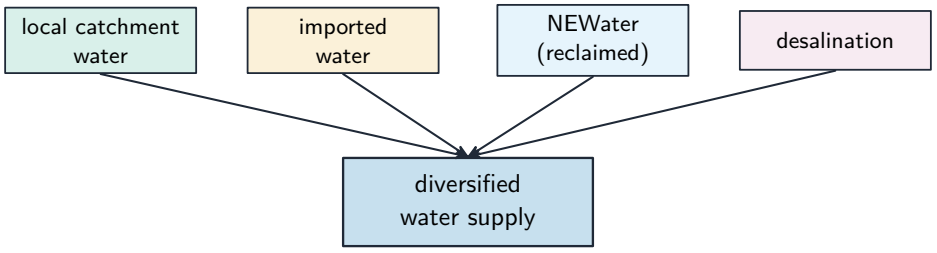
Nature has aesthetic value through beauty, cultural and spiritual connections through place and practice, economic value through income, environmental value through ecosystem processes, health value through clean water or recreation, social value through community use, and technological value through useful properties. **Intrinsic** value concerns worth independent of human usefulness. These values can overlap but cannot all be reduced to a timber price. Describing nature as capital is a useful stock/flow model, yet can imply that nature exists primarily for human use; acknowledge that perspective instead of presenting it as the only ethical view.

For a school survey, ask neutral, separate questions about services and reasons for valuing them; use voluntary participation, privacy and a stated sampling method. Willingness to pay depends on income as well as preference, and a small convenience sample is not the whole community. Changes in fashion, substitutes, scientific knowledge, scarcity and policy can raise or lower resource value: lithium demand rose with rechargeable-battery applications, while whale oil's lighting role declined as alternatives spread. A lower market price does not mean a species or habitat loses intrinsic worth.

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Security in two water contexts

Resource security means sufficient, reliable and accessible supply over time, not simply a large national stock. Singapore's Four National Taps combine local catchments, imports, NEWater reuse and desalination. Diverse sources reduce some rainfall and import risks, while treatment energy, infrastructure, cost and water quality require management. This is not complete independence from every external input.



Singapore's Four National Taps diversify supply

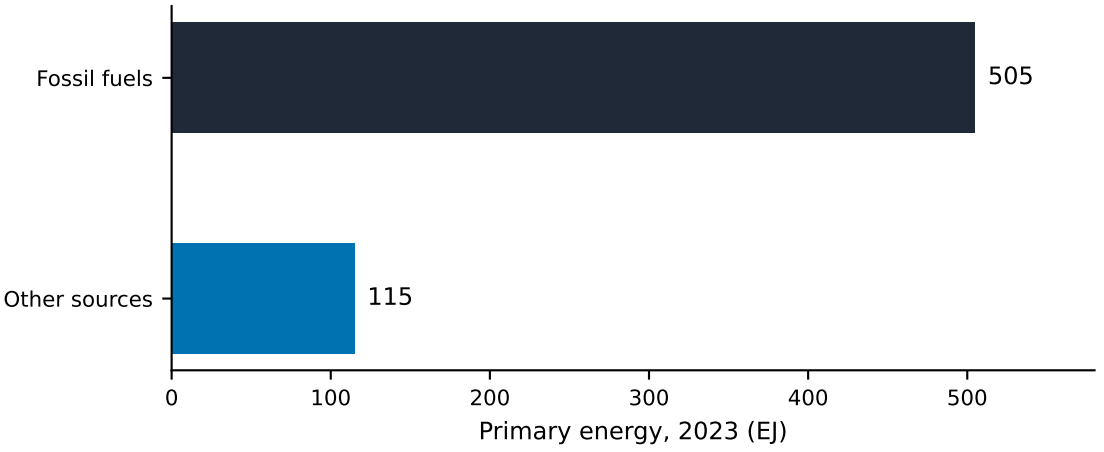
Jordan's National Water Strategy 2023–2040 describes severe scarcity, with about 61 m^3 of renewable freshwater per person per year in its 2023 account. Arid conditions, demand, groundwater pressure and unequal access complicate security. Leakage reduction, safe reuse, demand management and planned supply projects require finance and delivery; an announced project is not already completed capacity. Compare both countries' reliability, affordability, ecological flows and resilience rather than declaring one technology a universal answer. Water and food security are linked through farming, energy and trade, but national averages can hide household insecurity.

Energy sources

Why energy matters

Energy provides industrial work, transport, heat, cooling and communication, but access and consumption are unequal. Population and per-person demand can both raise total use; efficiency and conservation can change the relationship. **Primary energy** refers to energy in resources before conversion, while electricity is an energy carrier, not synonymous with all energy. Hydrogen is also a carrier: making it requires energy and a feedstock. Fuels additionally supply chemical feedstocks and process heat for steel, cement and fertiliser; alternatives must address those roles rather than electricity alone.

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Energy Institute's 2024 review: rounded 2023 total 620 EJ, fossil fuels 505 EJ. Share $505/620 \times 100 = 81.45\%$*, about 81.5%. Use a consistent accounting method when comparing years; these are not electricity-generation shares.*

Non-renewable energy sources

- Coal: **Benefits:** Cheap; large reserves; reliable. **Limits:** Most CO_2 per unit of energy; air pollution (particulates, sulfur dioxide); mining damages land.



A nuclear power station: low-carbon electricity, but long-lived radioactive waste to manage

- Oil: **Benefits:** High energy density; easy to transport; widely used in transport and chemical feedstocks. **Limits:** CO_2; oil spills; supply concentrated in a few regions.

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- Natural gas: **Benefits:** Often less direct CO_2 per comparable output than coal; flexible generation. **Limits:** Still fossil; upstream methane and extraction impacts affect net comparison.
- **Nuclear** 核能: **Benefits:** Generally low lifecycle carbon; high availability; small fuel mass. **Limits:** Mining, cooling and radioactive wastes; accident risk; financing, build time and decommissioning.

■ Renewable energy sources

- **Solar** 太阳能: **Benefits:** Low operating emissions; scalable roof or ground installations. **Limits:** PV needs sunlight; clouds, location, land, minerals and end-of-life treatment matter.



A geothermal power station in Iceland: steam from hot rock drives the turbines



Wind turbines: renewable sources replenish on human timescales; fossil fuels do not

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- **Wind** 风能: **Benefits:** Low cost; low emissions; can be offshore. **Limits:** Intermittent; visual and noise impact; risk to birds and bats.
- **Hydroelectric** 水电: **Benefits:** Reservoir hydro can be controllable and store potential energy. **Limits:** Dams flood land and displace people; block fish; change river flow and sediment.
- Geothermal: **Benefits:** Often steady where suitable; heat and/or electricity. **Limits:** High-temperature resources are site-dependent; useful geothermal heat also exists outside volcanic regions.
- Tidal and wave: **Benefits:** Tidal timing is predictable; wave energy follows sea conditions. **Limits:** Site and ecological constraints; wave output is weather-dependent.
- **Biomass** 生物质能: **Benefits:** Uses suitable organic fuels; can be stored. **Limits:** Land, food and biodiversity trade-offs; combustion pollution; not automatically carbon-neutral.

The main problem with solar and wind is that they are **intermittent** 间歇性: they produce power only when the sun shines or the wind blows. Solutions include batteries, pumped hydro storage (pumping uphill with input electricity and later releasing water through turbines), stronger interconnections, flexible demand and suitable dispatchable generation. Storage shifts energy through time; it is not a free primary source. Geographic diversity helps but does not guarantee every region has surplus simultaneously. Run-of-river hydro is less controllable than reservoir hydro, and drought can constrain both.

Choosing an energy mix

A country's **energy mix** 能源结构 depends on:

- the resources it has (coal in China and India, hydro in Norway and Brazil, sun in North Africa);
- cost and technology;
- **energy security** 能源安全: a reliable supply not dependent on unstable imports; the 2022 cut in Russian gas to Europe made many countries speed up renewables;
- environmental concerns and international climate agreements;
- public opinion and politics, such as opposition to nuclear power in Germany after Fukushima;
- the values of the society (Topic 1).

Compare Norway and Japan

Norway's energy authorities describe a hydro-rich electricity system with reservoirs providing flexibility. Topography, rainfall, existing dams and interconnections support that choice; drought, ecological flows, fish movement, flooded land and power prices still matter. A hydro-dominated electricity supply does not make all transport or industrial energy renewable.

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Norway: hydro-rich electricity
enablers: topography, rainfall, existing reservoirs, interconnections
limits: drought, ecological flows, fish movement, flooded land
transport and industry not all renewable

Japan: import-dependent
after 2011: Fukushima disrupted nuclear
constraints: limited domestic fuels, import routes and prices, terrain
responses: LNG diversification, efficiency, grid resilience, renewables, nuclear safety

geography and history shape each mix; neither is a template

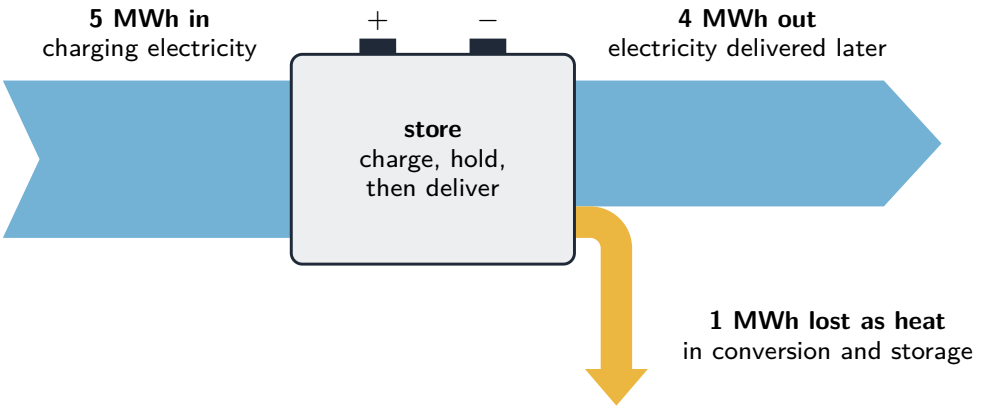
Norway and Japan: geography and history shape each energy mix

The IEA's Japan 2021 review describes import dependence and diversification after the 2011 Fukushima accident disrupted nuclear supply. LNG supplier diversification, efficiency, grid resilience, renewable development and nuclear safety involve different trade-offs. Import routes and prices, limited domestic fuels, terrain, urban demand, public trust and historical infrastructure influence choices. This is a dated policy context, not an assertion that the 2021 mix remains unchanged. Compare availability, affordability, reliability, carbon, local pollution, efficiency and restoration costs in both settings; neither country supplies a universal optimum.

■ Capacity, generation and storage

Power is a rate; energy is accumulated over time. **Invented:** a 50 MW wind installation at a capacity factor of 0.30 over 8760 hours generates $50 \times 8760 \times 0.30 = 131\,400$ MWh, or 131.4 GWh. Capacity factor compares actual output with continuous full-rated output; it is not thermodynamic conversion efficiency. Never compare installed MW directly with annual MWh.

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$$\text{round-trip efficiency} = \frac{4}{5} \times 100 = 80\%$$

band widths drawn to scale

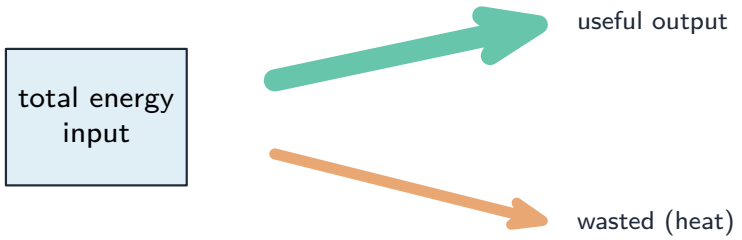
Round-trip efficiency $= 4/5 \times 100 = 80\%$. *Delivering 4 MWh at 1 MW can cover four hours, within the model's power and usable-energy limits.*

Batteries can respond rapidly, while pumped storage uses water and elevation and thermal storage can serve heating or cooling. A fuel cell converts a supplied fuel's chemical energy to electricity; a hydrogen-storage chain also needs production, storage and conversion, each with losses. Match storage power, duration, location, reliability and cost to the mismatch between demand and supply. Peak-shaving can shift flexible demand or discharge stores; a store empty after four hours cannot supply an unlimited week-long shortfall.

■ Energy efficiency and conservation

Conservation changes use, while efficiency reduces the input needed for a given useful service. Compare the costs and benefits of insulating buildings, efficient lighting and appliances, public transport, cycling, and smart grids. Efficiency is useful energy output divided by total energy input under a stated boundary. Conversion: 30 MJ useful output from 100 MJ input gives 30%; 70 MJ is outside the useful output, often dispersed as heat. Insulation can reduce energy needed for a safe indoor temperature; replacing an inefficient light can reduce electricity for comparable illumination. Behaviour, comfort and occupancy affect measured savings. Sometimes efficiency gains are partly lost because cheaper energy leads people to use more. This is called the **rebound effect** 反弹效应.

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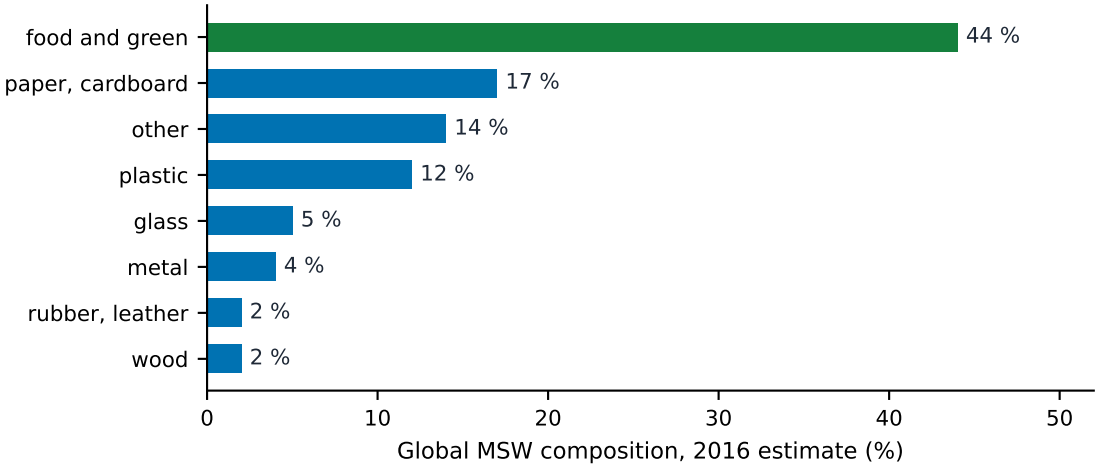
$$\text{efficiency} = \frac{\text{useful output}}{\text{total input}} \times 100\%$$

Efficiency: only part of the energy input leaves as useful output; the rest is wasted, usually as heat

Solid waste

How much we throw away

Municipal solid waste 城市固体废物 (MSW) includes collected household and similar commercial waste; definitions and coverage vary. The World Bank's 2018 What a Waste 2.0 report estimated 2.01 billion tonnes in 2016 and projected 3.40 billion in 2050 under its assumptions. These are dated observations/estimates and a conditional projection, not present measurements. Per-person amounts and composition vary with income, diets, packaging, collection, policy, technology and season; high-income waste does not consist only of packaging, nor low-income waste only of food.



World Bank 2018 report, approximately attributed 2016 composition. Categories sum to 100%; this is a global estimate, not every city.

Classify by **source** (domestic, industrial, agricultural) or **type** (food, plastics, e-waste,

biohazardous material); these are overlapping classifications, not additive categories. Domestic waste can include paper/cardboard, packaging, glass, metal, food/garden matter, clothing and some construction debris. Density and moisture matter: tonnes, volume and dry mass are not interchangeable. Other important types include **electronic waste** 电子垃圾 (e-waste: old phones and computers, containing valuable metals and toxic ones such as lead and mercury) and hazardous waste from industry and hospitals.

Plastic

Plastic is useful because of its low mass, durability and other properties, but losses can cause entanglement, ingestion, habitat effects and persistent contamination. Degradation depends on polymer and conditions; no single "hundreds of years" lifetime applies to all plastics. Fragmentation creates smaller pieces without necessarily mineralising the material. **Microplastics** 微塑料 are particles less than 5 mm; detection in an organism establishes exposure, not by itself a particular disease or proven dose–response.



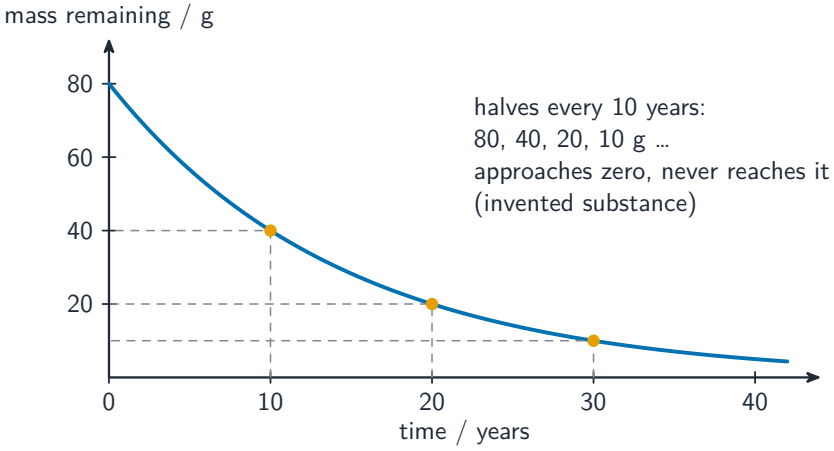
Most plastics are non-biodegradable, so waste plastic collects on beaches and in the oceans for hundreds of years

The OECD's 2022 Global Plastics Outlook estimates that 9% of plastic waste was ultimately recycled in 2019 after process losses. Keep this denominator and date: it is not 9% of every plastic product ever manufactured. Ocean accumulation zones contain distributed debris, not a solid island that can simply be lifted away. Prevention, collection and safe treatment on land complement targeted clean-up; removing fragments can be difficult and can disturb organisms.

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Persistence, accumulation and justice

Biodegradation transforms organic substances through organisms under suitable conditions; oxygen, moisture, temperature and chemistry affect rates. "Biodegradable" does not guarantee rapid breakdown in cold seawater or an anaerobic landfill. If a substance follows a constant 10-year half-life model, 80 g becomes 40 g after 10 years and 20 g after 20, not zero. Real weathering or decomposition need not obey one exponential half-life; metals can change form without disappearing as elements.



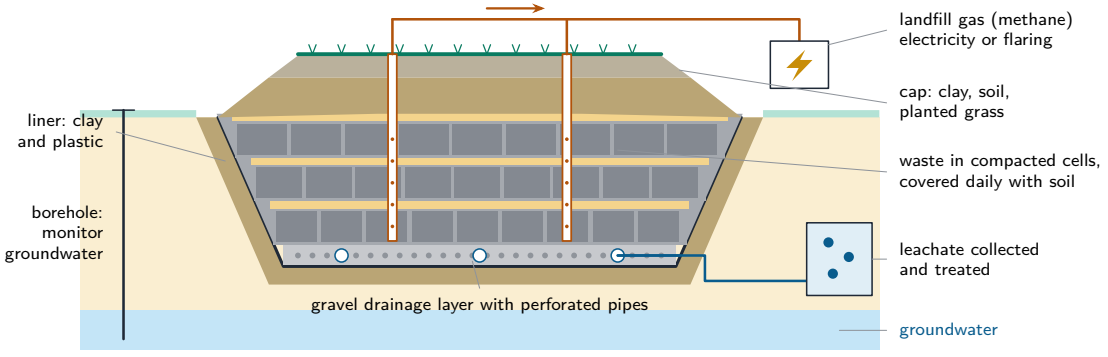
A constant half-life halves the amount each period; it never reaches zero

Pollution depends on toxicity, concentration, loading, exposure and transformation, not only whether waste is visible. Biological oxygen demand from decomposing organic waste can harm water even if the material eventually breaks down. Landfill leachate, smoke from uncontrolled burning and unsafe e-waste recovery can transfer health costs to workers and neighbouring communities. Waste exported for recovery can supply materials and livelihoods but can also shift risks away from consuming societies. The Basel e-waste amendments effective January 2025 extended prior-informed-consent controls to all electrical/electronic waste within that framework; do not equate this with a universal ban on every used working device or proof that illegal shipments ended.

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Ways of disposing of waste

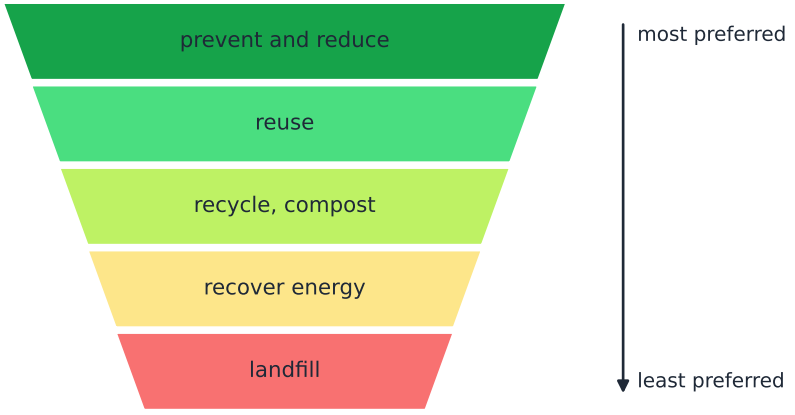
Method	Advantages	Disadvantages
Open dumping	Cheap	Disease, smells, water pollution, fires
Landfill 填埋	Engineered containment; some landfill gas can supply energy	Uses land; **leachate** 渗滤液 needs containment/treatment; liners and gas collection can fail or leak
Incineration 焚烧	Reduces volume, depending on feedstock; can recover useful energy	Needs emissions control/monitoring and ash management; contracts can discourage prevention
Composting 堆肥	Produces a useful soil amendment from suitable sorted organics	Needs sorting, oxygen, moisture, space and quality control
Anaerobic digestion	Produces biogas and digestate; digestate needs safe nutrient management	Needs separate collection
Recycling 回收利用	Saves resources and energy; reduces landfill	Needs sorting and markets; some materials degrade each time



An engineered sanitary landfill: a liner reduces risk rather than guaranteeing no leakage; collect and treat leachate, monitor groundwater and manage gas during and after operation.

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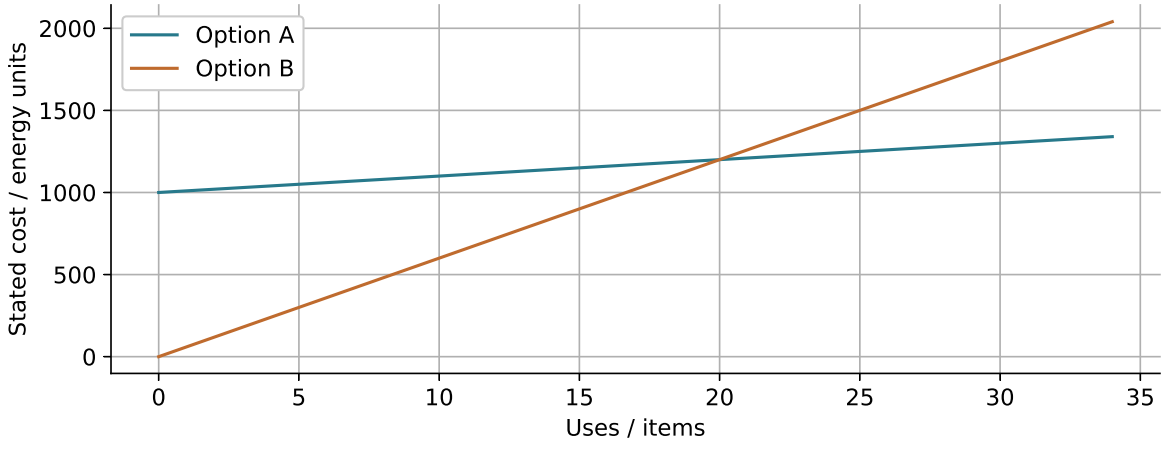
The waste hierarchy



The waste hierarchy

The **waste hierarchy** 废物等级 ranks ways of managing waste. Prevention normally avoids more upstream demand than end-of-pipe treatment, while controlled disposal can be necessary for residual or hazardous materials. Uncontrolled dumping and burning can be worse than engineered disposal; the hierarchy is not permission to recycle contaminated waste unsafely. This matches the three levels of pollution management (Topic 4): change the human activity, control the release, clean up the damage.

To compare products fairly, a **life cycle assessment** 生命周期评价 defines a functional unit and system boundary and estimates environmental impacts of a product from raw materials, through manufacture, transport and use, to disposal.



The reusable item wins after 20 uses: 1,000 + 10n = 60n

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Worked example. Making a reusable cup uses 1000 kJ, and washing it uses 10 kJ per use. A disposable cup uses 60 kJ each. After n uses the totals are $1000 + 10n$ and $60n$. They are equal when $1000 + 10n = 60n$, so $n = 20$. The reusable cup saves counted energy only after more than 20 uses, so the first whole-number use is 21. This model assumes one wash per use and no breakage; water, detergent, transport, hygiene and other impacts are not included. A real lifecycle assessment must compare an equivalent service and several impact categories, not energy alone.

Case study: Shanghai's waste sorting

Shanghai's household waste-management regulation took effect in July 2019, requiring separation into recyclables, hazardous waste, wet/food waste and dry/residual waste. Labels and local arrangements help households choose the correct stream; collection facilities, monitoring, education and penalties can reinforce participation. Not every battery belongs to the same household category: follow the applicable local guidance rather than assuming a rule for one chemistry fits all. Sorting is only one stage; track contamination, transport, actual processing, recovered output and safe residues. A before/after increase in sorted collection is encouraging but does not alone separate the law's effect from collection changes or prove every item was recycled.

Changing behaviour

Strategies to reduce waste include:

- deposit-return schemes for bottles and cans;
- charges or bans on single-use plastic bags and straws;
- extended producer responsibility, which makes manufacturers pay for collecting and recycling their products;
- designing products to be repaired, reused or easily taken apart;
- pay-as-you-throw charges for household waste;
- education, labelling and convenient collection.

Follow a material through a circular system

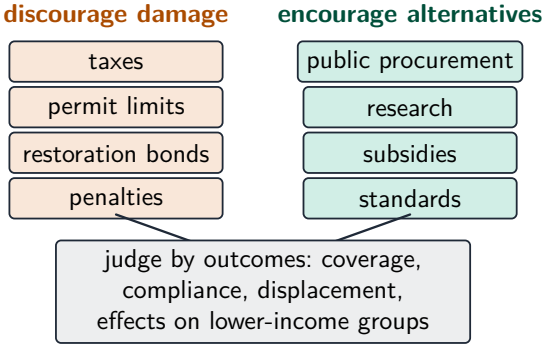
An aluminium drinks can begins with ore extraction, refining, metal production and manufacture; after use, collection, sorting, remelting and quality control can return material to new products. Prevention and suitable refill/reuse can reduce production before recycling is needed. Recovery: collect 80 of 100 units and recover 90% from those; output is 72 units, with 28 lost or uncollected. Recyclable design is a potential; actual recovery requires infrastructure, clean streams, energy and demand. Reducing impact per item can be outweighed by rising total consumption. Extended producer responsibility, deposit return, pay-as-you-throw, education and convenient facilities work through different incentives and need checks for dumping, access, fairness and real recovery.

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AHL: Govern natural capital across scales

Incentives, SDGs and lifecycle responsibility

Governments can discourage damaging extraction through taxes, permit limits, restoration bonds and penalties, and encourage alternatives through procurement, research, subsidies and standards. A policy name is not its outcome: verify coverage, compliance, displacement and effects on lower-income groups. A subsidy may accelerate useful technology while also rewarding activity that would have happened anyway. NGOs, communities and social movements can monitor extraction, organise repair/reuse and influence decisions; participation does not give every stakeholder equal bargaining power.



Instruments that discourage damage and encourage alternatives, both judged by their outcomes

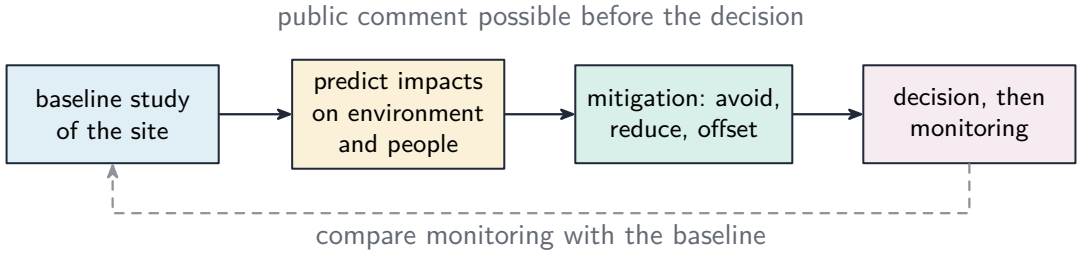
SDG 6 links water access and sustainable management; SDG 12 links consumption, production and waste. A water-reuse project can support both by improving supply and reducing discharges, but requires energy, treatment and access safeguards. These are two examples within a wider global partnership, not proof that one project fulfils every goal. Consider employment, equity and ecosystem outcomes alongside material efficiency. Carbon-storing concrete or recyclable turbine components require evidence about complete net emissions, durability and actual recovery; a technology label does not establish commercial maturity or universal suitability. Biological nitrogen fixation can reduce some fertiliser demand but is not an established replacement for every industrial ammonia requirement.

A renewable timber stock can be harvested destructively through road building, soil erosion, habitat fragmentation or fuel-intensive transport. Protecting volume alone does not conserve every species or service. Short-term revenue can favour rapid extraction even when long-term livelihoods lose. The northern cod case in Topic 4 illustrates a depleted renewable stock: incentives and uncertain assessments must be considered alongside biology. Non-renewable minerals can support low-carbon technologies while still requiring responsible land, water, labour and waste management.

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Environmental impact assessment and participation

An **environmental impact assessment** 环境影响评价 examines likely effects before a proposed development is approved, with follow-up monitoring and audit. The legal triggers, required documents, consultation and authorities vary among jurisdictions; one classroom sequence is not a universal legal procedure. A sound assessment defines the proposal and alternatives, including no project, studies the baseline, predicts impacts and uncertainty, proposes avoidance and mitigation, considers residual impacts, and identifies monitoring and responsibilities. Approval is not proof of no harm.



The steps of an environmental impact assessment

For a proposed reservoir, baseline parameters could include seasonal river flow, sediment, fish passage, habitats, water quality, settlement, land rights and livelihoods. Construction adds noise, dust, traffic and worker risks; operation changes flows, inundation and downstream sediment, while decommissioning has other effects. Compare sites and operating regimes before relying on compensation. Monitoring should specify indicators, sampling dates, independent scrutiny, trigger levels, actions and accountable funding. An annual average can conceal a damaging dry-season flow or short high-pollution event.

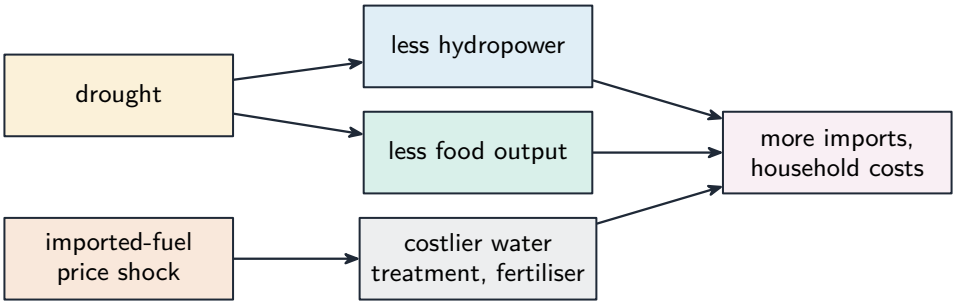
Public access helps local residents contribute knowledge and challenge omissions. Consultation should be timely, understandable and accessible, with privacy and recognition of rights; a late public meeting does not automatically establish informed consent. Stakeholders may disagree about jobs, relocation, habitat, electricity and cultural heritage. Document disagreements and who bears residual costs instead of treating participation as a vote that removes the need for scientific evidence. Economic benefits do not automatically cancel irreplaceable cultural or ecological loss.

Security, trade and data interpretation

Insecurity can interrupt production, raise household costs and encourage emergency extraction that worsens environmental harm. A drought can reduce hydropower and food output together, increasing import needs; an imported-fuel price shock can increase water-treatment and fertiliser costs. Multiple pathways do not mean conflict is inevitable. Analyse exposure, institutions and cooperation rather than attributing every dispute to a single resource. Mining and refining are different stages, and concentration differs among lithium, cobalt and rare earths: do not claim all their

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extraction or almost all processing occurs in one country.



exposure, institutions and cooperation decide the outcome: conflict is not inevitable

Linked pathways of resource insecurity; conflict is not inevitable

Demand reduction, new supply and technology can improve security. Food examples include reducing avoidable losses, protecting soils, improving storage and diversifying reliable supply; water examples include leakage control, safe reuse and suitable desalination; energy examples include efficiency, grids, storage and diverse sources. Each has costs and ecological limits. Imports can spread drought or production risk and improve access, but dependence on a narrow supplier, route or currency can create vulnerability. Food trade moves embodied water without physically shipping all the water used during production; energy and food self-sufficiency are not identical to affordable secure access.

For a secondary-data investigation, choose the same resource, period, boundary and unit for two societies; separate extraction, production, net imports and consumption. Download the original data and metadata, record revisions and missing values, and compare totals as well as per-person or output-normalised values. Graph time series against actual years, and check whether accounting methods changed. A correlation test does not identify a cause; successive annual values may not be independent observations.

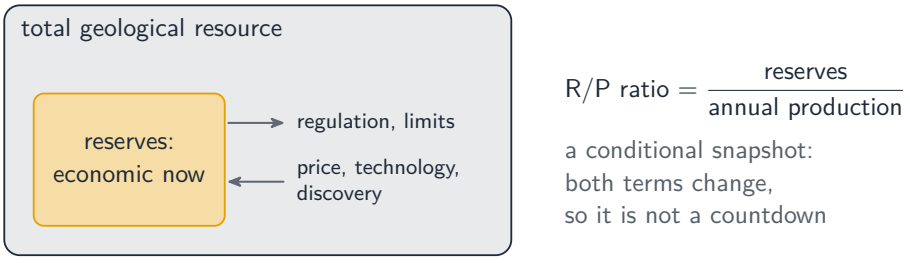
Ranking exercise: four matched observations of material use in society An are 2, 4, 6 and 8 units/person; corresponding B values are 3, 5, 7 and 9. Both rank orders are 1, 2, 3, 4. Spearman's $r_s = 1 - 6\sum d^2/[n(n^2-1)] = 1$ because all rank differences are zero. This perfect rank association does not mean equal amounts, independence, causation or universal future growth. Real country comparisons need suitable sample size, uncertainty and justification for the statistical design; do not invent data and attach real country names.

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AHL: Energy security, depletion and nuclear choices

Reserves are conditional estimates

Fossil fuels supply much global energy and industrial feedstock, but finite geological resources are not the same as currently economic **reserves**. Price, technology, discovery, regulation and environmental limits can change the recoverable quantity. Consumption may rise or fall as populations, efficiencies and alternatives change. A reserves-to-production ratio is a conditional snapshot, not a countdown to a guaranteed exhaustion date.



Reserves sit inside resources; the R/P ratio is a snapshot, not a countdown

Example: reported reserves 120 units and annual extraction 3 units give $R/P = 40$ years at unchanged values. If extraction becomes 4, the ratio is 30 years; if improved recovery raises reported reserves to 150 while extraction stays 3, it becomes 50 years. Neither calculation forecasts discoveries, policy or demand. Climate constraints may require leaving fuel unburned before physical exhaustion. Energy security means affordable, reliable access; domestic production can still suffer drought, outages, pollution or unequal prices, while diversified imports can sometimes improve resilience.

Nuclear energy needs a complete boundary

Most nuclear power stations use controlled fission of uranium or plutonium to release energy, generating heat, steam and electricity. The fuel is non-renewable under this classification, while lifecycle greenhouse-gas emissions are generally low relative to unabated fossil generation. Low-carbon does not mean zero-impact, and availability is not absolute: planned maintenance, faults, cooling-water constraints and extreme weather can interrupt output. Upfront cost, construction time, financing, operating cost, grid needs and decommissioning all affect economic assessment; low operating fuel cost does not guarantee a cheap new project.

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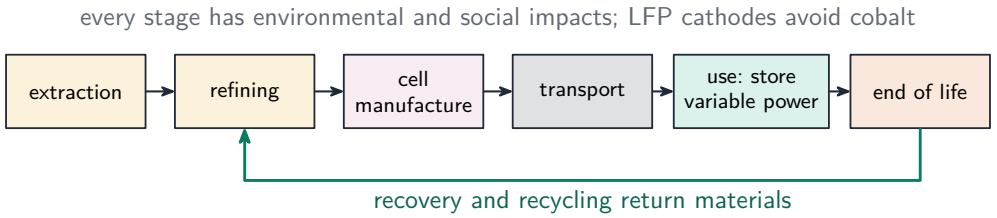
A nuclear power station uses the energy from fission to make electricity; the towers release waste heat as steam

Uranium mining, tailings, fuel preparation and transport have impacts. Warm cooling-water discharge can alter aquatic conditions; temperature, flow and dissolved oxygen need controls. Used fuel contains radionuclides with different half-lives and heat outputs. Initial cooling, shielding, containment, secure storage and appropriate long-term management serve different purposes; shielding alone does not prevent a leak. Not every radioactive waste requires identical treatment or poses an unchanged hazard forever. Accidents at Chernobyl (1986) and Fukushima Daiichi (2011) demonstrate severe risks requiring context-specific prevention, emergency arrangements and institutional learning. Neither an accident's existence nor absence alone establishes a complete comparative risk per unit energy.

■ Storage materials, chemistry and recovery

Battery systems can support variable generation, but extraction, refining, cell manufacture, transport, use and end-of-life treatment have environmental and social impacts. Lithium is an alkali metal, not a rare earth; cobalt is a transition metal. Some lithium-ion cathodes contain cobalt, whereas lithium iron phosphate chemistry does not. Rare earths are important in some magnets and technologies, but they are not a universal required ingredient of all lithium-ion batteries, motors or wind turbines.

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A battery's lifecycle: impacts at every stage, recovery closes the loop

For a lithium supply chain, compare ore mining or brine extraction, water availability, energy, chemical processing, tailings or waste brines, community rights and working conditions. A dry salt-flat basin can have complex groundwater–ecosystem connections; water use cannot be evaluated from the word "brine" alone. Mine concentration and refinery concentration are separate vulnerabilities. Alternatives, chemistry changes, longer product life and recycling can reduce some demand without proving all impacts disappear.

Collection and safe handling determine whether technical recyclability becomes actual recovery. **Chain:** of 100 units of a target metal in retired batteries, 80 are collected; a process recovers 90% of the collected content. Output is $100 \times 0.80 \times 0.90 = 72$ units, or 72% overall, not 90% or 170%. The remaining 28 require tracing across uncollected material and process losses. Performance depends on chemistry, contamination, energy, transport and safe worker protection. Recovered material cannot instantly supply a fast-growing market whose new demand exceeds the returning end-of-life stock. Circularity supports lower primary demand but is not an unlimited material supply.

Exam tips

- Name the functional unit, period and boundary: stock/flow, primary energy/electricity, MW/MWh, capacity factor/efficiency, collection/recovery and mass/volume are distinct.
- Evaluate a source or policy for a named context, including lifecycle impacts, security, affordability and who bears costs. A renewable or recyclable label is not an observed outcome.
- Show inequalities for break-even: equality at 20 uses means lower counted energy first occurs at 21 whole uses. State omitted impacts and assumptions.

Practice

1. (a) Distinguish between renewable and non-renewable resources, and explain how a renewable resource can be used unsustainably. (b) Explain, with two examples, why the value of a resource can change over time.

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2. **AHL:** Outline two ways of managing non-renewable resources sustainably. (b) Reserves are 120 units and extraction is 3 units/year. Calculate R/P and explain why it is not a fixed depletion date.
3. Using the dated 2023 Energy Institute values, 505 EJ fossil energy and 620 EJ total, calculate the fossil share.
4. **AHL:** Evaluate nuclear power as an energy source. (b) Explain why lithium-ion battery manufacture does not always require cobalt or rare earths, and evaluate collection losses.
5. Compare solar and hydroelectric power as sources of electricity.
6. Explain why intermittency is a problem for solar and wind power, and outline two solutions.
7. (a) Outline four factors that affect a country's choice of energy sources. (b) Explain what is meant by energy security, with an example.
8. Describe how the amount and composition of solid waste differ between richer and poorer countries.
9. Explain why plastic waste is a serious environmental problem.
10. Compare landfill and incineration as methods of waste disposal.
11. Describe the waste hierarchy and explain why prevention is ranked above recycling.
12. A reusable bottle uses 1500 kJ to make and 15 kJ per wash. A disposable bottle uses 90 kJ. After how many uses does the reusable bottle use less energy?
13. Outline the features of Shanghai's waste-sorting scheme and suggest why it changed behaviour.
14. Evaluate two strategies for reducing plastic waste.

Answers.

1. (a) Renewable stocks or recurring flows are replenished on relevant timescales; non-renewable resources form or are replaced too slowly relative to use. Harvest can exceed regeneration, as with fish or groundwater. Soil and fossil groundwater may be effectively non-renewable on planning timescales; a renewable label does not guarantee sustainable extraction. (b) Value depends on technology, culture, economics and substitutes. Uranium's role changed with fission; lithium demand rose with rechargeable batteries; whale oil lost its lighting role as alternatives spread. Market price does not capture all intrinsic, cultural or ecological values.
2. **AHL:** Reduce primary demand through efficiency, durability and suitable substitution; repair, reuse and recycle with attention to losses and energy. Diverse supply improves security but does not by itself make extraction sustainable. (b) R/P=40 years only if values remain fixed. Discovery, recovery, prices, technology, policy and demand can change them; climate constraints may limit use before exhaustion.
3. $505/620\times100=81.45\%$, about 81.5%, under the dated report accounting. These are primary-energy quantities, not electricity shares.

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4. **AHL:** Generally low lifecycle carbon and high availability with small fuel mass; assess mining, cooling, waste, accidents, build time, financing, decommissioning and alternatives under the same output boundary. Not zero-impact, absolutely constant or guaranteed cheapest. (b) Lithium is not a rare earth; LFP chemistry has no cobalt. Material requirements vary. Collection and recovery efficiencies multiply: $80\% \times 90\% = 72\%$ overall; uncollected stock cannot be recovered by a plant alone.
5. PV is scalable and needs sunlight; compare weather, minerals, land and recovery. Reservoir hydro can store water and be dispatchable, but drought, inundation, displacement, fish and sediment matter. Run-of-river hydro has different flexibility. Choose using the place and required service.
6. Variable output may not match demand. Batteries or pumped storage shift energy with losses and limited power/duration; interconnections, flexible demand and suitable dispatchable generation can also help. No one measure guarantees unlimited backup.
7. (a) Any four: available resources; cost and technology; energy security; environmental concerns and climate agreements; public opinion and politics; values. (b) Affordable, reliable access over time, not necessarily self-sufficiency. Diversified sources, efficiency, storage and resilient grids can reduce vulnerabilities; domestic hydro can still face drought and imports can sometimes spread risk.
8. Income often correlates with per-person waste and packaging shares, but diet, policy, technology, season, collection and definitions also matter. Organic waste can be substantial across societies. Compare dated per-person mass and matching category definitions; avoid treating each income group as uniform.
9. Persistence and fragmentation can cause ingestion, entanglement and ecological effects, with difficult recovery. Lifetimes differ by polymer and environment. OECD estimated 9% of 2019 plastic waste ultimately recycled. Microplastic detection establishes exposure, not by itself a specific health outcome.
10. Engineered landfill contains residuals but needs liners, leachate treatment, gas management and long-term monitoring. Incineration reduces volume and may recover energy but needs emissions controls, ash management and consistent evaluation of fossil carbon. Compare local conditions, costs and impacts; neither eliminates all waste.
11. Prevent/reduce, reuse, recycle/compost, recover energy, dispose of residuals. Prevention can avoid extraction, production and treatment burdens; recycling still needs collection and energy and loses material. Hazardous contamination or hygiene can limit recovery; uncontrolled dumping is not preferable to safe disposal.
12. $1500+15n<90n$ gives $n>20$; the first whole-number use is 21. At 20 uses the energy totals are equal, not lower. This boundary counts production and one wash per use, not every lifecycle impact.
13. Regulation effective July 2019 requires recyclables, hazardous, wet/food and dry/residual streams. Facilities, labels, education, monitoring and penalties can

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change incentives. Verify downstream treatment and contamination; before/after collection totals alone do not prove causation or complete recycling.

14. Charges/restrictions can cut targeted demand but shift burdens to other materials. Deposits can improve collection if accessible facilities and processing exist. Producer responsibility can fund collection/design but depends on coverage, fees and enforcement. Judge actual reductions, lifecycle effects, leakage, cost and equity.

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Human populations and urban systems

International Baccalaureate · IB Diploma · Environmental Systems and Societies · HL

Scope and prerequisites

This handout teaches Topic 8, Human populations and urban systems (8.1 Human populations, 8.2 Urban systems and urban planning, 8.3 Urban air pollution), for the course first assessed in 2026. Common sections teach SL understandings; separate higher-level extensions develop migration, planning and atmospheric chemistry. Sections marked **AHL** are for Higher Level only. Numerical datasets described as are teaching examples, not observations or past-paper questions.

Prerequisites: Topic 1 (systems, inputs and outputs, ecological footprint, sustainability), Topic 2 (population growth curves and carrying capacity) and Topic 6 (the atmosphere, greenhouse gases and stratospheric ozone).

Human populations

A country that started to shrink

China's 2024 national statistical communiqué reports 9.54 million births and 10.93 million deaths, giving a natural decrease of 1.39 million. Births increased from 2023 even while the population declined: birth totals and population change are different measures. Ageing also changes needs for workers, care and infrastructure. Compare dates, age structure, migration and access to services rather than treating every country as following one fixed path.



A crowded city crossing: human population dynamics depend on birth rates, death rates and migration

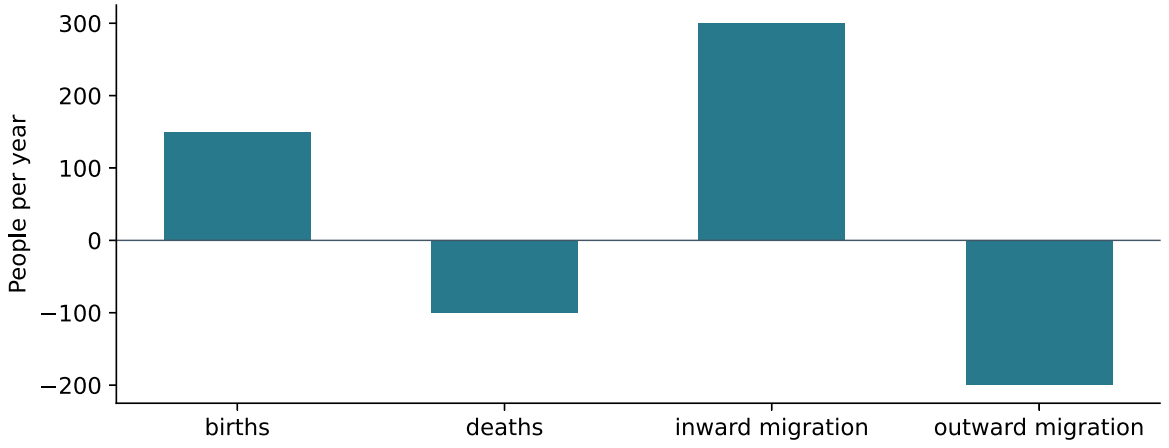
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Projections depend on assumptions

The UN's 2024 population projection placed the global peak around 10.3 billion in the mid-2080s under its central assumptions. This is a dated conditional projection, not an observed future or a permanent current count. Fertility, mortality and migration assumptions can change the result. Regional and national trends differ; a national average also hides differences among age groups and communities.

Measuring population change

A population changes through four flows: births and **immigration** 迁入 add people; deaths and **emigration** 迁出 remove them.



Change = births − deaths + immigration − emigration = +150 people, 1.5% of 10,000

Demographers compare populations of different sizes with rates:

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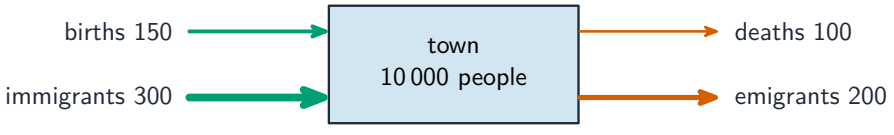
Measure	Meaning	How to calculate
Crude birth rate 粗出生率 (CBR)	Live births per 1000 people per year	births ÷ population × 1000
Crude death rate 粗死亡率 (CDR)	Deaths per 1000 people per year	deaths ÷ population × 1000
Natural increase rate 自然增长率 (NIR)	Growth from births and deaths only, as a percentage	(CBR − CDR) ÷ 10
Doubling time 倍增时间	Years for a population to double at a constant growth rate	70 ÷ growth rate in %
Total fertility rate 总和生育率 (TFR)	Expected births per woman if current age-specific fertility rates applied throughout her reproductive life	from age-specific birth rates

A period TFR is a synthetic measure from current age-specific birth rates, not the completed family size of every woman. **Replacement level** 更替水平 is often approximately 2.1 in low-mortality populations, allowing for survival and the sex ratio at birth; it is higher where mortality is greater. It is not a universal exact threshold. Age structure creates population momentum: growth can continue for a time below replacement, and migration also changes totals. Long-term conclusions require stated mortality, fertility and migration assumptions.

Note that CBR and CDR are "crude" because they ignore the age structure. A country with many old people can have a high death rate even though healthcare is good.

■ Worked example: rates from a town

A town with a mid-year population of 10 000 has 150 births, 100 deaths, 300 immigrants and 200 emigrants in one year.



natural increase $150 - 100 = +50$ (0.5%); migration $300 - 200 = +100$
total $+150$ people $= 1.5\%$ a year; doubling time $\approx 70/1.5 \approx 47$ years (invented)

Flows into and out of a town: migration triples the growth

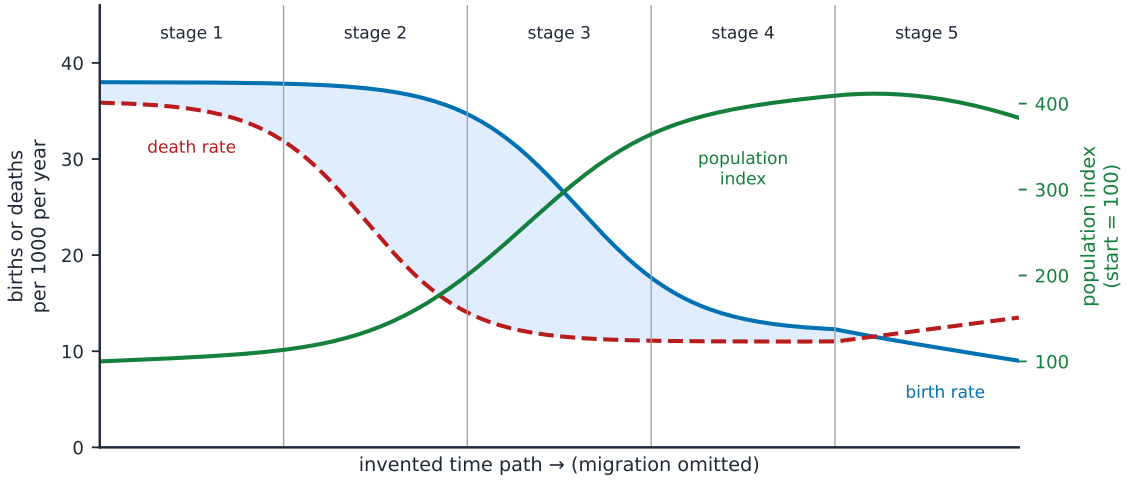
1. CBR $= 150 \div 10\,000 \times 1000 = 15$ per 1000.

2. CDR = 100 ÷ 10 000 × 1000 = 10 per 1000.
3. NIR = (15 − 10) ÷ 10 = 0.5 %.
4. Total change = 150 − 100 + 300 − 200 = +150 people, which is 1.5 % growth.
5. Approximate doubling time if total growth stays at 1.5 % = 70 ÷ 1.5 ≈ 47 years.

Migration makes this town grow three times faster than natural increase alone. Many cities grow mainly through migration.

The demographic transition model

The **demographic transition model** 人口转变模型 (DTM) describes how birth and death rates have changed as countries develop.



The demographic transition model (schematic)

Stage	Birth rate	Death rate	Population	Reasons
1	High	High, varies	Small, stable	Famine, disease, no healthcare; children needed for work
2	High	Falls fast	Grows fast	Better food supply, clean water, sanitation, vaccines
3	Falls	Low	Growth slows	Contraception, education and jobs for women, urban living, lower infant mortality
4	Low	Low	Large, stable	Children are costly; people marry later
5	Very low	Rises slightly	May decline	Ageing population; many choose few or no children

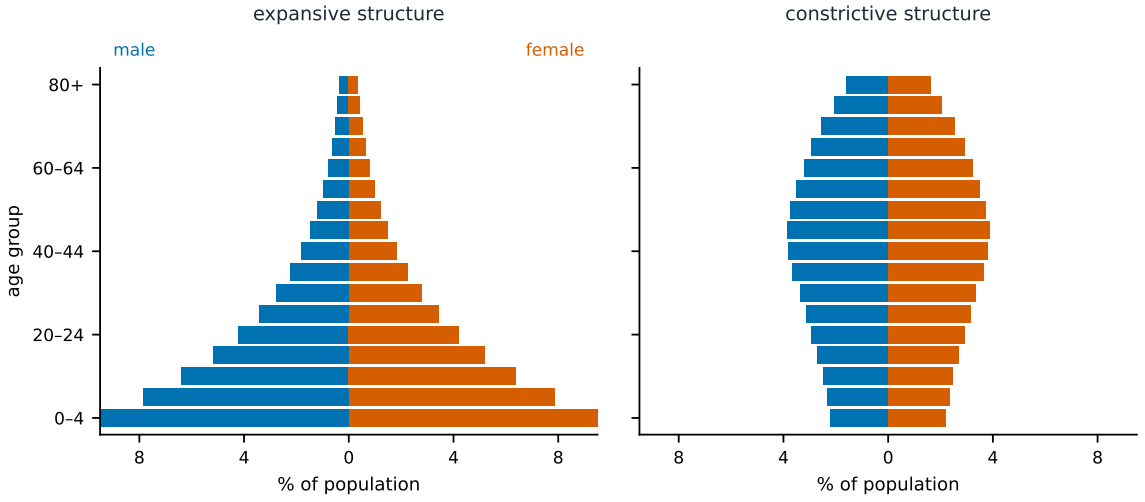
Stages summarise patterns rather than assigning every country a permanent rank. The schematic does not include migration or predict transition dates; fertility, mortality,

policy and age structure vary within countries. A fifth stage is an extension often used to discuss sustained natural decrease, not an inevitable destination.

Limits of the model: it was based on Europe, where the transition took about 200 years; many countries now pass through it much faster because medicine arrived suddenly. It ignores migration, and it does not show government policies or diseases such as HIV/AIDS that raised death rates in some African countries.

Age-sex pyramids

An **age-sex pyramid** 人口金字塔 shows numbers or percentages in stated age groups, males on one side and females on the other.



Expansive and constrictive age structures (percentages; shape alone does not prove growth)

- An **expansive** pyramid has a relatively wide young-age base, consistent with large recent birth cohorts and possible growth momentum; migration and survival also affect the shape.
- A roughly **stationary** pyramid has similar-sized successive cohorts before older-age mortality narrows the top; it is consistent with relatively stable recent births, but migration can alter it.
- A **constrictive** pyramid has relatively small young cohorts and a wider middle; fewer recent births, survival and selective migration can all contribute.

The **dependency ratio** 抚养比 below compares conventional age groups, not actual employment:

$$\text{dependency ratio} = \frac{\text{people aged 0–14} + \text{people aged 65 and over}}{\text{people aged 15–64}} \times 100$$

A larger child or older-age share can increase demand for different services. People aged 15–64 are not all employed, and people outside that band may work; productivity,

retirement rules and participation affect economic support. A pyramid alone does not directly measure birth rate or life expectancy.

Population policies

Governments try to change birth rates with **pronatalist** 鼓励生育 policies (to raise them) or **antinatalist** 限制生育 policies (to lower them).



China's birth policies moved from antinatalist towards pronatalist

- **China.** Birth restrictions under the one-child era were followed by the two-child policy in 2016 and three-child policy in 2021. Evaluate fertility alongside education, living costs, pre-existing trends and reproductive rights. Restrictions and coercive enforcement had serious human costs; an observational national trend cannot measure the policy's effect by itself. Ageing and a male-biased sex ratio also have multiple causes.
- **Singapore.** The Baby Bonus scheme has offered financial support to eligible families; the official service now announces transition into the SG Child Support Package. Date the policy version rather than assuming benefits never change. It is a pronatalist example, not evidence that a cash payment alone produces a particular fertility rate. Compare eligible groups, timing, childcare, housing and employment conditions.
- **Voluntary family planning.** Access to contraception and reproductive healthcare can help people choose family size. A falling national fertility rate is not automatically evidence of coercion, and a numerical population target does not override consent or equal rights.

Education, reproductive autonomy, voluntary contraception, child survival and economic opportunities can influence fertility. Associations vary by context and do not establish one cause or rank every policy without evidence.

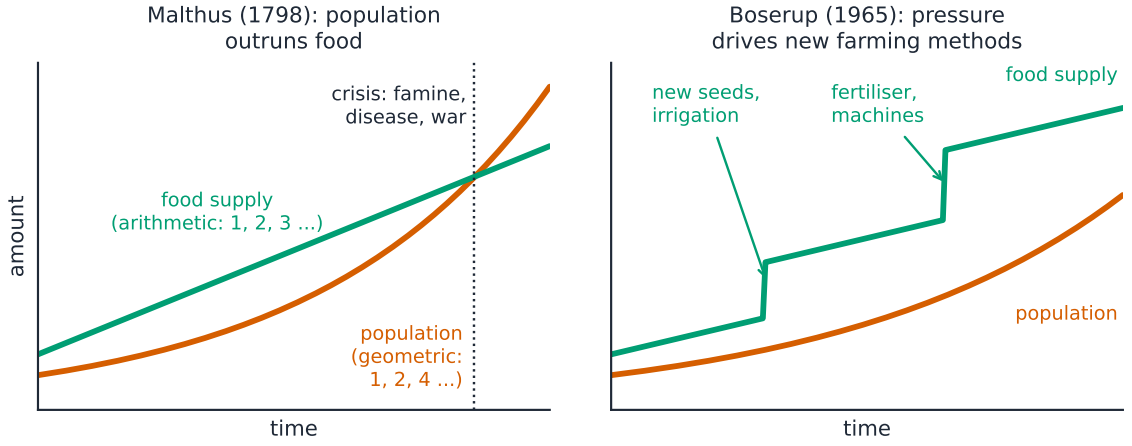
Policies that change population indirectly

Two examples illustrate mechanisms rather than single-cause explanations. In **Bangladesh**, girls' education and employment opportunities developed alongside family-planning services; the World Bank's historical analysis discusses both education and service delivery in fertility decline. Education policy changes opportunities and desired timing of births; it is not a birth quota. In **Kerala, India**, education, public health and child survival are discussed together in the state's 2026 development report. Better survival can reduce the perceived need for extra births, while schooling

and social support alter choices. Neither example proves education alone caused the observed trend. Evaluate access, autonomy and wellbeing as well as the birth count.

Population and the environment

Is a larger population a problem? Two classic views:



- **Thomas Malthus** (1798) argued that population grows faster than food supply, so famine, disease and war would eventually limit numbers.
- **Ester Boserup** (1965) argued that "necessity is the mother of invention": population pressure drives new farming methods, so food supply rises to meet demand. The Green Revolution (Topic 5) seems to support her.

Neither view is complete. The impact of a population depends on how many people there are **and** how much each person uses. One way to show this is the equation $I = P \times A \times T$: impact equals population times affluence (consumption per person) times technology (impact per unit consumed).

The **ecological footprint** 生态足迹 estimates demand on biologically productive area under a stated accounting method; biocapacity measures ecological supply. A dated footprint/biocapacity ratio can express overshoot, but it does not directly measure every pollutant, biodiversity effect or human **carrying capacity** 承载力. Trade, technology, consumption and ecological constraints alter the population a place can support. IPAT is an accounting framework only when its quantities and units are defined consistently; it does not imply every person has equal impact or technology has no limits.

Urban systems and urban planning

The rise of cities

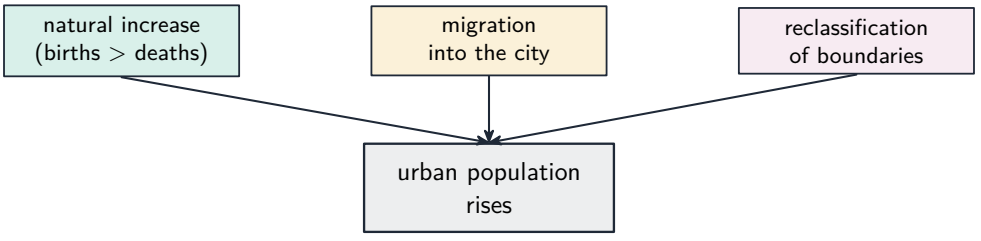
Urbanisation 城市化 is an increasing urban share of population; urban growth is an increase in urban population or built area. Definitions of urban boundaries differ among countries and datasets. Natural increase, migration and reclassification can all

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change the count. Compare maps at the same scale and boundary before attributing expansion only to migration. Cities contain ecosystems with plants, animals, soils, water, air and microclimates as well as infrastructure.



An informal settlement (favela) on a hillside in Rio de Janeiro, built where housing and services could not keep up with fast urban growth



compare maps at the same scale and boundary before blaming migration alone

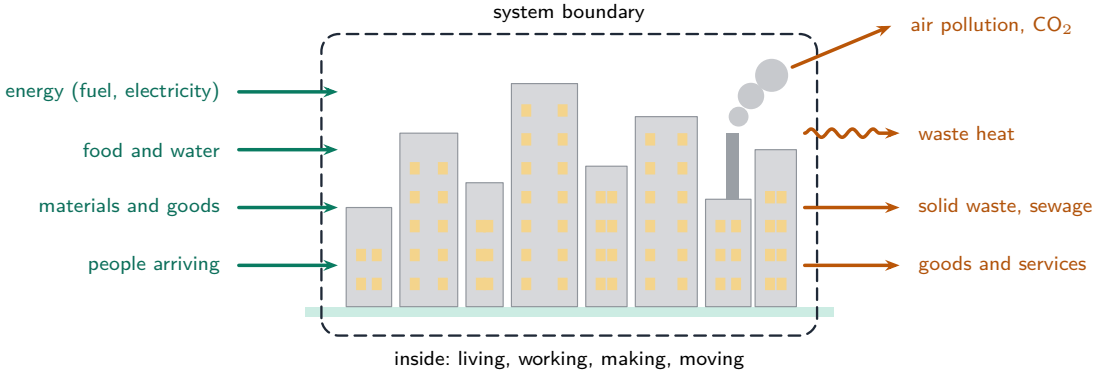
Three ways an urban population count rises

People move to cities because of **push factors** 推力因素 in the countryside (few jobs, poor services, low farm incomes, drought) and **pull factors** 拉力因素 in cities (jobs, higher wages, schools, hospitals, entertainment). A **megacity** 特大城市 commonly means an urban agglomeration with at least 10 million people; totals depend on the year and boundary, not simply administrative city limits.

Suburbanisation is movement towards lower-density urban edges. **Counter-urbanisation** 逆城市化 is movement away from larger urban areas towards smaller settlements or rural places; it is not identical to suburbanisation. Costs, work, transport and preferences affect both, and neither occurs only in wealthy countries.

A city as a system

A city is an **open system** 开放系统: it takes in energy, food, water, materials and people from a much larger area, transforms them, and sends out products, wastes and pollution.



A city exchanges energy and matter with a wider region

A city's resource demand extends beyond its built boundary through food, energy, water and materials. A footprint depends on consumption, trade, population, year and method; it is not a fixed multiple of city area. Distinguish energy flows from material stores and transformations when drawing the system boundary.

Cities change their local environment:

- **Urban heat island** 城市热岛: concrete and asphalt absorb heat, buildings block wind, and vehicles and air conditioners release waste heat, so cities can be several degrees warmer than the countryside, especially at night.
- **Impermeable surfaces** 不透水表面 make rain run off quickly, raising flood risk (the problem that China's sponge cities, Topic 6, address).
- Habitat is lost and split up as cities spread outward (**urban sprawl** 城市蔓延), often onto good farmland.

Urban problems

Fast urban growth brings problems, especially where services cannot keep up:

- **Informal settlements** 非正规住区 can lack secure tenure, safe housing or reliable services; conditions differ, so do not assume that every informal settlement lacks every service.
- Traffic congestion and air pollution.
- Solid waste and sewage that are not collected or treated.
- Water shortages and lost farmland.

Sustainable urban planning

Urban planning 城市规划 decides how land in a city is used and how the city grows. A **sustainable city** 可持续城市 meets the needs of its people without degrading the environment or the needs of future residents. Common strategies:



Urban sprawl at the city edge: human–environment interaction reshapes landscapes

Strategy	How it helps	Example
Compact, mixed-use design	Shorter trips; less land taken	Homes, shops and offices together in one district
Public transport	Fewer cars, less pollution and congestion	Curitiba's bus rapid transit (Brazil); China's metro systems
Green belts and green space	Limit sprawl; cool the city; habitats	London green belt; urban parks and green roofs
Energy-efficient buildings	Lower energy demand and emissions	Insulation, solar panels on roofs, district heating
Water-sensitive design	Store rainwater; reduce flooding	Sponge cities such as Wuhan
Waste recovery	Less landfill	Shanghai's sorting scheme (Topic 7)

Case study: Freiburg, Germany. Vauban's municipal energy documentation distinguishes low-energy and passive-house buildings: not every home meets the identical standard. Redevelopment of a former military site, transit access, cycling, reduced car dependence and efficient buildings illustrate complementary measures. Compare affordability, actual travel, operational and embodied energy, accessibility and who benefits; design targets alone are not achieved outcomes.

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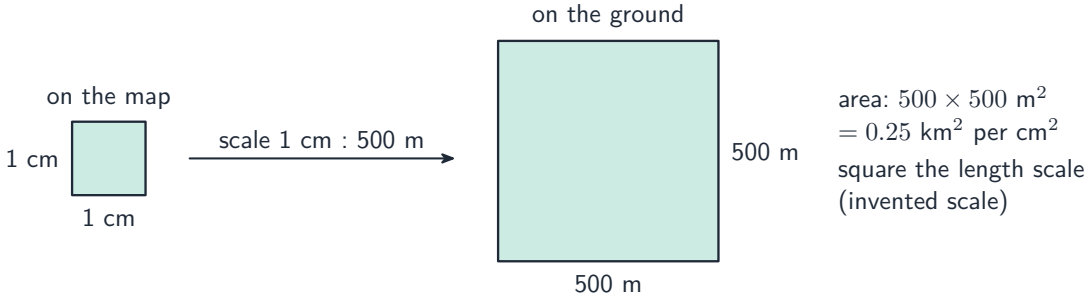
Evaluate an eco-city proposal. Ask whether residents can afford housing, reach jobs and maintain installed systems. Report actual occupancy and measured water, energy and transport outcomes separately from design targets. A successful pilot does not establish that the same design will work in another climate or housing market.

Measuring urban sustainability

Indicators help compare cities and track change: PM2.5 concentration, green space per person, public-transport share of trips, recycling rate, water use per person and the share of homes with sanitation. An **indicator** 指标 measures one specified condition; no single indicator shows how sustainable a whole city is, and an average can hide unequal access between rich and poor districts.

Read a map and test a planning proposal

Compare dated maps with the same scale, legend and boundary. Measure built area, habitats and permeable surfaces; identify fragmentation as well as total green area. Use a scale bar to convert map length to ground distance, then square that conversion for area. Satellite appearance alone does not show housing security, affordability or biodiversity quality. Combine spatial evidence with service, ecological and resident data, protecting privacy and including people whose needs are often missed.



Square the length scale to convert map area

In an **invented** district, population rises from 100 000 to 120 000 while urban population rises from 60 000 to 66 000. Urban numbers grow by 10%, but the urban share falls from 60% to 55%: this is urban growth without urbanisation. In another storm comparison, 10 mm of rain falls on 1 square kilometre. The rainfall volume is $0.010 \times 1\,000\,000 = 10\,000$ cubic metres. If runoff fractions are 0.8 for a sealed site and 0.3 for a vegetated site, runoff is 8000 versus 3000 cubic metres. This simple model omits storage, infiltration capacity, slope and changing rainfall intensity; it illustrates why land cover matters, not a site-specific flood forecast.

A plan must connect physical land use, housing, employment, commerce, finance, education and health services. Green roofs, wetlands and urban farming can link habitat, cooling, drainage and food learning; they still need suitable soils, water, safety and maintenance. Regenerative design aims to restore ecological functions, not merely

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install a visible green feature. Indicators should include reliability and distribution: a park that residents cannot safely reach provides less practical access than its mapped area suggests.

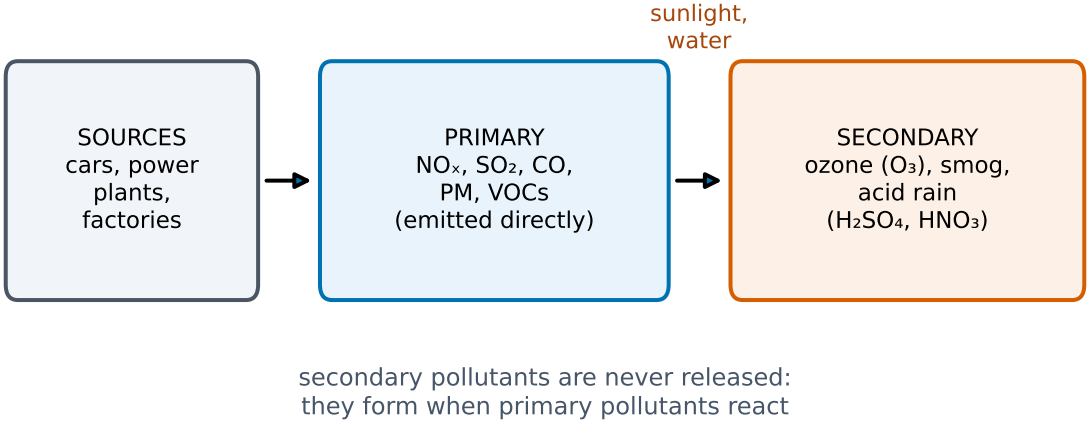
Urban air pollution

Primary and secondary pollutants

Burning fossil fuels in vehicles, power stations, factories and homes releases **primary pollutants** 一次污染物, which are emitted directly:



Haze over Salt Lake City: exhaust from cars and industry, trapped over the valley, hides the skyline



Primary pollutants are emitted directly; secondary pollutants form in the air

- carbon monoxide (CO), from incomplete combustion;

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- nitrogen oxides (NO and NO_2, together called NO_x), from high-temperature combustion in engines;
- sulfur dioxide (SO_2), from burning coal and oil that contain sulfur;
- **particulate matter** 颗粒物 such as soot and dust: PM10 includes particles with aerodynamic diameters up to 10 micrometres, and PM2.5 up to 2.5 micrometres; PM2.5 is a subset, not an additional disjoint category;
- **volatile organic compounds** 挥发性有机物 (VOCs), such as unburnt fuel and solvents.

Secondary pollutants 二次污染物 form through atmospheric reactions: examples include tropospheric ozone, sulfuric and nitric acids, and particulate sulfates and nitrates. Some particles are emitted directly and others form later. Natural sources include wind-blown dust, wildfires and volcanic emissions; natural origin does not mean harmless. Fine particles can enter the lungs deeply, while exposure and toxicity depend on concentration, composition and duration.

Exposure can damage respiratory and cardiovascular health, affect plants and reduce visibility. Distinguish the amount emitted per time from the concentration people breathe: dilution, atmospheric chemistry and weather connect them. Tropospheric ozone is harmful near the ground even though stratospheric ozone protects against ultraviolet radiation.

■ Acid deposition

SO_2 and NO_x dissolve in water in the air and are oxidised to sulfuric and nitric acids. These fall as acid rain, snow or fog (**wet deposition**) or as dry particles and gases (**dry deposition**), together called **acid deposition** 酸沉降. Effects include acidified lakes that lose fish, damaged forests (aluminium released from soil harms roots), and weathered buildings made of limestone and marble. Acid deposition is a **regional** problem because pollution travels hundreds of kilometres downwind: in the 1970s and 1980s acid rain from British and German power stations damaged lakes in Norway and Sweden, and in the 1990s and 2000s parts of southern China received heavy acid rain from coal burning.

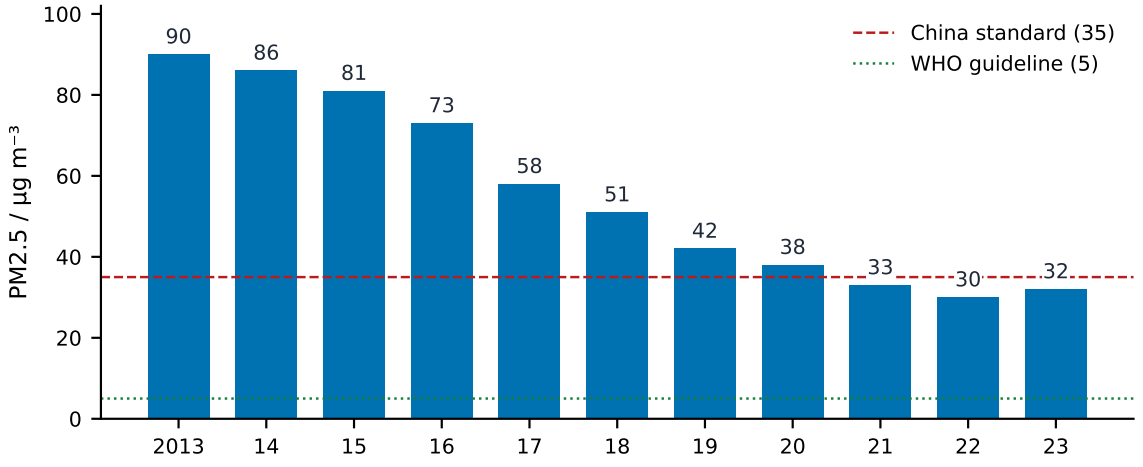
■ Managing urban air pollution

The three levels of pollution management (Topic 1) apply:

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Level	Examples
Change the human activity	Public transport, cycling, car-free zones, switching from coal to renewables, working from home
Control the release of pollutants	Catalytic converters, flue-gas desulfurisation (scrubbers), electrostatic precipitators, emission standards, low-emission zones
Clean up and restore	Liming acidified lakes; replanting damaged forests; healthcare and restoration of damaged habitats

Case study: Beijing. The city's 2023 environment report and official summary give annual mean PM2.5 of 32 micrograms per cubic metre, down 64.2% from 2013. The rounded graph below shows the long-term improvement and a small rise from 2022 to 2023. Measures included cleaner heating, industrial and vehicle emission controls, and regional cooperation. A before/after trend supports evaluation but does not isolate each measure from weather and changes in activity.

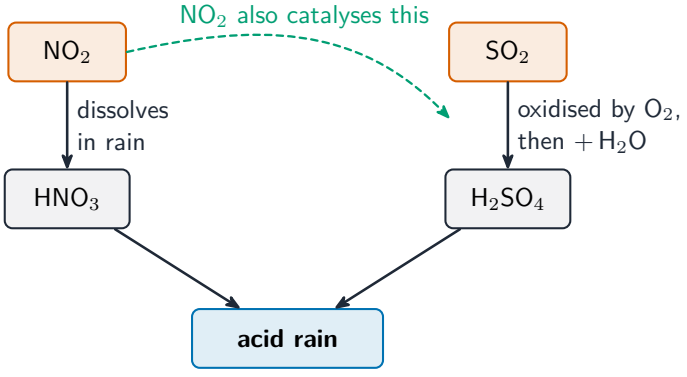


Dated annual averages, not daily peaks; China Grade II annual PM2.5 limit 35 and WHO 2021 annual guideline 5 are different benchmarks.

Using rounded endpoints, the reduction is $(90 - 32)/90 \times 100 = 64.4\%$; the official 64.2% uses unrounded data (2013: 89.5). The 2023 value is $32/5 = 6.4$ times the WHO annual guideline. Meeting one legal concentration limit does not mean zero health risk or meeting every pollutant standard. Evaluate affordability of heating, worker transitions, displacement of emissions and effects in neighbouring places as well as city averages.

Acid chemistry and ecological effects

Useful balanced **net** reactions are $2SO_2 + O_2 + 2H_2O \rightarrow 2H_2SO_4$ and $4NO_2 + O_2 + 2H_2O \rightarrow 4HNO_3$. They summarise products, not single atmospheric reaction steps. Oxidants and liquid droplets affect the actual pathways. Acidification can mobilise aluminium and leach calcium and magnesium from soils, damage roots and reduce aquatic reproduction; buffering by local geology changes sensitivity. Nitrogen deposition can also fertilise ecosystems and alter species composition. Air pollution affects organisms as well as people.



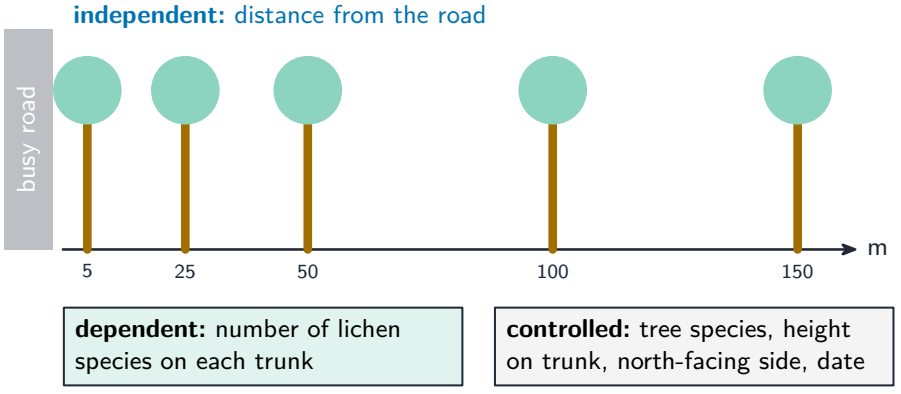
Nitrogen and sulfur oxides make acid rain: NO_2 forms nitric acid directly and also catalyses the oxidation of SO_2 to sulfuric acid

Liming an acidified lake neutralises some acidity: $CaCO_3 + 2H^+ \rightarrow Ca^{2+} + CO_2 + H_2O$. It treats an effect and may need repeating; it does not stop the upwind emission source. Scrubbers mainly remove sulfur dioxide, catalytic converters target selected vehicle gases, and particle collectors remove particles. No one device removes every pollutant. Trees may cool and intercept particles, but species, maintenance and street ventilation matter; dense planting in a narrow street can restrict dispersion.

Investigating air quality safely

Use existing calibrated monitors or an approved passive sampling method; never expose people deliberately to exhaust. To investigate lichens as biological indicators, record species presence or percentage cover in equal-sized quadrats on comparable tree species, bark aspect and height. Sample several trees at each distance from a road, using a consistent selection method, season and identification guide. Avoid damaging protected organisms. Include background sites and record moisture, shade, bark pH and nearby land use: these can influence lichens independently of pollution.

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The lichen plan: one variable changed along the transect, one measured, the rest standardised

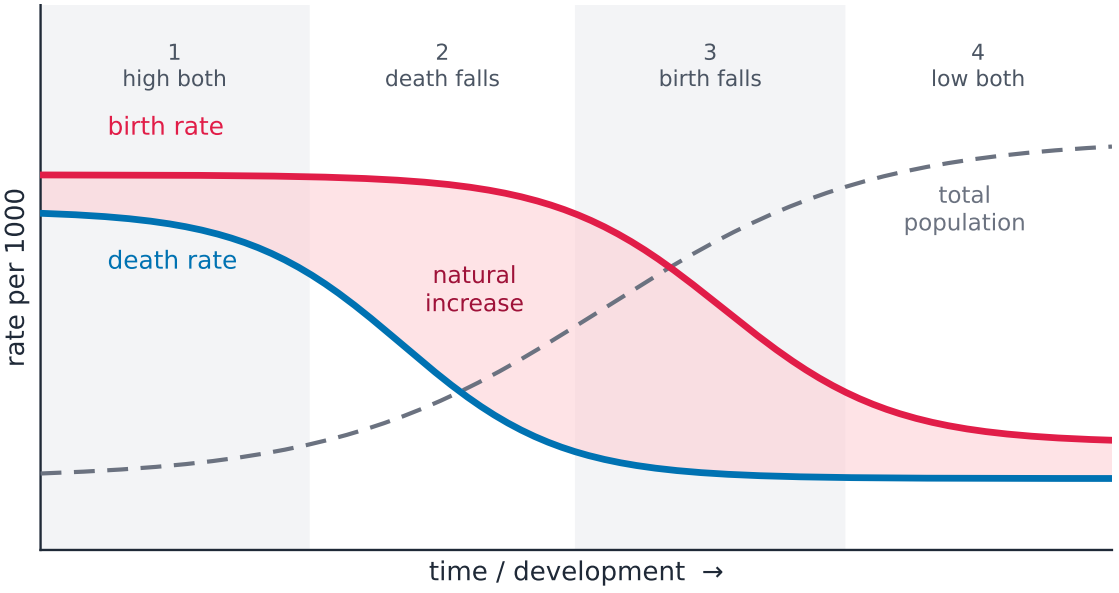
Lichens integrate conditions over time but do not measure a particular gas concentration directly. Compare their pattern with monitored pollution; a correlation is evidence consistent with a relationship, not proof that one pollutant caused the difference. Instrument calibration, repeated observations and uncertainty must accompany an air-quality comparison. A health warning reduces exposure rather than cleaning the outdoor air; distinguish exposure management from emissions prevention and ecosystem restoration.

AHL: Population pressure, migration and evidence

■ Demographic momentum and environmental impact

Population momentum follows age structure. A large cohort entering reproductive ages can produce many births even when births per woman fall; later, a small cohort can produce fewer births at the same fertility rate. Compare age-specific fertility, survival and migration, not only period TFR. Global projections are conditional models: compare central and alternative assumptions at the same 50- and 100-year horizons, including uncertainty. Do not extend a current growth rate as if it were a guarantee. The UN 2024 central projection's peak near the mid-2080s is consistent with slowing and later declining global totals, not endless exponential growth.

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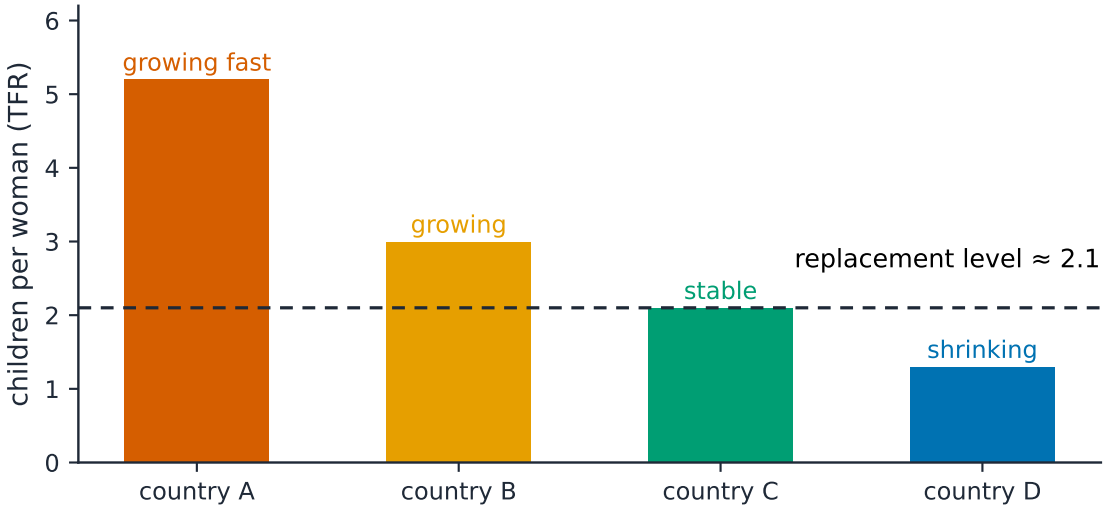
The four stages of the demographic transition

Population growth can increase demand for food, freshwater, energy, land and waste treatment, but unequal consumption and technology modify the stress. In an IPAT comparison, population rises 20%, consumption per person rises 10% and impact per consumed unit falls 25%. The combined multiplier is $1.20 \times 1.10 \times 0.75 = 0.99$, so modelled impact falls 1%, not 5% from simply adding percentages. Define the chosen impact and its units: a reduction in carbon intensity need not reduce habitat loss or water stress.

■ Compare countries across time, not permanent stage labels

China and Niger illustrate different demographic trajectories. Compare the UN World Population Prospects age structures and birth/death series around 1990, around 2024 and projected around 2060: the last is a scenario, not an observation. China experienced falling fertility before the one-child era and later large cohorts moving into older ages; its low fertility and ageing contribute to natural decrease. Housing, work, education, reproductive policy and family preferences interact, so a stage 5 label is a summary, not an explanation. Niger has had a much younger structure and higher fertility, so falling mortality with large birth cohorts supports strong growth and school demand. Access to education, voluntary reproductive healthcare, child survival, rural livelihoods and social expectations affect that path; do not equate one religious or cultural identity with one fertility outcome.

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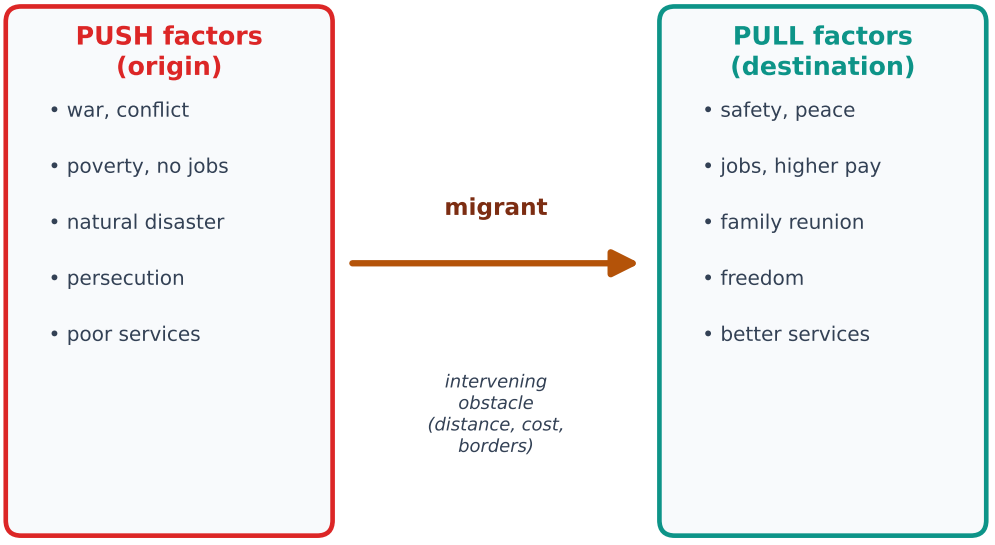
Total fertility rate compared with the replacement level of about 2.1

The WHO Niger profile explicitly labels its 2023 estimate and 2050 projection from the UN 2022 series; that edition projects roughly a doubling, but 2050 is not a 30-year forecast from 2026. Use the newer UN series consistently for a 2060 comparison rather than silently mixing revisions. Compare youth and older-age shares, absolute cohort sizes, service demand and conditional migration/fertility assumptions. Neither country's future is fixed by its present pyramid.

For a 50-year versus 100-year horizon, uncertainty compounds: a small annual rate difference changes several generations. An **sensitivity calculation**, not an UN forecast, starts at an index of 100. At constant 0.5% growth, 50- and 100-year indices are $100(1.005)^{50} \approx 128.3$ and $100(1.005)^{100} \approx 164.7$; at 1% they are about 164.5 and 270.5. Constant-rate extrapolation omits demographic transition and constraints. WPP 2024 provides projections to 2100; do not label a value beyond that endpoint as an official 100-year forecast from today. Identify the source's horizon and say where evidence ends. Population demand, biocapacity and the doughnut's social and ecological boundaries must be evaluated together, not inferred from a head count.

■ Migration in a connected world

Migration can be internal or international, temporary or permanent, relatively voluntary or forced. Global labour markets, transport and communication link origin and destination. Remittances can support households, while loss of skilled workers may affect services at origin; destination economies gain workers but housing and public services may face pressure. Effects differ among groups, and migrants have rights rather than being only population inputs. Environmental hazards interact with employment, assets, conflict, adaptation and government policy: not everyone exposed can afford to move.



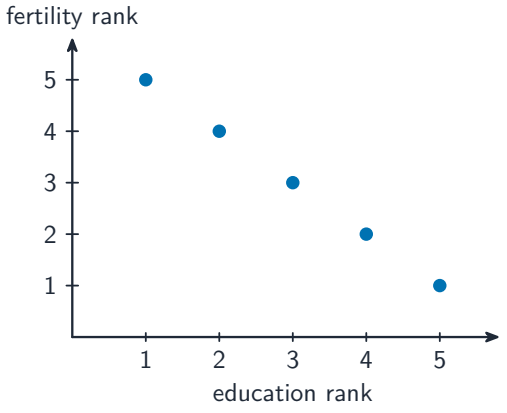
Migration decisions weigh push factors against pull factors, across an intervening obstacle

Named example: Mozambique after Cyclone Idai, 2019. IOM's displacement monitoring documents people displaced after the cyclone and continuing needs months later. Use this as evidence of disaster-related displacement, largely within the country, rather than labelling every move an international climate-refugee movement. Short-term evacuation, longer displacement and permanent migration are different. Safe housing and drainage at destinations, restoration of livelihoods and participation in relocation decisions affect recovery. A cyclone's occurrence alone cannot attribute an individual migration decision entirely to anthropogenic climate change.

A small secondary-data investigation

Ask whether fertility is associated with a defined education measure across comparable regions. Select one year, compatible boundaries, sampling rules and a documented source; missing values must be reported. Draw a scatterplot, check for outliers and consider a rank association when only order is defensible. Regions have education ranks 1, 2, 3, 4, 5 and fertility ranks 5, 4, 3, 2, 1. Rank differences are -4, -2, 0, 2, 4; their squared sum is 40. With no tied ranks, $r_s = 1 - 6(40)/(5(5^2 - 1)) = -1$. This means perfectly inverse rank order in these five observations, not a causal effect, a slope or a universal law. Real ties require an appropriate tie method; income, healthcare, policies and shared histories can confound comparisons. A country-level correlation cannot establish what happens within every household.

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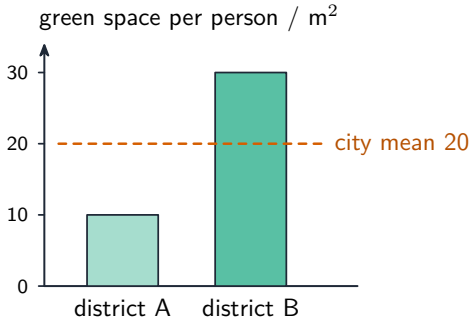


Perfectly reversed ranks give r_s = -1 across regions

AHL: Ecological urban planning and justice

Compact development can protect surrounding land and support frequent public transport. Mixed land use puts homes, shops and jobs near one another; social mix aims to include different incomes and needs rather than separating access to services. Density alone does not guarantee low emissions or wellbeing: overcrowding, poor ventilation, unaffordable housing and inadequate open space can undermine the benefits. Plan safe walking and cycling, accessible transport, affordable homes and reliable services together.

Environmental justice asks who receives benefits, who bears costs and who participates in decisions. In districts An and B, green space is 10 and 30 square metres per person. Even if their equal populations give a city mean of 20, residents have unequal provision. Public access, shade, habitat quality and walking routes matter as well as area. A new park can raise nearby rents and displace the people intended to benefit; protect housing access and involve residents, including disabled people and informal workers. Report distribution before and after a project, not only an improved city average.



Equal populations, unequal provision - the city mean of 20 square metres per person hides districts with 10 and 30

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Named circular-economy example: Amsterdam. The city's Circular Strategy 2020–2025 uses a doughnut approach: meet social needs while respecting ecological limits. It connects food and organic materials, consumer goods and the built environment. Repair, shared use, procurement and reuse can reduce demand for virgin materials, but collection is not the same as successful reuse. Measure actual material flows and lifecycle effects, including imported impacts. A city adopting a framework has not thereby achieved its goals; some material and energy losses remain and growing consumption can offset efficiency.

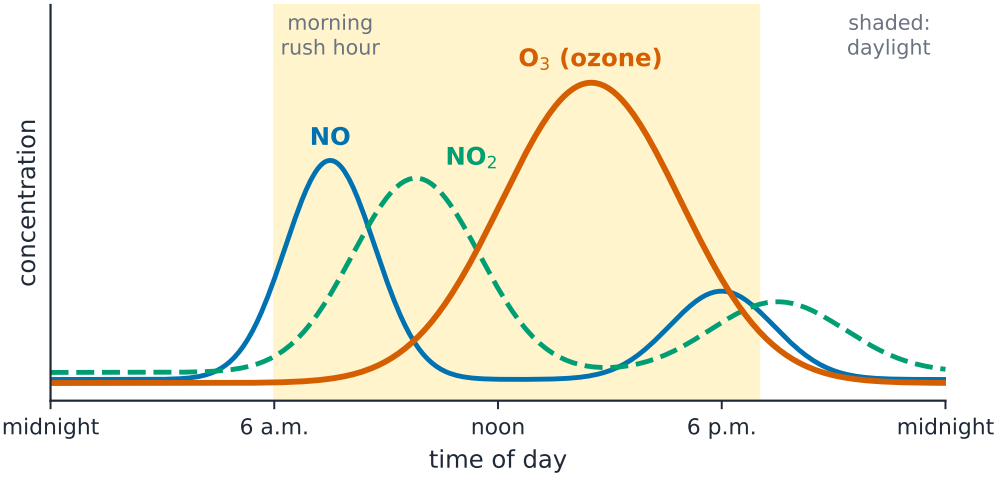
■ Buildings that respond to climate

Green architecture combines operational efficiency, material choices, water, habitat, comfort and access over the building's life. Reuse of an existing building may avoid new embodied emissions; compare maintenance and renovation with operating-energy savings. Solar shading, insulation, ventilation and thermal mass must fit local weather and occupancy. Vernacular designs offer tested local approaches, not a universal blueprint. A windcatcher can capture air movement and support ventilation; evaporation can cool air where water and dry conditions allow, with water-use and humidity limits. Vauban's documented low-energy and passive-house approaches illustrate modern envelope and energy design. Do not equate a green appearance, a design certificate or a solar panel with measured whole-life sustainability.

AHL: Photochemical smog and atmospheric stability

■ Photochemical smog and tropospheric ozone

Photochemical smog 光化学烟雾 is a brown haze that forms on sunny days in cities with heavy traffic, such as Los Angeles, Mexico City and many Chinese cities in summer.



Daily smog cycle: NO peaks at morning rush hour, NO2 about two hours later, and ozone in mid-afternoon

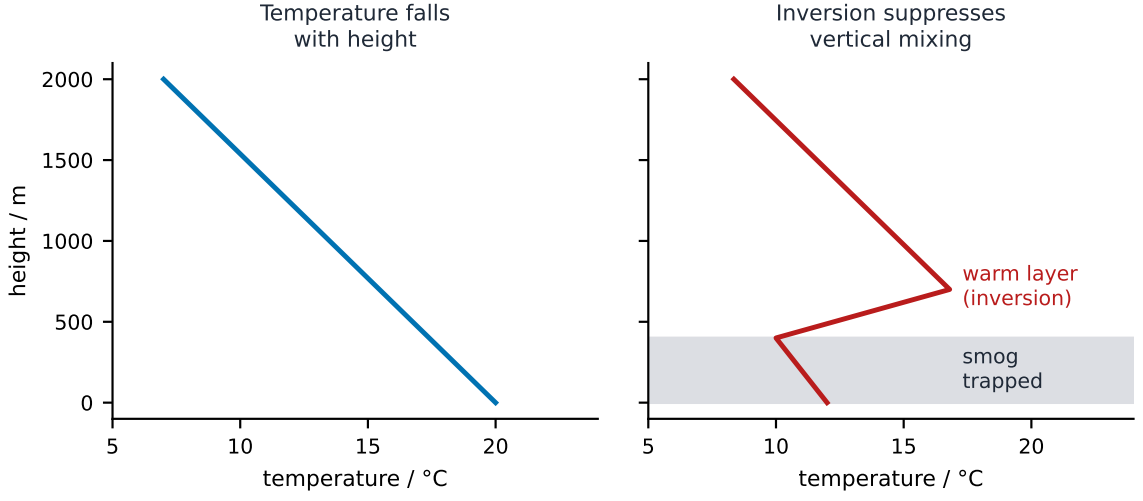
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1. Vehicle exhausts release NO_x and VOCs during the morning rush hour.
2. Sunlight splits nitrogen dioxide: $NO_2 \rightarrow NO + O$.
3. The oxygen atom joins an oxygen molecule: $O + O_2 \rightarrow O_3$, forming **tropospheric ozone** 对流层臭氧.
4. VOCs react with these gases to form more ozone and other irritants (such as PAN), which can contribute to an afternoon ozone peak under suitable conditions.

Ozone in the stratosphere protects us from ultraviolet radiation (Topic 6), but ozone near the ground is a pollutant: it irritates eyes and lungs, makes asthma worse, damages leaves and lowers crop yields, and is a greenhouse gas.

Temperature inversions

Vertical mixing depends on parcel buoyancy, wind and the environmental temperature profile; a falling environmental temperature alone does not guarantee strong mixing. In a **temperature inversion** 逆温, a layer of warm air sits above cooler air near the ground. The stable layer suppresses vertical mixing, so pollutants are trapped near the ground and smog builds up, sometimes for days.



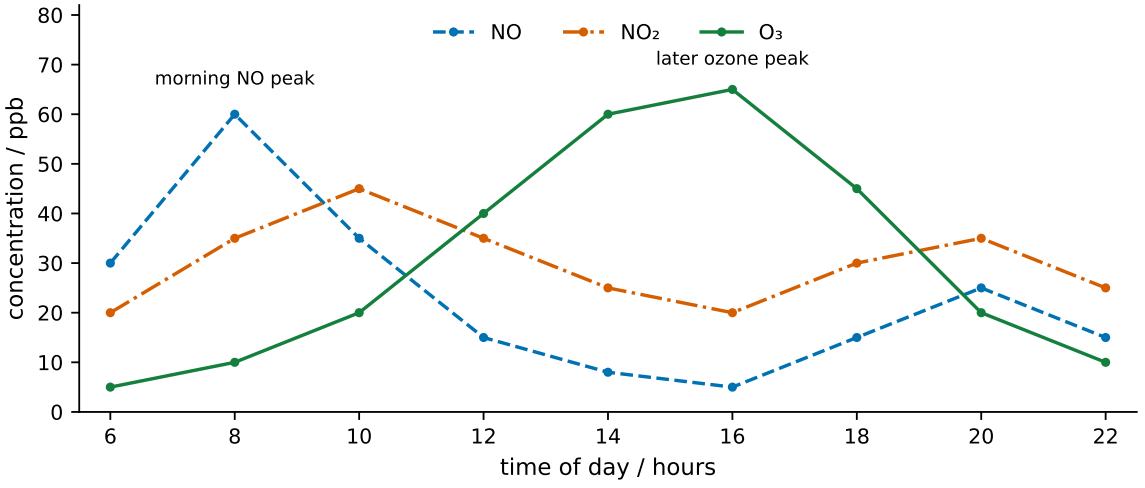
Normal conditions and a temperature inversion

Inversions are common on calm, clear winter nights and in cities in valleys or basins surrounded by hills, such as Mexico City, Los Angeles and Beijing (mountains to the north and west). In the **Great Smog of London** 伦敦烟雾事件 of December 1952, an inversion trapped smoke from coal fires for five days and caused about 4000 extra deaths within weeks (later estimates are much higher). It led to the UK Clean Air Act of 1956.

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Explain the ozone chemistry precisely

Photolysis requires light: $NO_2 + h\nu \rightarrow NO + O$. Ozone forms through $O + O_2 + M \rightarrow O_3 + M$, where M takes away excess energy. Fresh NO can remove ozone: $NO + O_3 \rightarrow NO_2 + O_2$. This cycle alone does not explain sustained net accumulation. VOC oxidation produces reactive radicals that convert NO to NO_2 without consuming an ozone molecule; further photolysis can then generate net ozone. Other products include peroxyacetyl nitrate (PAN), an irritant. These are simplified pathways; local VOC/NO_x sensitivity makes the response to cutting one precursor non-linear.



Sequence for reasoning; it is not monitored data or a prediction for every city.

For the graph, ozone rises from 10 ppb at 08:00 to 65 ppb at 16:00, an increase of 55 ppb or 550%. Its peak follows, rather than coincides with, the morning NO peak. Sunlight-driven reactions take time; fresh NO can also lower ozone near roads. Clouds, wind, transported ozone, precursor chemistry and evening traffic alter this pattern. An afternoon maximum is common under suitable conditions, not a necessary daily law. Compare matching sampling intervals and instruments before calculating a correlation between pollutants; adjacent hours are not automatically independent observations.

Higher insolation can promote photochemistry, while weak winds and stable air restrict dispersion. An inversion means temperature increases with height in a layer, discouraging a rising parcel from continuing upward. Valley topography can shelter a city and concentrate emissions, but a falling environmental temperature profile alone does not prove vigorous convection: compare the parcel's temperature and surroundings. Radiative cooling, subsidence and wind can create or remove stable layers. Explain both emissions and meteorology rather than attributing a severe episode to population alone.

Smog can irritate eyes and airways and damage plant tissues; ozone also damages materials such as rubber. Indirect effects include healthcare costs, lost work and school time, reduced crop production and unequal exposure for outdoor workers and poorly housed residents. Evaluate policy through measured exposure, health, livelihoods

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and regional emissions, as well as compliance. Health advice and indoor filtration can reduce exposure during an episode, but lasting improvement requires appropriate precursor and particle controls.

Practice

1. A country of 50 million has 900 000 births and 400 000 deaths in one year. Calculate CBR, CDR and NIR; then find doubling time for a different population growing at 2.5% annually.
2. Explain the approximate replacement TFR of 2.1 in a low-mortality population. Describe and explain DTM stages 2 and 3; give two limitations of that model.
3. Compare expansive and constrictive age structures without claiming shape alone measures life expectancy. For 18 million aged 0–14, 60 million aged 15–64 and 22 million aged 65+, calculate dependency ratio and explain its limits.
4. Evaluate fertility restrictions and voluntary family support using China and Singapore. Explain how education may influence fertility and why a correlation is not sufficient causal evidence.
5. Compare Malthus and Boserup. Explain why population size alone cannot predict environmental impact, using defined IPAT quantities.
6. Explain why a city is an open system, giving two inputs and two outputs. Describe two effects of replacing vegetated land with impermeable surfaces.
7. A district grows from 100 000 to 120 000 people; its urban population grows from 60 000 to 66 000. Calculate both urban shares and percentage urban growth. Has urbanisation occurred?
8. Outline three sustainable planning strategies with named examples where appropriate. Explain how a dated map and indicators could test a proposal, including unequal access.
9. Distinguish primary and secondary pollution, PM10 and PM2.5. Write a balanced net reaction for sulfuric acid formation and distinguish wet and dry deposition.
10. Design a safe lichen investigation near roads, including repeat sampling, controls, confounding variables and the limits of inference.
11. Evaluate Beijing's PM2.5 measures using rounded annual means 90 in 2013 and 32 in 2023. Calculate percentage reduction and the ratio to the WHO annual guideline 5; distinguish monitoring evidence from proof of policy causation.
12. **AHL:** Explain migration after Cyclone Idai without reducing every move to one cause. Calculate the IPAT multiplier for +20% population, +10% consumption per person and −25% impact per consumed unit. For five untied ranks with squared differences summing to 40, calculate Spearman's coefficient and interpret it.
13. **AHL:** Evaluate compactness, mixed land use and social mix. Use Amsterdam to explain circular/doughnut planning, then assess a green building over its life and the distribution of park access between districts.

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14. **AHL:** Explain photochemical smog with the NO_2/NO/ozone cycle and VOCs. Calculate the ozone change from 10 to 65 ppb, explain a possible afternoon peak, and explain how an inversion worsens pollution. Include biological, material and economic effects.

Answers.

1. CBR = 900 000/50 000 000 ×1000 =18 per 1000 per year; CDR=8 per 1000 per year; NIR=(18−8)/10=1.0% per year. For the separate constant-growth example, doubling time≈70/2.5=28 years; migration and changing rates invalidate an unconditional prediction.
2. Approximately two births replace two parents, with an allowance for survival and sex ratio at birth in low-mortality settings. Momentum and migration prevent an immediate threshold interpretation. Stage 2: deaths fall while births stay high, so natural increase rises; sanitation, nutrition and healthcare help explain it. Stage 3: births fall with changing opportunities, autonomy, costs and survival, slowing growth. The model omits migration and does not specify universal timings or account fully for policy and shocks.
3. Expansive structures have large young cohorts; constrictive structures have smaller young cohorts and a wider middle. Fertility history, survival and migration can contribute, but the picture alone does not measure their separate effects. Dependency=(18+22)/60 ×100=66.7 conventionally dependent-age people per 100 aged 15–64. School and care needs differ by age, and these bands are not a count of employed workers or actual financial dependence.
4. Restrictions may affect births but must be evaluated alongside coercion, rights, other demographic drivers and trends before implementation. China later relaxed restrictions; Singapore's Baby Bonus supports eligible families but does not isolate a cash-payment effect. Education can affect autonomy, reproductive knowledge and employment opportunities. Income, costs, healthcare and norms confound a simple comparison; neither lower fertility nor higher fertility alone proves improved wellbeing.
5. Malthus emphasised population pressure on a more slowly growing food supply; Boserup emphasised innovation stimulated by pressure. Both illuminate mechanisms, but neither guarantees a particular outcome: innovation has resource and distribution limits. With compatible units, population × consumption per person × impact per unit consumed gives an identified total impact. Consumption inequalities, trade and technology prevent population alone from determining it.
6. An open city exchanges matter and energy: inputs include food and water or fuel; outputs include sewage and waste heat or products. Impermeable surfaces can increase rapid runoff and flood risk; removing vegetation reduces habitat and cooling. Heat storage and waste heat can contribute to an urban heat island. State system boundary and timescale.

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7. Initial urban share=60 000/100 000 ×100=60%; final=66 000/120 000 ×100=55%. Urban-number growth=(66 000−60 000)/60 000 ×100=10%. Urban population grew, but urbanisation did not occur under the increasing-share definition. Boundaries and reclassification must be checked.
8. Possible strategies: transit such as Curitiba BRT, efficient building and transport design in Vauban, and water-sensitive drainage such as sponge-city systems. Explain the mechanism and an access, cost or maintenance limit for each. Compare same-scale, same-boundary maps and measures before/after; include habitat, runoff, housing affordability, travel and access by district. A city mean can hide unequal benefit.
9. Primary pollutants are emitted directly; secondary ones form in air, such as ozone or sulfate particles. PM2.5 is contained within PM10 rather than added as a separate size category. Balanced net formation: $2SO_2+O_2+2H_2O \rightarrow 2H_2SO_4$. Wet deposition arrives in rain, fog or snow; dry deposition involves gases and particles without precipitation. Net equations summarise rather than identify one elementary step.
10. Use equal quadrats on several comparable trees at each defined distance, with a consistent sampling/identification method and background sites. Record tree species, bark properties, aspect, shade and moisture; use repeat calibrated monitor data if available. Protect organisms and avoid deliberately exposing people. Lichen patterns integrate several conditions, so association with distance is not a direct concentration reading or proof of one pollutant's effect.
11. Rounded reduction=(90−32)/90 ×100=64.4%; 32/5=6.4 times the WHO annual guideline. The published 64.2% uses unrounded endpoints including 89.5 in 2013. Cleaner heating, industry/vehicle controls and regional cooperation can contribute; weather and economic activity also matter. Evaluate costs, reliability, jobs, displacement of emissions and exposure distribution. Meeting a national Grade II annual PM2.5 limit does not establish zero risk or compliance for every pollutant.
12. **AHL:** Idai damaged housing and livelihoods and displaced people; assets, services, policy and personal choices also shape whether and where people move. Internal displacement is not automatically international refugee status or attributable entirely to climate change. IPAT multiplier=1.20×1.10×0.75=0.99, a 1% fall in the defined impact. Spearman r=1−6×40/(5×24)=−1: perfect inverse rank order for the sample, not a causal effect or universal rule; untied-rank formula and sampling assumptions must hold.
13. **AHL:** Compactness can limit sprawl, mixed uses shorten trips and social mix supports access; density without housing protections and services can worsen inequality. Amsterdam's dated circular strategy links social needs with ecological limits, repair/reuse and material flows; adoption does not prove target achievement. Compare embodied/operating impacts, climate suitability, comfort and maintenance for buildings. A mean of 20 square metres of green space can hide equal-population districts at 10 and 30; assess safe access, quality, rents and dis-

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placement.

14. **AHL:** Sunlight splits NO_2; oxygen atoms combine with O_2 to form ozone. NO can consume ozone; VOC-derived radicals can convert NO to NO_2 without consuming ozone, allowing net accumulation and other products including PAN. Ozone rises by 55 ppb, or $55/10\times100=550\%$. Sunlight and reaction time can give an afternoon maximum, but emissions, titration, transport and weather change it. An inversion suppresses vertical mixing and weak winds/topography can retain pollutants. Effects include respiratory/eye irritation, plant injury, rubber damage, healthcare costs and lost work; control sources as well as reduce immediate exposure.

Exam tips

- Show working in rate calculations, and give units: births per 1000 per year, or a percentage.
- Use 70 ÷ growth rate (%) for doubling time.
- When describing the DTM, give the change in birth rate, death rate and total population, and a reason for each.
- Use a pyramid to describe age/sex structure; births, migration and survival affect shape, which does not directly measure life expectancy or employment.
- Do not confuse tropospheric ozone (a pollutant) with stratospheric ozone (which protects us).
- Organise answers on pollution management using the three levels: activity, release, clean-up.

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Environmental law

International Baccalaureate · IB Diploma · Environmental Systems and Societies · HL

Scope and prerequisites

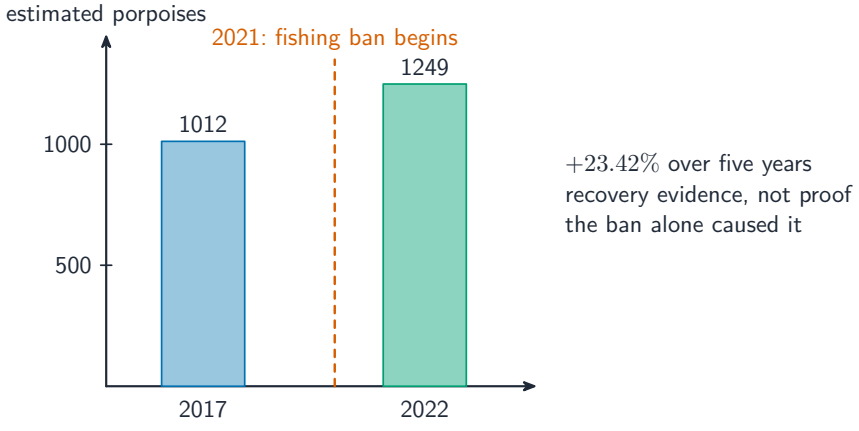
This handout teaches HL lens a, Environmental law, for the course first assessed in 2026. It is for HL students only. Environmental law is one of three HL lenses, with environmental and ecological economics (unit 10) and environmental ethics (unit 11), that you apply to the case studies of Topics 1 to 8.

Prerequisites: Topic 1 (sustainability, perspectives and the three levels of pollution management), Topic 3 (conservation and CITES), Topic 4 (the tragedy of the commons and fisheries), Topic 6 (the Paris Agreement and the Montreal Protocol) and Topic 8 (urban air pollution).

Environmental law and its purposes

Ten years without fishing

China's ten-year commercial fishing ban in key Yangtze waters began in 2021, alongside other conservation and livelihood measures. The agriculture ministry's 2022 survey, reported in 2023, estimated 1249 Yangtze finless porpoises compared with 1012 in 2017: a 23.42% increase. This is evidence of recovery across five years, not proof that a policy beginning in 2021 caused the whole change. The **Yangtze River Protection Law** 长江保护法 entered into force in March 2021. Enforcement, habitat, other pressures and support for former fishers all affect outcomes. The baiji is classified as Critically Endangered (Possibly Extinct), not simply declared extinct; distinguish it from the finless porpoise. This unit asks how laws change behaviour and how to test whether that change protects ecosystems fairly.

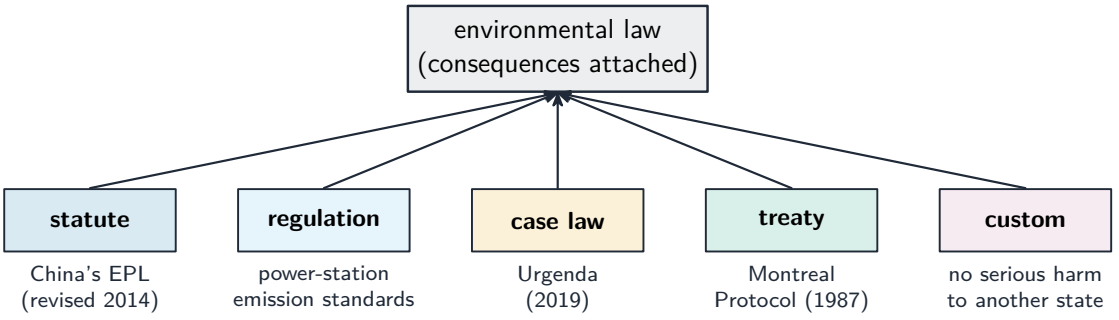


Porpoise estimates rose 23.42% from 2017 to 2022; the ban began in 2021

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What is environmental law?

Environmental law 环境法 is the set of rules, established and enforced through relevant public or recognized social authorities, that controls how people use and affect the environment. Unlike a voluntary code, a law carries consequences: fines, closure, compensation or prison.



Five sources of environmental law

Environmental law comes from several sources:

Source	Meaning	Example
Statute 成文法	A law passed by a parliament or legislature	China's Environmental Protection Law (revised 2014)
Regulation 法规	Detailed rules made by a government agency under a statute	Emission standards for power stations
Case law 判例法	Decisions by courts that guide later cases	The Urgenda climate case (Netherlands, 2019)
Treaty 条约	A written agreement between states, binding on those that join	The Montreal Protocol (1987)
Customary international law 国际习惯法	General state practice accepted as law; a different source from treaty consent	A state must not cause serious harm to another state's environment

Every law applies within a **jurisdiction** 管辖范围: the area or group of people a government or court has authority over. Pollution and wildlife do not respect borders, so a problem may cross many jurisdictions.

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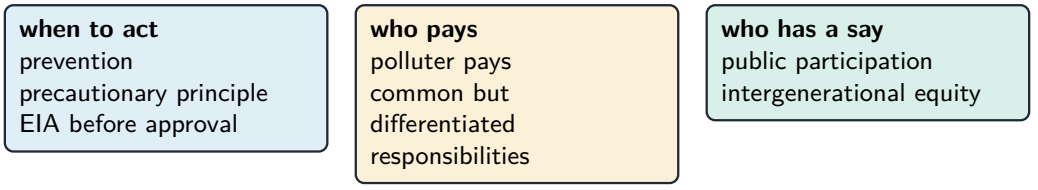
Hard law and soft law

- **Hard law** 硬法 is legally binding: treaties, statutes and regulations that can be enforced.
- **Soft law** 软法 is not binding but still guides behaviour: declarations, principles, guidelines and targets, such as the Rio Declaration (1992) or the Sustainable Development Goals.

Soft law can allow agreement without a binding treaty obligation and can influence later legislation, standards or treaties. Its political and practical effects may still be substantial; non-binding does not mean unimportant.

Key principles of environmental law

Many environmental laws are built on a small set of principles, most of them stated in the Rio Declaration of 1992:



The principles grouped by the question each answers

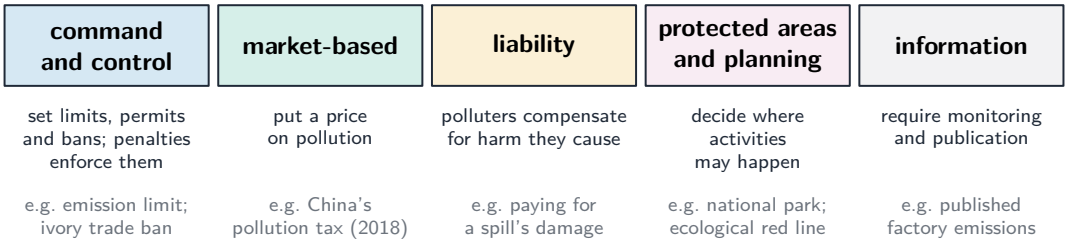
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Principle	Meaning
Prevention principle 预防原则	It is better to prevent environmental harm than to repair it
Precautionary principle 风险预防原则	Where there is a threat of serious or irreversible damage, lack of full scientific certainty is not a reason to delay action
Polluter pays principle 污染者付费原则	Those who cause pollution should pay the costs of preventing it or cleaning it up
Environmental impact assessment 环境影响评价	Large projects must be assessed for environmental effects before approval (Topic 1)
Public participation 公众参与	People have a right to information, to take part in decisions and to go to court on environmental matters
Intergenerational equity 代际公平	The present generation must not leave the environment worse for future generations
Common but differentiated responsibilities 共同但有区别的责任	All states share the duty to protect the environment, but richer states that caused more of the damage should do more

Precaution supports proportionate preventive action despite scientific uncertainty about serious or irreversible harm. Some legal systems place evidence requirements on project proponents, but the principle does not universally reverse the burden of proof or require proof of zero risk. State the applicable instrument, evidence, seriousness, alternatives and review arrangements.

Types of legal instrument

Laws use different tools to change behaviour:



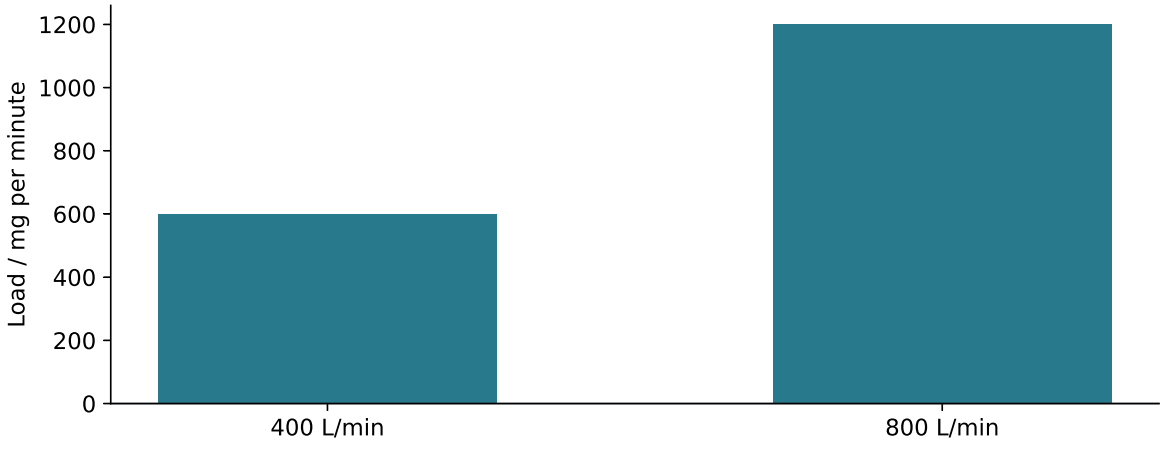
Five legal tools that change behaviour in different ways; outcomes depend on enforcement

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- **Command and control** 命令与控制: standards, permits, quotas and bans set by the government and enforced with penalties. Examples: emission limits, a ban on ivory trade, a fishing ban. They specify permitted conduct or limits, but actual outcomes depend on enforcement; a minimum standard alone may give little incentive to go further.
- **Market-based instruments** 市场手段: taxes, charges, subsidies and tradable permits that put a price on pollution (unit 10). Example: China's Environmental Protection Tax Law (2018) charges polluters per unit of pollutant released.
- **Liability** 责任: polluters must pay compensation for harm they cause, which encourages care.
- **Protected areas** 保护区 and land-use planning: national parks, ecological red lines and zoning (Topics 3 and 8).
- **Information** 信息: rules requiring companies to monitor and publish their emissions, so the public and investors can put pressure on them.

■ Worked example: concentration and load

A discharge permit may limit the **concentration** of a pollutant, the **total load** (mass per unit time), or both.



A concentration limit is not a load limit: the same 1.5 mg/L at double the flow doubles the load

A factory's permit allows a maximum concentration of 2 mg/L of a pollutant. Its discharge is 1.5 mg/L at 400 L per minute.

1. Load = concentration × flow = 1.5 mg/L × 400 L/min = 600 mg per minute.
2. The factory doubles its output, so the flow rises to 800 L/min at the same 1.5 mg/L.
3. New load = 1.5 × 800 = 1200 mg per minute.

The factory still obeys the concentration limit, but twice as much pollutant now reaches the river. A permit that limits only concentration can also be met by **diluting** the waste with clean water. For this reason many permits also cap the total load, and

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China's water laws set total load controls for key pollutants in many river basins.

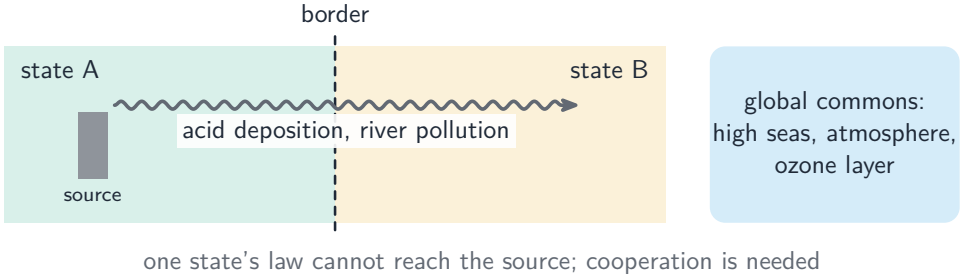
International environmental law

Why international law is needed

Many environmental problems are **transboundary** 跨界: acid rain, river pollution, migratory species, ozone depletion and climate change. Others concern the **global commons** 全球公域, a term used for shared spaces or environmental systems whose protection needs international cooperation. The term does not give every example the same legal status. No state may claim sovereignty over the high seas, but activities there are still governed by international law; shared does not mean unregulated.



Seized raw ivory: CITES makes international trade in it illegal, but national agencies must enforce the ban



Transboundary harm and the global commons need cooperation

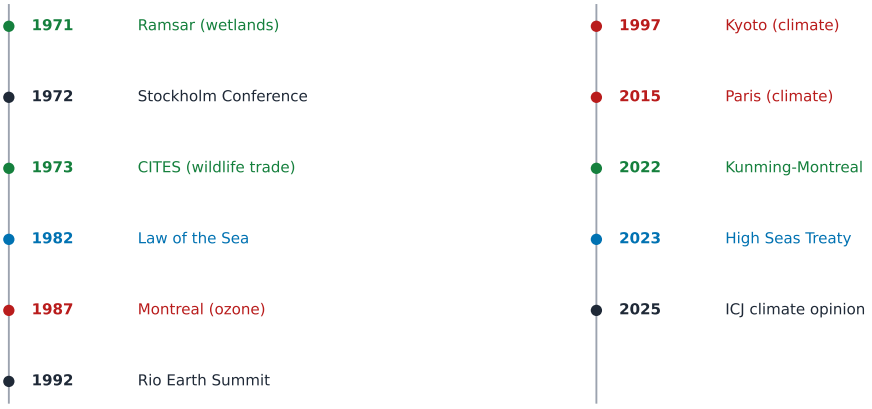
Distinguish the atmosphere as a connected environmental system from legal authority over airspace. States have sovereignty over the airspace above their territory, as ICAO explains under Article 1 of the Chicago Convention. That authority does not keep

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greenhouse gases inside national borders. Antarctica has a different arrangement: Article IV of the Antarctic Treaty preserves parties' positions on existing territorial claims and their recognition, while preventing new or enlarged claims during the treaty's operation. It does not simply erase every claim. Cooperation addresses shared effects while respecting the applicable legal regime; without effective arrangements, free-riding can weaken protection (Topic 4).

The basic rule of customary international law comes from the **Trail Smelter case** (1941): a smelter in Canada damaged farms and forests in the USA with sulfur dioxide, and a tribunal ruled that no state may allow its territory to be used to cause serious environmental harm to another. This rule appears again as Principle 21 of the Stockholm Declaration (1972) and Principle 2 of the Rio Declaration (1992).

Major agreements



Some milestones in international environmental law (green: biodiversity; red: atmosphere and climate; blue: oceans)

Agreement	Year	What it does
Ramsar Convention 拉姆萨尔公约	1971	Protects wetlands of international importance; over 2500 listed sites
CITES 濒危野生动植物种国际贸易公约	1973	Controls trade in endangered species through permits; international commercial trade in wild Appendix I specimens is generally prohibited, subject to defined exceptions and permit rules
UN Convention on the Law of the Sea 联合国海洋法公约	1982	Sets territorial waters and 200-nautical-mile exclusive economic zones; duty to protect the marine environment
Montreal Protocol	1987	Phases out ozone-depleting substances; ratified by every UN member state

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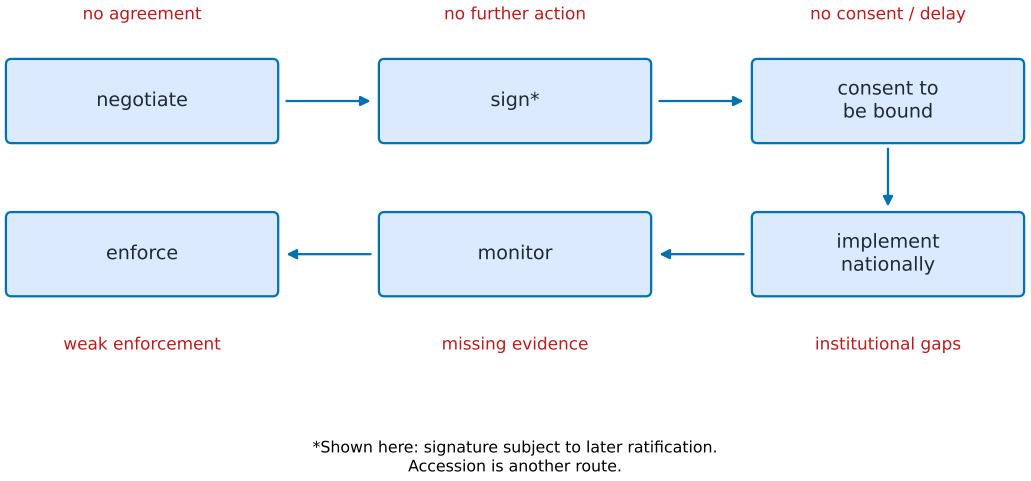
Agreement	Year	What it does
Convention on Biological Diversity 生物多样性公约	1992	Conservation, sustainable use and fair sharing of the benefits of genetic resources
UN Framework Convention on Climate Change 联合国气候变化框架公约	1992	Aims to stop dangerous human interference with the climate; meets every year at a Conference of the Parties (COP)
Kyoto Protocol	1997	Binding emission cuts for developed countries only
Paris Agreement	2015	Parties submit nationally determined contributions; well below 2 °C with efforts towards 1.5 °C; binding procedural duties differ from achieving each target
Kunming-Montreal Global Biodiversity Framework 昆明-蒙特利尔全球生物多样性框架	2022	23 targets for 2030, including protecting 30 % of land and sea ("30 by 30"); agreed under China's presidency of COP 15
High Seas Treaty 公海条约	2023	Allows marine protected areas and impact assessments in waters beyond national jurisdiction; in force from January 2026

Many agreements follow a **framework-protocol** model: a framework convention sets general aims, and later protocols add binding details. The Vienna Convention (1985) was followed by the Montreal Protocol (1987); the UNFCCC (1992) by the Kyoto Protocol (1997) and the Paris Agreement (2015).

From treaty to change on the ground

States are **sovereign** 主权: they exercise state authority, but sovereignty does not remove international duties. A state can **ratify** 批准 a treaty through the prescribed process or use another form of consent allowed by that treaty. Treaty obligations depend on the agreement's provisions, consent to be bound and entry into force for the state. The UN treaty guidance distinguishes signature, ratification, acceptance, approval and accession. Signature subject to ratification does not itself establish consent to be bound by the whole treaty, but it is not merely meaningless symbolism. Accession can make a state a party without the same prior signature sequence. Withdrawal must follow applicable rules; leaving one treaty does not remove independent customary obligations.

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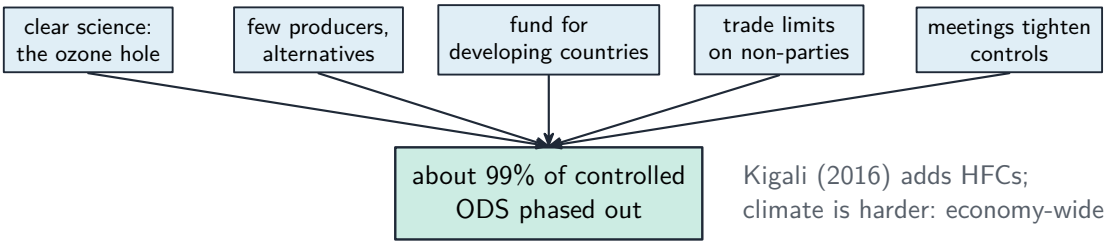
A route, not a compulsory sequence for every treaty or legal system; red labels identify implementation risks.

The USA signed but never ratified Kyoto. Its first Paris withdrawal took effect in 2020, it rejoined in 2021, and the second withdrawal took effect on 27 January 2026. Date participation claims rather than using an announcement as the effective date.

International judgments can bind parties within a court's jurisdiction, although implementation and enforcement may be difficult. Advisory opinions, such as the ICJ's 2025 climate opinion, have a different legal status. Treaty reporting, review, technical assistance, finance and applicable trade measures can support compliance. Neither a signature nor a judgment alone demonstrates an ecological improvement.

■ Why the Montreal Protocol worked

The Montreal Protocol is often called the most successful environmental treaty. About 99 % of controlled ozone-depleting substances have been phased out, and the ozone layer is expected to recover by about 2066 over Antarctica. Reasons:



Why the Montreal Protocol worked

- strong scientific evidence and a clear, frightening signal (the ozone hole);

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- a more concentrated set of producers and uses than economy-wide greenhouse emissions, with alternatives becoming available (not every substitute is harmless or equally affordable);
- a fund paid by rich countries to help developing countries switch;
- trade restrictions on non-parties, which made staying outside costly;
- regular meetings that tightened controls as the science improved.

The **Kigali Amendment** 基加利修正案 (2016) added HFCs, which do not harm ozone but are powerful greenhouse gases. Climate agreements also use science, finance and review, but economy-wide emissions, different development needs, investment lifetimes and unequal costs make implementation difficult. Montreal is a comparison, not proof that every climate measure lacks affordable alternatives (Topic 6).

Courts and climate

Courts have become an important part of environmental law:



Three climate rulings, 2019 to 2025

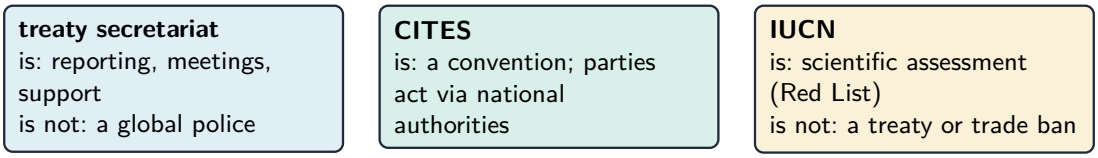
- **Urgenda Foundation v the Netherlands** (2019): the Dutch Supreme Court ordered the government to cut emissions by at least 25 % from 1990 levels by the end of 2020, to protect citizens' rights to life and family life.
- **KlimaSeniorinnen v Switzerland** (2024): the European Court of Human Rights ruled that Switzerland's weak climate action violated the rights of a group of older women.
- **International Court of Justice advisory opinion** (2025): asked by the UN General Assembly after a campaign led by students from Vanuatu, the ICJ said that states have legal duties under international law to protect the climate system, and that failing to act could be a breach of international law. An advisory opinion is not binding, but courts and governments around the world refer to it.

Institutions, influence and compensation

Treaty secretariats organize reporting, meetings and support; they do not replace national inspectors or create an automatic global police force. CITES is a convention with parties and national management/scientific authorities. IUCN is a conservation union providing scientific assessment and expertise; its Red List is not itself a treaty or a legally binding trade ban. A scientific risk classification can inform a legal decision

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without being the decision.



a risk classification can inform a legal decision without being the decision

What each institution is, and is not

Negotiations can be slow because scientific understanding changes, states disagree over finance and historical responsibilities, and domestic stakeholders face different costs. Lobbying can supply information or protect powerful interests; transparent consultation and conflict-of-interest rules help judge whose evidence is heard. A weak agreement can result from these pressures, while an ambitious agreement still needs implementation. For alleged transboundary harm, separate evidence of damage, legal responsibility, causal attribution and valuation. A court cannot infer an appropriate compensation sum merely from a pollution reading: health, livelihoods, restoration, uncertainty and the legal basis for a remedy matter.

National and local law

China's environmental laws

China has built one of the world's largest bodies of environmental law since the 1980 s. Key features:

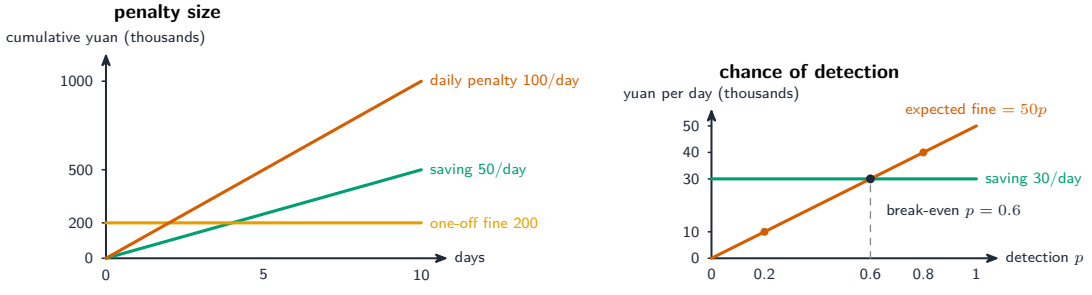
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Law or tool	What it does
Environmental Protection Law (revised 2014, in force 2015)	**Daily penalties** 按日计罚 that continue until a polluter stops; officials can be held responsible; NGOs can bring public interest cases
Environmental Protection Tax Law (2018)	Replaced pollution fees with a tax on each unit of pollutant released
Ecological red lines 生态保护红线	Areas where development is strictly restricted; about 30 % of China's land is inside them
Central environmental inspections 中央生态环境保护督察	Teams from Beijing inspect provinces since 2016; thousands of officials have been disciplined
Yangtze (2021) and Yellow River (2023) Protection Laws	Whole-basin rules for water, pollution, fishing and development
Environmental public interest litigation 环境公益诉讼	NGOs (since 2015) and public prosecutors (since 2017) can sue polluters on behalf of the public

Worked example: daily penalties. A factory saves 50 000 yuan a day by not running its treatment plant. Under an old system it pays a one-off fine of 200 000 yuan.

1. Over a year of illegal discharge: savings $= 50\,000 \times 365 \approx 18.3$ million yuan.
2. The one-off fine is about 1 % of the savings, so breaking the law pays.
3. Under a daily penalty of 100 000 yuan, each day of pollution costs the factory $100\,000 - 50\,000 = 50\,000$ yuan more than it saves.

If a penalty is smaller than the money saved by breaking the law, a rational company will pay the fine and keep polluting. Effective penalties must be larger than the gain, and the chance of being caught must be high.

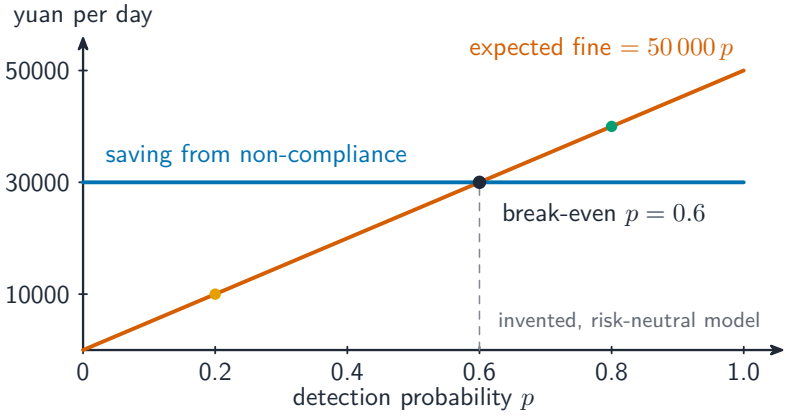


A law deters only when the expected penalty beats the gain: make it larger (left) or make detection likelier (right)

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Worked example: detection changes an incentive

A firm saves 30 000 yuan per day through non-compliance. Suppose a detected breach costs a 50 000-yuan fine and the model treats each day separately. At detection probability 0.2, expected daily fine is $0.2 \times 50\,000 = 10\,000$ yuan, below the saving. At probability 0.8 it is 40 000 yuan, above the saving. Break-even probability is $30\,000/50\,000 = 0.6$ under these simplified assumptions.



Expected fine against detection probability: break-even at 0.6

This is a risk-neutral expected-cost model, not permission to break a law or a prediction of every firm's behaviour. Cleanup liability, closure, reputational effects, repeated offences and ethical commitments can change the decision. Monitoring quality, staffing and funding matter as well as the maximum fine written in legislation. Laws define obligations; economic incentives and support can help achieve them, but a calculated price cannot settle every rights question or irreversible ecological loss.

Local and community rules

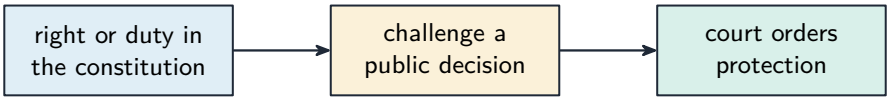
Not all environmental rules come from national governments. Cities make their own rules, such as Shanghai's waste-sorting regulation (Topic 7) or Beijing's vehicle limits (Topic 8). Indigenous and local communities often have **customary rules** 习惯规则 about fishing seasons, sacred forests and grazing, which can manage commons sustainably. Elinor Ostrom, the first woman to win the Nobel Prize in economics (2009), showed that many communities avoid the tragedy of the commons through their own clear rules, monitoring and fair punishments.

Environmental constitutionalism

Environmental constitutionalism places environmental rights and duties in a country's constitution or develops their protection through constitutional interpretation. It can help people challenge public decisions and require authorities to protect health, ecosystems and future generations; access to a court, standing, costs and effective remedies remain important. Do not assume every constitution gives identical rights or every

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court applies them in the same way.

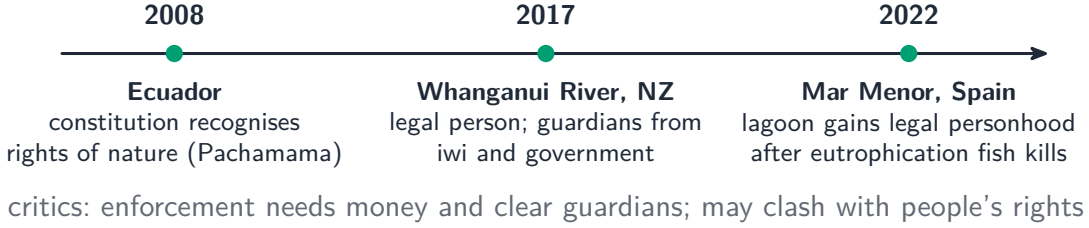


How a constitutional right can become protection

Named example: Colombia's Atrato River. In decision T-622 of 2016, the Constitutional Court addressed harm associated with illegal mining and protection of affected communities' rights, recognizing the river as a subject of rights with representation involving the state and communities. This connects constitutional protection with rights of nature. The legal recognition is an achieved legal outcome, not evidence that contamination has already ended. Evaluate budgets, safety, restoration and implementation separately.

Rights of nature

A newer legal idea gives nature itself legal rights, so that a river or forest can be represented in court:



Rights of nature in three legal systems

- **Ecuador**'s constitution (2008) recognised the rights of nature (Pachamama) to exist and regenerate.
- **New Zealand** made the Whanganui River a **legal person** 法人 in 2017, with guardians from the Māori iwi and the government, after a 140-year campaign by the Whanganui iwi.
- **Spain** gave legal personhood to the Mar Menor lagoon in 2022, after eutrophication killed tonnes of fish.

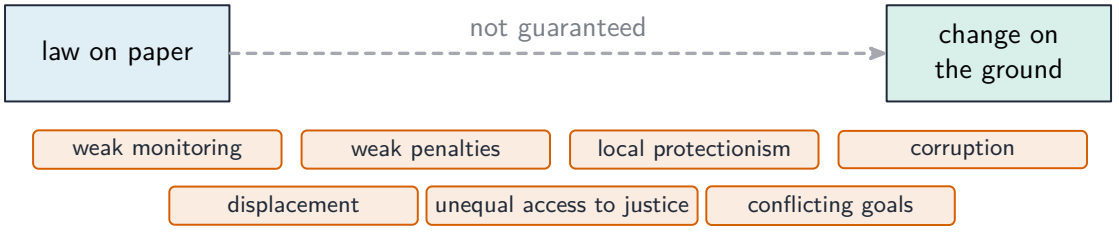
Supporters say this matches many indigenous worldviews and gives nature a voice. Critics say rights are hard to enforce without money and clear guardians, and may clash with the rights of people who depend on the resource. Some campaigners also want **ecocide** 生态灭绝罪, the mass destruction of ecosystems, to become an international crime.

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Evaluating environmental law

Why laws fail

A law on paper does not guarantee a change on the ground. Common problems:

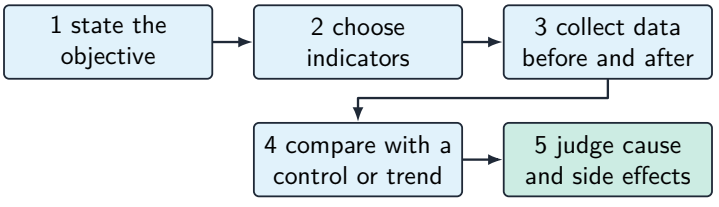


Seven reasons a law on paper may not change things on the ground

- **Weak monitoring** 监测: regulators may lack staff, equipment or data; companies may falsify readings.
- **Weak penalties**: fines smaller than the profit from breaking the law.
- **Local protectionism** 地方保护主义: local governments may protect polluting firms that provide jobs and taxes.
- **Corruption** 腐败 and lack of transparency.
- **Displacement** 转移: pollution or harvesting moves to places with weaker laws (such as illegal fishing moving elsewhere, or polluting industries moving to other provinces or countries).
- **Unequal access to justice**: poor communities may not be able to afford lawyers or obtain information.
- **Conflict with other goals**: jobs, energy security or development.

How to judge whether a law works

To evaluate a law, compare the outcome with the objective:



Judge a law against its objective, with indicators, before-and-after data and a control

1. State the objective (for example, raise fish numbers in the Yangtze).
2. Choose indicators and collect data before and after (porpoise counts, fish surveys).
3. Compare with a control or with trends that were already happening; changes can be caused by rainfall, economic change or other policies at the same time.

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4. Look at compliance: how many breaches are detected and punished?
5. Consider costs and fairness: who paid (fishers losing their livelihoods), and were they compensated?
6. Check for displacement and unintended effects.

Environmental justice 环境正义 asks whether environmental benefits and harms are shared fairly. Exposure to pollution and access to legal remedies can be distributed unequally; test a particular claim with local siting, exposure, income and participation evidence rather than assuming every case has the same pattern. The Escazú Agreement (2018, Latin America and the Caribbean) is the first treaty to protect environmental defenders, after hundreds of activists were killed.

Practice

1. (a) Distinguish between hard law and soft law, with one example of each. (b) Outline precaution and explain why it does not universally reverse the burden of proof.
2. Explain the polluter pays principle and give one example of a law based on it.
3. (a) A factory discharges 2.4 mg/L of a pollutant at 600 L per minute. Calculate the load per minute and per day. (b) Explain why a permit that limits only concentration may not protect a river.
4. Compare command-and-control instruments with market-based instruments.
5. (a) Explain consent to treaty obligations, including ratification and accession. Why does leaving a treaty not remove every international environmental obligation? (b) Explain why calling the atmosphere and Antarctica global commons does not establish that neither has territorial sovereignty issues.
6. Outline the steps by which a treaty leads to change on the ground, and explain one way each of two steps can fail.
7. Explain four reasons for the success of the Montreal Protocol.
8. Explain why climate change has been harder to control through international law than ozone depletion.
9. Describe the role of courts in climate law, with one named case.
10. A company saves 30 000 yuan a day by not treating its waste. Compare a one-off fine of 500 000 yuan with a daily penalty of 50 000 yuan over a year. Then use the model of a 30 000-yuan daily saving,50 000-yuan fine and detection probability 0.2: find expected fine and the break-even detection probability.
11. Outline three features of China's environmental laws since 2014.
12. Evaluate the ten-year fishing ban on the Yangtze River.
13. Discuss the strengths and limitations of giving legal rights to rivers. Use Colombia's Atrato decision to explain environmental constitutionalism and distinguish a legal result from ecological recovery.
14. Explain why environmental laws often fail in practice.

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Answers.

1. (a) Hard law is legally binding and enforceable, such as a treaty like the Montreal Protocol or a national statute. Soft law is not binding but guides behaviour, such as the Rio Declaration or the Sustainable Development Goals. (b) A threat of serious or irreversible damage can justify proportionate prevention despite incomplete scientific certainty. Evidence duties and burdens depend on the legal instrument; precaution does not universally require proponents to prove zero risk.
2. Those who cause pollution should pay for preventing it or cleaning it up. Examples: China's Environmental Protection Tax Law, a charge per unit of pollutant; landfill taxes; liability laws requiring polluters to pay for clean-up.
3. (a) Load = $2.4 \times 600 = 1440$ mg per minute. Per day: $1440 \times 60 \times 24 = 2\ 073\ 600$ mg, about 2.07 kg per day. (b) The company can meet the concentration limit while increasing its pollutant load if discharge flow rises at the same concentration. Dilution with clean water can lower concentration without changing the pollutant load. A load limit is also needed.
4. Command-and-control instruments specify conduct or limits but need monitoring and enforcement; a minimum limit alone may offer little reward for further improvement. Taxes and tradable permits use incentives. A tax fixes a price while emissions responses vary; a well-enforced cap can constrain covered quantity while allowance prices vary. Neither guarantees complete compliance, fairness or ecological safety.
5. (a) Treaties bind according to consent, entry into force and their provisions; consent can be expressed through ratification, acceptance, approval or accession, and sometimes definitive signature. Withdrawal follows applicable rules. Customary law and other independent duties can still apply; international law is not limited to whichever treaties a state currently joins. (b) States have sovereignty over airspace above their territory, although atmospheric pollution crosses borders. Antarctica's treaty preserves positions on existing territorial claims and recognition while barring new or enlarged claims during its operation. Shared environmental interests do not erase these different legal arrangements.
6. A route is negotiation, signature subject to ratification, consent to be bound, national implementation, monitoring and enforcement. Kyoto illustrates US non-ratification; Paris illustrates withdrawal under its rules. Monitoring gaps and weak institutions can frustrate implementation. Accession and different national legal systems mean this is not one compulsory sequence.
7. Any four with explanation: strong science; a comparatively concentrated set of relevant industries; workable alternatives for many uses; finance and technical support; applicable trade restrictions; periodic review and stronger controls. Substitutes and transition costs differ, and success does not mean zero remaining ozone risk.

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8. Greenhouse gases come from the whole economy, not a few products; there are no cheap substitutes for all fossil fuel uses; costs and benefits are shared unequally between countries and generations; the benefits come slowly; and states fear losing competitiveness, so free-riding is tempting.
9. Courts can order governments to act and interpret rights to include protection from climate harm. For example, in Urgenda (2019) the Dutch Supreme Court ordered a 25 % emissions cut from 1990 levels by 2020; in 2024 the European Court of Human Rights found Switzerland in breach of rights; the ICJ's 2025 advisory opinion said states have legal climate duties.
10. Savings over a year = 30 000 × 365 = 10.95 million yuan. A one-off fine of 0.5 million is far smaller, so polluting pays. A daily penalty of 50 000 costs 18.25 million a year, 20 000 yuan a day more than the saving, so it makes compliance the cheaper option. In the separate simplified model, expected daily fine=0.2×50 000=10 000 yuan, below 30 000 saved; break-even detection probability=30 000/50 000=0.6. This omits other liabilities and behavioural factors.
11. Any three: daily penalties that continue until a polluter stops; an environmental protection tax; ecological red lines; central environmental inspections that hold officials responsible; public interest litigation by NGOs and prosecutors; river-basin laws for the Yangtze and Yellow Rivers.
12. The 2022 survey estimated 1249 porpoises versus 1012 in 2017, a 23.42% increase, providing evidence of recovery. The commercial fishing ban began in 2021, within that interval, so the whole increase cannot be assigned to it. Evaluate enforcement, fishing pressure, habitat, shipping, pollution and livelihoods/compensation; compare methods and other trends before claiming a causal effect.
13. Strengths: nature can be represented in court; it reflects indigenous worldviews (Whanganui River); it can protect ecosystems for their own sake. Limitations: rights need guardians, money and enforcement; it may conflict with the needs of people who use the river; courts have sometimes overturned such rulings. It is most useful when combined with other laws and local support. Colombia's Constitutional Court connected constitutional rights, affected communities and river rights in T-622/2016. Representation and legal recognition can support protection, while ecological outcomes depend on implementation and resources.
14. Weak monitoring and falsified data; penalties smaller than profits; local protectionism; corruption; pollution displaced to other places; unequal access to justice; conflicts with jobs and development; states withdrawing from treaties.

Exam tips

- Name the law or agreement, its date and who it binds, then judge its effect with evidence.
- Separate what a law says from whether it has changed the environment.

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- Use the principles (precautionary, polluter pays, common but differentiated responsibilities) by name.
- In calculations, give units and compare a penalty with the gain from breaking the law.
- In evaluation, consider monitoring, enforcement, fairness and displacement, then reach a judgement.

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Environmental and ecological economics

International Baccalaureate · IB Diploma · Environmental Systems and Societies · HL

Scope and prerequisites

This handout teaches HL lens b, Environmental and ecological economics, for the course first assessed in 2026. It is for HL students only. Economics is one of three HL lenses, with environmental law (unit 9) and environmental ethics (unit 11), that you apply to the case studies of Topics 1 to 8.

Prerequisites: Topic 1 (natural capital and natural income, sustainability, the circular economy, environmental value systems), Topic 3 (the value of biodiversity and ecosystem services), Topic 4 (the tragedy of the commons) and Topic 6 (climate mitigation). No previous study of economics is needed.

Two ways to think about the economy and nature

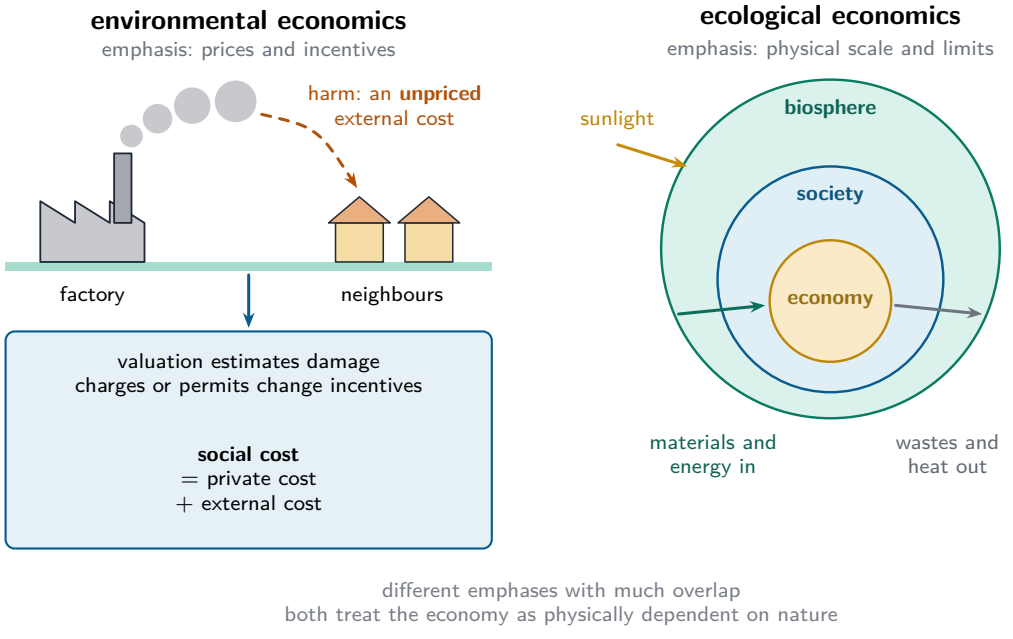
Putting a price on carbon

China opened national carbon trading in July 2021. The environment ministry's 2025 progress report documents expansion from power generation to steel, cement and aluminium smelting. It describes intensity-based allowance allocation: allocation depends on production benchmarks, so this is not identical to the simple fixed absolute cap taught below. A cleaner producer can sell surplus allowances and another can buy to meet its obligation, but the rules, coverage and allocation period must be stated. A carbon price creates an incentive; it does not establish a fixed outcome for every pollutant or remove monitoring requirements. Compare a dated policy design with the model instead of treating all trading schemes as identical.

Environmental economics and ecological economics

Environmental economics often analyses incentives, externalities and non-market valuation; ecological economics gives particular attention to biophysical limits, scale and distribution. These are broad emphases with overlap, not claims that every economist in each field agrees on one policy or that environmental economists deny physical dependence on nature.

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Compare analytical emphasis; both approaches concern an economy physically dependent on nature.

Feature	**Environmental economics 环境经济学**	**Ecological economics 生态经济学**
Typical focus	Incentives, external costs and benefits, non-market valuation	Biophysical scale, throughput, distribution and ecological limits
Useful question	How can institutions and prices account for omitted effects?	What activity is compatible with ecological limits and fair wellbeing?
Possible tools	Charges, permits, standards and valuation	Ecological limits, resource budgets and institutional redesign
Sustainability discussion	Often associated with **weak sustainability** 弱可持续性 and substitution assumptions	Often associated with **strong sustainability** 强可持续性 and limits to substitution

These descriptions do not make one instrument exclusive to one field. A price can help meet an ecological limit, and a legal limit can complement an incentive.

Weak sustainability says that if we use up a forest but build a school with the money,

total capital may be unchanged. Strong sustainability says that some natural capital, such as a stable climate, the ozone layer or a species, cannot be replaced by anything we build, so it must be kept.

Market failure and externalities

Why markets damage the environment

In a free market, buyers and sellers agree a price that covers the costs they pay themselves. **Market failure** 市场失灵 happens when the market does not produce the best result for society. Three causes matter most for the environment:



Traffic congestion: each driver bears their own cost but not the delay and pollution imposed on everyone else (an externality)

	excludable	non-excludable
rival	**private goods** timber from a private forest	**common-pool resources** fish stocks: overuse risk
non-rival	**club goods** a fee-paying nature park	**public goods** clean air, stable climate: free-riding risk

plus **externalities**:
costs outside the price

Goods by excludability and rivalry, with environmental examples

1. **Externalities** 外部性: costs or benefits that fall on people outside the transaction and are not included in the price.

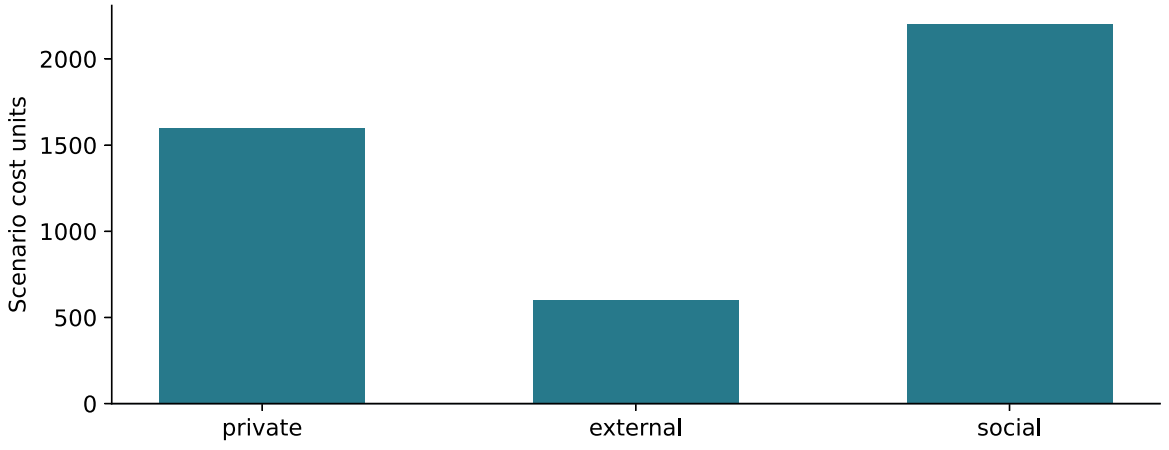
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2. **Public goods** 公共物品: goods that are **non-excludable** (excluding users is difficult or costly) and **non-rival** (one person's use does not reduce what others have), such as clean air or a stable climate. Free-riding can make voluntary private provision too low; public funding, collective rules and other institutions can support provision. Clean-air quality has public-good features, but the atmosphere's capacity to receive pollution is finite.
3. **Common-pool resources**: resources from which exclusion is difficult but use is rival, such as fish stocks; open access or weak governance can lead to overuse, while effective community rules can change the outcome (the tragedy of the commons, Topic 4).

■ Private, external and social cost

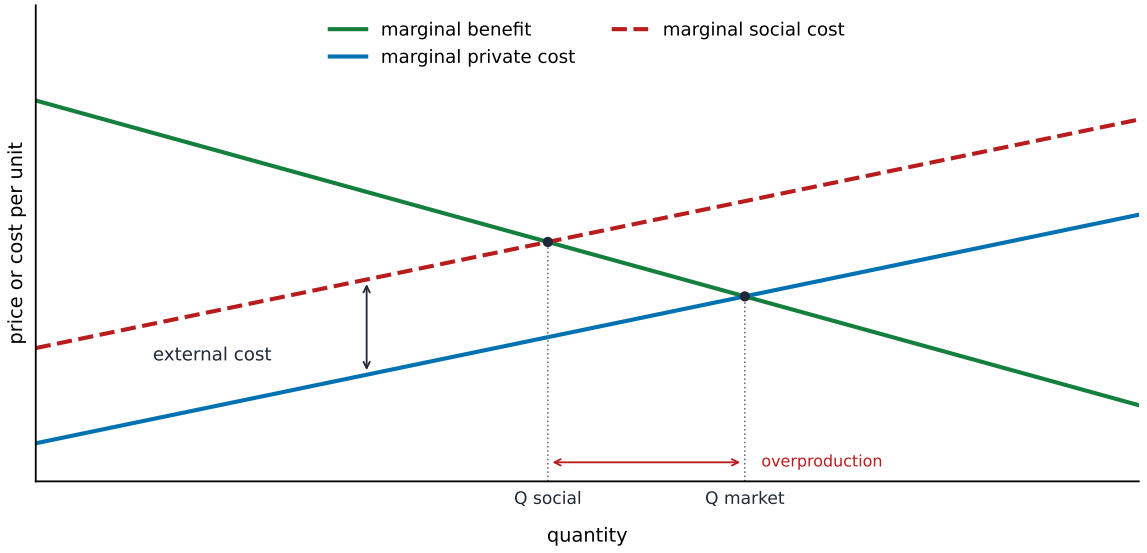
A **negative externality** is a cost imposed on others: a factory's smoke damages the health of people downwind, but the factory does not pay for it. A **positive externality** is a benefit to others: a farmer's hedges shelter wildlife and pollinators that help neighbouring farms.

$$\text{social cost} = \text{private cost} + \text{external cost}$$



Social cost = private cost + external cost = 1,600 + 600 = 2,200 units

When the market ignores external costs, the product is too cheap, so people buy and produce too much of it.



A negative externality leads to overproduction

In this simplified competitive model, demand represents marginal benefit, the supply curve marginal private cost, and the upper curve marginal social cost. There are no external benefits. The market produces where demand meets marginal private cost (Q market). Society would be best off where demand meets the full social cost (Q social). The difference is overproduction: units whose cost to society is greater than the benefit to buyers.

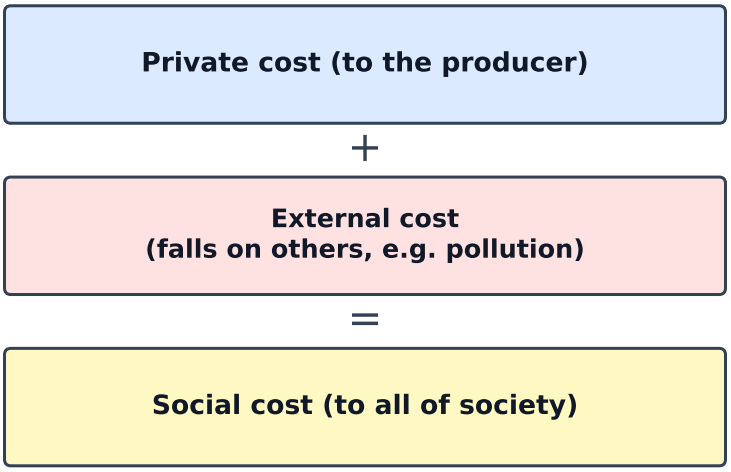
Climate change has been called "the greatest market failure the world has ever seen" (the Stern Review, 2006), because every tonne of CO_2 imposes costs on people around the world and in the future who have no say in the transaction.

Tools to correct market failure

Making the polluter pay

Economists use several tools to **internalise** externalities, that is, to bring external costs into the price.

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MSC = MPC + external cost

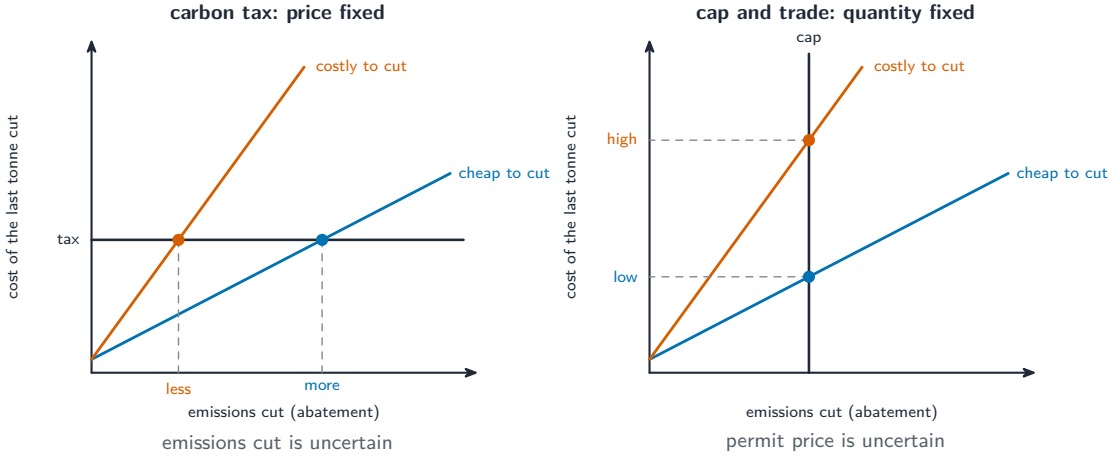
An external cost (e.g. pollution) falls on third parties, so the social cost is greater than the producer's private cost

Tool	How it works	Example
Pigouvian tax 庇古税	A corrective tax equal to marginal external damage at the target output in the simplified model	Sweden's carbon tax (introduced 1991; rates depend on year and fuel); China's environmental protection tax
Charges and fees	A small price on a harmful item	England's plastic bag charge (2015)
Cap and trade 总量控制与交易	A limit (cap) on total pollution, divided into permits that can be traded	EU ETS (2005); compare China's benchmark-based allocation rather than assuming an identical absolute cap
Subsidies	Payments that reward good practice or clean technology	Subsidies for electric vehicles and solar panels
Removing harmful subsidies	Ending payments that encourage damage	Fossil-fuel and fishing subsidies
Payment for ecosystem services 生态系统服务付费	Those who benefit from a service pay those who provide it	Costa Rica's forest payments; China's eco-compensation schemes

A charge that worked. When England introduced a 5 p charge on single-use plastic bags in large shops in 2015, the number sold by the main supermarkets fell by more than 95 % over the following years. The dated sales trend is consistent with an incentive effect; later charge changes, retailer practices and substitution also matter. A reduction in counted bags is not automatically the same percentage reduction in plastic waste or lifecycle damage.

Carbon tax or cap and trade?

Feature	Carbon tax 碳税	Emissions trading 排放交易
What is fixed?	The price of pollution	Covered quantity under a specified absolute cap
What is uncertain?	How much emissions will fall	What the price will be
Strengths	Simple; predictable for businesses; raises revenue	Can constrain covered emissions if monitored and enforced; trading can lower abatement cost
Weaknesses	Politically unpopular; emissions may not fall enough	Prices can collapse if too many permits are given; complex to monitor



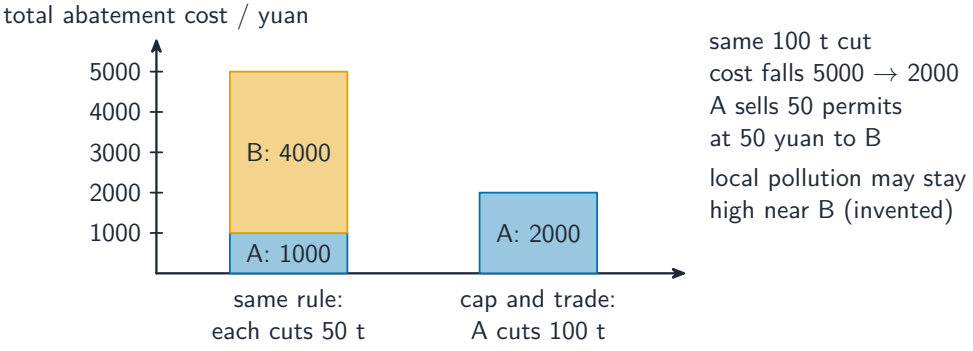
A tax fixes the price and leaves the cut uncertain; a cap fixes the quantity and leaves the price uncertain

The European Commission's 2024 progress report reports emissions from covered power and industrial installations in 2023 about 47.6% below 2005. Renewable generation, fuel switching and activity changes also matter; a before/after total does not isolate the causal effect of trading. Compare compatible sector coverage and dates, not a changing market price with a fixed timeless number. Allowance banking, offsets,

enforcement and allocation rules affect how a particular scheme works.

■ Worked example: why trading cuts the cost

In this example, two factories each emit 100 tonnes of the same pollutant. Costs per tonne are constant, A can technically eliminate its 100 tonnes, and the cap is enforced; real abatement costs often rise with additional cuts. The government wants total emissions cut by 100 tonnes. Factory A can cut emissions for 20 yuan per tonne; factory B's cuts cost 80 yuan per tonne.



Trading moves the cuts to the cheaper firm

1. **Same rule for both:** each must cut 50 tonnes. Cost $= 50 \times 20 + 50 \times 80 = 1000 + 4000 = 5000$ yuan.
2. **Cap and trade:** each receives permits for 50 tonnes. A cuts 100 tonnes at 20 yuan per tonne, costing 2000 yuan, and sells its 50 spare permits to B. B does not need to cut at all.
3. If the permits sell for 50 yuan each, A receives 2500 yuan (a gain of 500 over its cost of cutting) and B pays 2500 yuan instead of 4000.
4. The total reduction is still 100 tonnes, but the total cost falls from 5000 to 2000 yuan.

Trading lets cuts happen where they are cheapest. Critics point out that local pollution may stay high near factory B, which can be unfair to people living there.

■ Payment for ecosystem services in China

- **Grain for Green** 退耕还林 (since 1999) pays farmers to turn steep, eroding cropland back into forest or grassland. It is one of the largest payment-for-ecosystem-services programmes in the world, involving tens of millions of rural households, and it helped restore the Loess Plateau (Topic 5).
- **Eco-compensation** 生态补偿 on the Xin'an River (since 2012) links Anhui province upstream with Zhejiang province downstream. If the water crossing the border meets an agreed quality standard, Zhejiang pays Anhui; if it fails, Anhui pays Zhejiang. Upstream farmers and towns are paid to protect the clean water

that downstream cities such as Hangzhou depend on, and the river's water quality has stayed among the best in China.

PROVISIONING	REGULATING	CULTURAL	SUPPORTING
goods we take: food, timber, water, medicine	natural control: climate, floods, pollination, clean water	non-material: recreation, tourism, spiritual, education	underlie the rest: soil formation, nutrient cycling, habitat

The four kinds of ecosystem services

Valuing nature

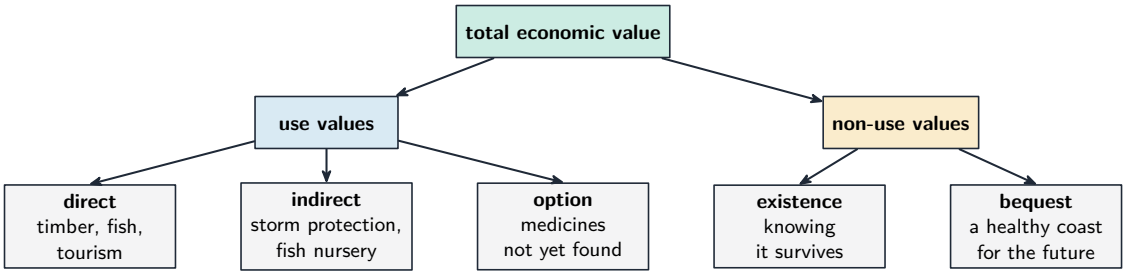
Total economic value

Many ecosystem services have no market price, so they are treated as if they were free. Economists try to estimate their **total economic value** 总经济价值:



Mangrove roots trap sediment, calm waves and shelter young fish: services worth money that no market price records

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Total economic value of a mangrove adds use and non-use values

Type of value	Meaning	Example (a mangrove forest)
Direct use value	Products and activities people use directly	Timber, fish, tourism
Indirect use value	Services that support other activities	Coastal storm protection, nursery for fish, carbon storage
Option value	Keeping the choice to use it in future	Undiscovered medicines
Existence value	Knowing it exists, even if you never visit	Knowing that wild tigers survive
Bequest value	Passing it on to future generations	A healthy coast for grandchildren

Methods include market prices (for timber or fish), the **travel cost method** (how much people spend to visit a national park), **hedonic pricing** (how much more houses cost near parks or clean lakes) and **contingent valuation** 条件价值评估, which asks people in surveys about their **willingness to pay** 支付意愿 to protect something.

A widely discussed ecosystem-services study estimated an annual value around 125 trillion US dollars for 2011. Such estimates depend on methods and assumptions; they are not cash revenue, a sale price for the biosphere or an amount that can simply be added to GDP. Check overlapping services to avoid double counting. China has begun measuring **gross ecosystem product** 生态系统生产总值 (GEP), the value of the services an area's ecosystems provide, alongside GDP. Lishui in Zhejiang was one of the first cities to use GEP to judge its officials' performance.

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Arguments for and against putting a price on nature

- **For:** decision-makers listen to numbers; omitting non-market effects can bias a monetary comparison; valuation can make some effects visible; values help design payments and fines.
- **Against:** some values cannot be measured honestly (what is a species worth?); surveys give different answers depending on how questions are asked; a price suggests that nature can be bought and replaced; it may favour what rich people are willing to pay for.

Cost-benefit analysis and discounting

Cost-benefit analysis 成本效益分析 adds up all the costs and benefits of a project, in money, to decide whether it is worthwhile. Because a benefit today is usually valued more than the same benefit in the future, future costs and benefits are reduced using a **discount rate** 贴现率:



Discounting, the idea behind NPV: the same £100 is worth less the longer you wait for it, so future cash flows are shrunk back to today's value

$$\text{present value} = \frac{\text{future value}}{(1+r)^t}$$

Worked example. Climate damage of 1 million yuan will happen in 100 years.

1. At a discount rate of 1 %: present value $= 1\,000\,000 \div 1.01^{100} = 1\,000\,000 \div 2.70 \approx 370\,000$ yuan.
2. At 5 %: present value $= 1\,000\,000 \div 1.05^{100} = 1\,000\,000 \div 131.5 \approx 7600$ yuan.

With a high discount rate, damage to future generations counts for almost nothing today, so strong action now looks too expensive. The Stern Review (2006) used a low discount rate and concluded that cutting emissions early was far cheaper than the damage; other economists used higher rates and recommended slower action. Choosing

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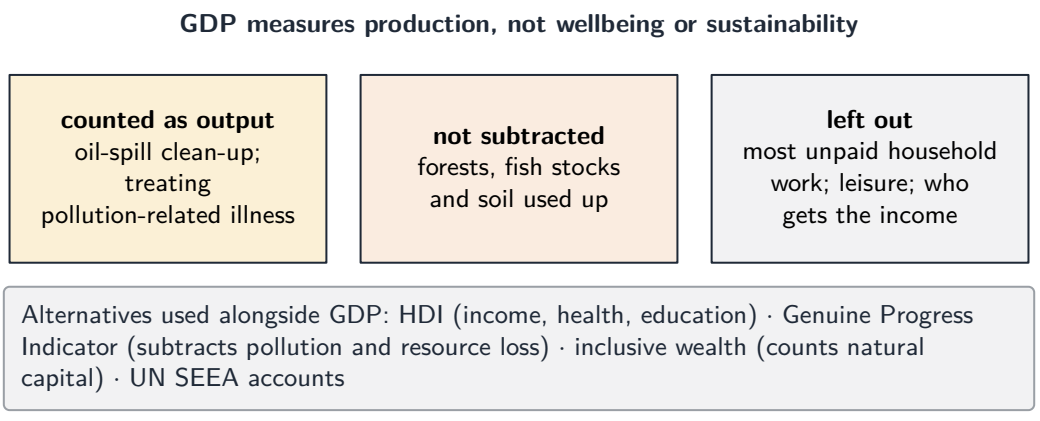
a discount rate is partly an **ethical** choice about how much future people matter (unit 11).

The **social cost of carbon** 碳的社会成本 is the estimated cost of the damage done by emitting one more tonne of CO_2. The EPA's 2023 report gave a central estimate of 190 in 2020 US dollars per metric tonne of CO_2 for emissions occurring in 2020, using its 2% near-term discount-rate case. This is a dated, assumption-dependent damage estimate, not a permit price or a claim about current administrative policy. Emission year, dollar year, discounting and model coverage affect comparisons.

Growth, limits and alternatives

■ Is GDP a good measure of progress?

Gross domestic product 国内生产总值 (GDP) measures domestic production of final goods and services over a stated period, or equivalently value added; intermediate transactions are not all added again. Some non-market production is valued through national-accounting conventions. It is not designed to measure wellbeing or sustainability:



GDP measures production: clean-up counts as output, lost natural capital is not subtracted, and unpaid work is left out

- It counts the cost of cleaning up an oil spill or treating pollution-related illness as growth.
- It does not subtract the loss of forests, fish or soil (natural capital is used up but counted as income).
- It omits much unpaid household work and does not directly measure leisure, distribution or ecological condition.

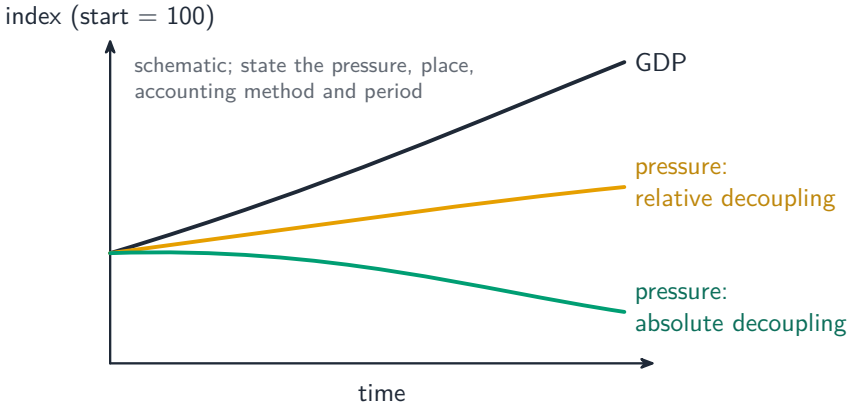
Alternatives include the Human Development Index (income, health and education), the Genuine Progress Indicator (which subtracts pollution and resource loss), inclusive wealth (which counts natural capital) and the UN System of Environmental-Economic Accounting, which many governments now use alongside GDP.

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For a production chain, a farm sells grain for 100 units, a mill sells flour for 160, and a baker sells final bread for 250. Final output is 250; value added is 100+(160−100)+(250−160)=250. Adding every sale gives 510 and double counts intermediate value. GDP can be measured without counting the same production repeatedly, yet it still does not directly measure wellbeing or ecological sustainability.

Can growth be green?

Decoupling 脱钩 means GDP grows while environmental pressure grows more slowly (relative decoupling) or falls (absolute decoupling). A dated territorial-emissions series can demonstrate one country's absolute decoupling from GDP, but consumption-based emissions include imported production. Do not infer global decoupling, every environmental pressure or permanent success from one territorial trend. Specify the pressure, geography, accounting method and period.



Relative and absolute decoupling (schematic)

The **environmental Kuznets curve** 环境库兹涅茨曲线 suggests that some pollution first rises as a country industrialises and then falls as it becomes richer and can afford cleaner technology, as with sulfur dioxide in Europe and China. An inverted-U relationship is a hypothesis for particular pollutants and contexts, not a law that income growth automatically repairs climate or biodiversity damage.

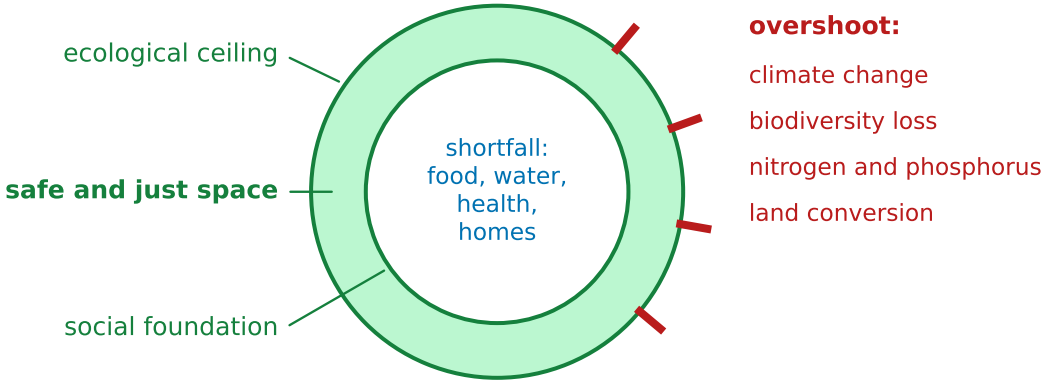
The **rebound effect** 回弹效应 can cancel some efficiency gains: when cars use less fuel, driving becomes cheaper, so people may drive more.

Ecological economics: limits and wellbeing

- **Steady-state economy** 稳态经济 (Herman Daly): the economy should keep its throughput of energy and materials at a level the biosphere can sustain, improving quality rather than growing in size.
- **Degrowth** 去增长: rich countries should deliberately reduce production and consumption, while sharing income more fairly, so that poorer countries can still develop.

- **Green growth** 绿色增长: the opposing view that innovation and clean energy allow growth to continue without increasing environmental damage.

Doughnut economics 甜甜圈经济学 (Kate Raworth, 2017) combines social and ecological goals in one picture.

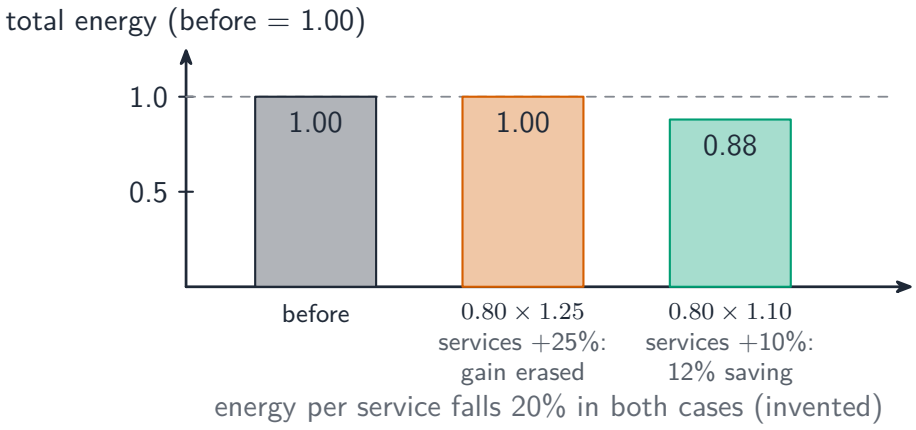


Doughnut economics: the safe and just space for humanity (schematic)

The aim is to meet everyone's basic needs (staying above the social foundation) without overshooting planetary boundaries (staying below the ecological ceiling). Today the world falls short on the inside and overshoots on the outside at the same time. Amsterdam's 2020–2025 circular strategy applied a doughnut framework; adoption is not evidence that the city has met every social and ecological goal. The figure is schematic, not a measured current global or city assessment.

■ Test efficiency and distribution with invented data

A device's energy use per service falls 20%, but services used rise 25%. Total energy multiplier is $0.80 \times 1.25 = 1.00$: no total saving remains under these assumptions. If services rise only 10%, total multiplier is 0.88, a 12% fall; rebound need not erase all gains. Separate engineering efficiency from actual total use, and do not assume rebound always exceeds 100%.



Rebound can erase or only trim an efficiency gain

For a wetland project, compare construction cost, maintenance, avoided flood damage and habitat indicators over the same period. Do not add a property-price increase to a full willingness-to-pay estimate if they capture the same benefit. A positive monetary net benefit can coexist with relocation costs for a low-income group; show distribution and rights as well as the aggregate. Environmental accounting can track stocks, depletion and services in physical as well as monetary units. Greenwashing occurs when environmental marketing is misleading relative to evidence; assess the claimed boundary, lifecycle and verified change rather than assuming any green label proves performance.

■ Using the economics lens in an answer

When you apply this lens to a case study, ask:

1. Which externality or market failure causes the problem?
2. Who pays, who benefits, and who is left out of the market?
3. Which tool (tax, permits, subsidy, payment for ecosystem services) could correct it, and what are its strengths and limits?
4. How are non-market values and future generations counted?
5. Does the answer assume that growth can continue, or that the economy must stay within limits?

Practice

1. (a) Distinguish between environmental economics and ecological economics. (b) Distinguish between weak and strong sustainability, with an example.
2. (a) Explain what is meant by an externality, with one negative and one positive example. (b) Explain why clean air is a public good, and why markets do not provide enough of it.

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3. A product has a private cost of 12 yuan and an external cost of 5 yuan per unit. Calculate the social cost and the tax needed to internalise the externality. Assume the external cost per extra unit is constant in this model.
4. Using a diagram, explain why a negative externality causes overproduction.
5. Compare a carbon tax with a cap-and-trade system.
6. Factory A can cut pollution for 30 yuan per tonne and factory B for 90 yuan per tonne. Each must cut 40 tonnes. Calculate the total cost with a fixed rule and with trading, if A makes all 80 tonnes of cuts. Assume constant marginal abatement costs, sufficient feasible cuts at A and an enforced cap.
7. Explain how payment for ecosystem services works, with a named example.
8. Outline the components of total economic value for a wetland.
9. Evaluate the use of contingent valuation to value biodiversity.
10. Damage worth 2 million yuan will occur in 50 years. Calculate its present value at discount rates of 2 % and 6 %, and comment.
11. Explain three limitations of GDP as a measure of progress.
12. Distinguish between relative and absolute decoupling. Calculate total energy change for 20% less energy per service but 25% more services.
13. Outline doughnut economics.
14. Evaluate the claim that putting a price on nature is the best way to protect it.

Answers.

1. (a) Environmental economics often examines incentives, externalities and valuation; ecological economics emphasizes biophysical limits, scale and distribution. These are overlapping emphases, not a claim that environmental economists deny nature's physical role or that every member supports one growth policy. (b) Weak sustainability permits substitution among forms of capital if the stated aggregate is maintained, subject to its assumptions. Strong sustainability protects critical natural capital that cannot adequately be substituted. A new school can provide benefits but cannot by itself replace the ecological functions of a lost forest.
2. (a) An externality is a cost or benefit to people outside a transaction that is not included in the price. Negative: smoke from a factory harming health downwind. Positive: hedges planted by a farmer supporting pollinators for neighbouring farms. (b) Clean-air quality has non-excludable and non-rival features, encouraging free-riding and underprovision by voluntary private markets. Exclusion can be difficult or costly rather than logically impossible. The atmosphere's pollution-assimilation capacity is finite and can be rival; distinguish air quality from unlimited waste disposal.
3. Under the stated constant per-unit model, social cost=12+5=17 yuan per item and a 5-yuan charge matches the marginal external cost. In a variable-damage model, the corrective tax relates to marginal damage at the target output, not an arbitrary average total cost.

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4. The market produces where demand equals private cost. The social cost curve lies above the private cost curve by the external cost, so the socially best quantity, where demand equals social cost, is smaller. The market therefore produces too much, at too low a price.
5. A carbon tax fixes a price while covered emissions responses can vary. A specified absolute cap can constrain covered quantity if monitored and enforced, while allowance prices vary. Trading can lower abatement cost, but banking, offsets, allocation and non-compliance matter. China's benchmark-based intensity allocation should not be described as identical to this fixed-cap model.
6. Fixed rule: $40 \times 30 + 40 \times 90 = 1200 + 3600 = 4800$ yuan. Trading: A cuts 80 tonnes at 30 = 2400 yuan. The same total cut costs 2400 yuan less.
7. Those who benefit from an ecosystem service pay those who provide it, so protecting the service earns money. Example: on the Xin'an River, downstream Zhejiang pays upstream Anhui if the water reaching the border meets a quality standard; or Grain for Green pays farmers to restore forest on steep land.
8. Direct use (fish, reeds, tourism); indirect use (flood control, water purification, carbon storage); option value (possible future uses such as medicines); existence value (knowing it and its birds exist); bequest value (leaving it for future generations).
9. Strengths: it can value things with no market, such as existence value; it gives decision-makers numbers. Limits: answers depend on how questions are asked and on people's income; people may state values they would not really pay; some people refuse to put a price on a species. It is useful as a rough guide but not a precise measure.
10. 2 % rate: $2\,000\,000 \div 1.02^{50} = 2\,000\,000 \div 2.69 \approx 743\,000$ yuan. 6 % rate: $2\,000\,000 \div 1.06^{50} = 2\,000\,000 \div 18.4 \approx 109\,000$ yuan. A higher discount rate makes future damage look much smaller, so it weakens the case for acting now; the choice of rate is partly ethical.
11. Any three: it counts clean-up and pollution-related spending as growth; it does not subtract the loss of natural capital; it ignores unpaid work and leisure; it says nothing about how income is shared; it does not measure wellbeing.
12. Relative decoupling means the specified pressure grows more slowly than GDP; absolute decoupling means it falls while GDP grows. State boundary, period and pressure, including territorial versus consumption accounting. The energy multiplier $0.8 \times 1.25 = 1.00$ gives no total energy saving; a service-level efficiency gain alone does not establish absolute decoupling.
13. Kate Raworth's model has an inner ring, the social foundation of human needs, and an outer ring, the ecological ceiling of planetary boundaries. The goal is the safe and just space between them: meeting everyone's needs without overshooting the planet's limits.
14. For: decision-makers respond to money; unmeasured non-market effects may be omitted from a monetary comparison; prices and payments (carbon markets, eco-compensation) have changed behaviour. Against: many values cannot be mea-

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sured; a price suggests nature can be replaced or bought; poor people's values may count less; markets can fail if prices are set too low. Pricing is a useful tool, but it works best alongside laws, protected areas and ethical arguments.

Exam tips

- Use the terms externality, market failure, public good and internalise correctly.
- Say whether you are using an environmental-economics or an ecological-economics view.
- For each tool, state what it fixes (price or quantity), give a named example and weigh strengths against limits.
- Show working in social cost, trading and discounting calculations.
- Link the choice of discount rate and the valuing of nature to ethics (unit 11).

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Environmental ethics

International Baccalaureate · IB Diploma · Environmental Systems and Societies · HL

Scope and prerequisites

This handout teaches HL lens c, Environmental ethics, for the course first assessed in 2026. It is for HL students only. Ethics is one of three HL lenses, with environmental law (unit 9) and environmental and ecological economics (unit 10), that you apply to the case studies of Topics 1 to 8.

Prerequisites: Topic 1 (environmental value systems, perspectives and sustainability), Topic 3 (the value of biodiversity and conservation), Topic 6 (climate change) and units 9 and 10.

What environmental ethics asks

The last turtles

In April 2019 a female Yangtze giant softshell turtle died at Suzhou Zoo during recovery after an artificial-insemination procedure. WCS's account explains the conservation effort; "last known" describes knowledge at that time, not proof that no undiscovered animals exist. Do not turn an old count into a timeless claim that the species is certainly doomed. How should limited conservation funds be allocated when outcomes are uncertain? Evidence can inform survival prospects, costs and alternatives. It cannot by itself establish which interests ought to have priority: a moral argument also needs a stated value principle.

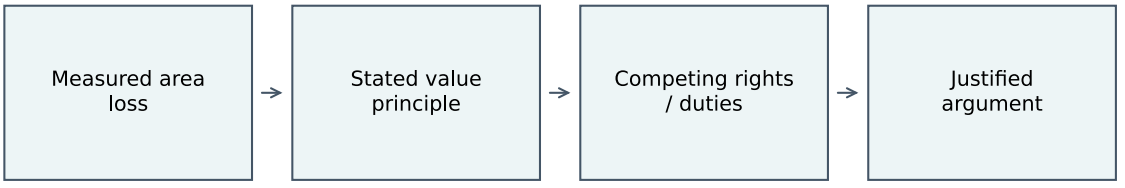
Facts and values

Environmental ethics 环境伦理 is the study of what is morally right and wrong in how humans treat the environment, and why. It begins by separating two kinds of statement:

- A **descriptive** 描述性 claim says what is the case and can be tested with evidence: "The project will drain 12 hectares of a 60-hectare wetland (20 %)."
- A **normative** 规范性 claim says what ought to be the case and depends on values: "The wetland should be protected."

You cannot reach a normative conclusion from facts alone: you also need a value principle. Good ethical arguments make that principle explicit.

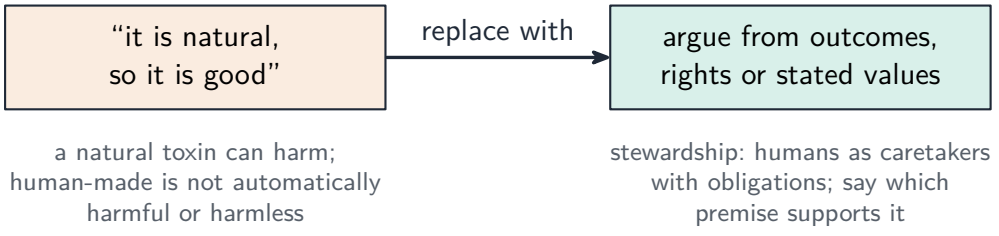
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Measure the change first, then argue from a stated value position

Context, stewardship and an appeal to nature

Modern academic environmental ethics expanded in the 1960s and 1970s as pollution and ecological crises prompted questions about the moral standing of non-human and non-living nature. This does not mean earlier cultures lacked environmental ethical reasoning. Environmental and social-justice movements have different histories but can share concerns about exploitation, participation and unequal burdens; their priorities can also conflict and need argument rather than assumed agreement.



An origin label is not an argument

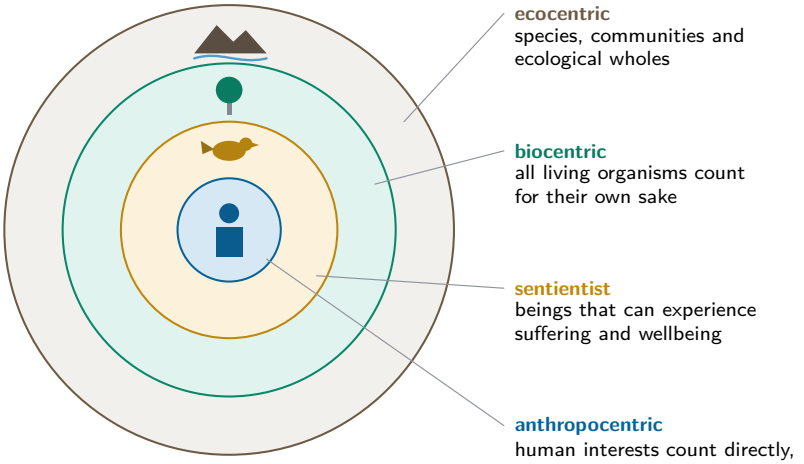
Stewardship treats humans as responsible caretakers with obligations towards the world and those who depend on it. Religious or secular premises can support stewardship; specify the actual reason rather than assigning it automatically to a whole culture. A belief in technology's ability to solve a problem is also different from deciding whose interests count morally.

The **appeal to nature** claims that something is right or good merely because it is natural. Natural origin alone does not establish safety, wellbeing or moral acceptability: a naturally occurring toxin can cause harm. Equally, being human-made does not establish that a thing is harmless or harmful. Valuing a wild place for its own sake is a stated value position; it is not evidence that every natural process is beneficial. Explain outcomes, rights or other premises rather than using an origin label as the whole argument.

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Who counts? Moral standing

An entity has **moral standing** 道德地位 if its interests or wellbeing count for their own sake in our decisions. Ethical positions differ in whose interests count directly; these are analytical categories, not one inevitable historical progression or a ranking of cultures.



wider rings compare whose interests count directly
not a ranking, a ladder or a historical sequence
positions can overlap

Compare the scope of a reason, not a moral-development ladder or a fixed identity for a person.

These positions link to the environmental value systems of Topic 1:

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Position	Who has moral standing?	Thinkers and ideas
Anthropocentric 人类中心主义	Humans only, including future generations; nature has **instrumental value** 工具价值 as a means to human ends	Most economic and legal systems; "wise use" of resources
Sentientist	Humans and all animals that can feel pain	Jeremy Bentham: "The question is not, Can they reason? ... but, Can they suffer?"; Peter Singer, *Animal Liberation* (1975)
Biocentric 生物中心主义	Every living organism has **intrinsic value** 内在价值, value in itself	Albert Schweitzer's "reverence for life"; Paul Taylor
Ecocentric 生态中心主义	Whole species, ecosystems and the biosphere have value, not just individuals	Aldo Leopold's land ethic (1949); Arne Naess's **deep ecology** 深层生态学 (1973)

Leopold's land ethic places people within a biotic community and emphasizes its integrity, stability and beauty. It directs attention to ecological wholes without making every ecocentric support the same policy. A person may prioritize a seabird colony's survival while also requiring humane methods and evidence that invasive-rat removal will work. Animal-welfare reasoning may oppose suffering, support a less harmful alternative or compare harms to several sentient species; it does not mechanically imply one verdict.

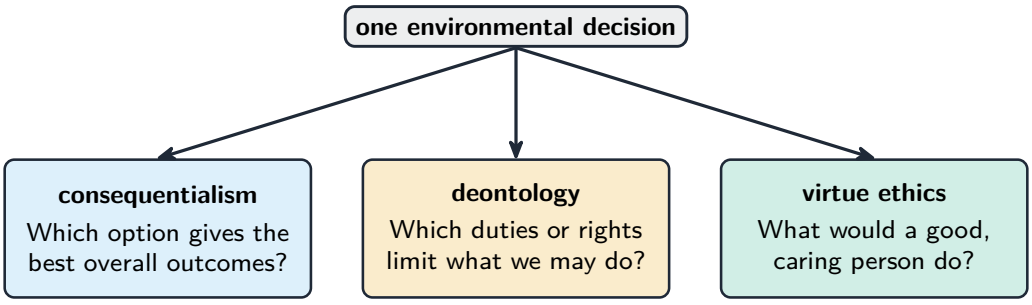
These are labels for kinds of argument, not fixed boxes for people or cultures. Most people combine several positions, and their views shift with the issue.

Ethical theories

■ Three main approaches

Philosophers judge actions in different ways. Each can be applied to environmental choices.

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Three ethical approaches ask different questions of the same decision.

Theory	What makes an action right?	Applied to the environment	Weaknesses
Consequentialism 后果主义 (such as utilitarianism)	Consequences under a stated account of good; utilitarian variants assess aggregate welfare	Compare expected outcomes, severity, distribution and alternatives; monetary cost-benefit analysis is one limited tool	Outcomes are hard to predict and measure; a minority may be sacrificed for the majority
Deontology 义务论 (duty and rights)	Duties and rights constrain choices; theories differ over conflicts and exceptions	Some acts are wrong even if profitable, such as driving a species to extinction or polluting someone's water; rights of nature (unit 9)	Duties can conflict; justify priorities and explain how consequences are considered
Virtue ethics 美德伦理	Acting as a good person would, with good character	Humility, moderation, care, respect for life; living simply	Gives less clear guidance in hard cases

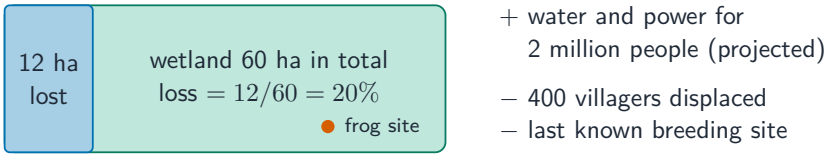
Other important traditions include **care ethics**, which stresses relationships and responsibility for the vulnerable, and many **indigenous** 原住民 worldviews, which see people as relatives within a network of land, water, animals and ancestors, with duties of **reciprocity** 互惠 (giving back for what is taken).

Chinese traditions have their own resources. The Daoist teaching that **the Way follows nature** 道法自然 and the Confucian ideal of the **unity of heaven and humanity** 天人合一 can inform interpretations of relationships between people and the world, and Mencius discusses avoiding fine-meshed nets as part of sustaining re-

sources. Interpret these traditions in their historical contexts: "nature" in an ancient philosophical translation is not identical to a modern conservation policy, and people within a tradition disagree. In 2018 China wrote the goal of building an **ecological civilisation** 生态文明 into its constitution.

■ Worked example: one decision, three theories

In an **invented** planning case, a reservoir is projected to supply water and power to 2 million people, remove 12 hectares of a 60-hectare wetland and displace 400 villagers. The affected area contains the last known breeding site of a local frog species. These are scenario assumptions, not observations or proof that every promised benefit will occur.



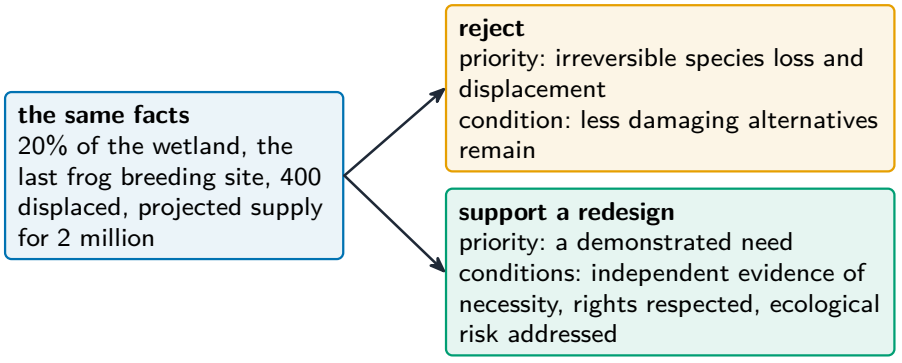
consequences, duties and virtues weigh the same facts differently (invented scenario)

The reservoir case: the same facts for three theories

1. **Descriptive evidence:** area loss=12/60×100=20%; identify the projected benefits, displaced people and potential species-level risk. A last breeding site is not safely dismissed as merely "one population". Test forecasts, habitat quality, hydrology and alternatives.
2. **Consequentialist reasoning:** compare expected benefits and harms, their probabilities, severity, duration and distribution. Two million beneficiaries versus 400 displaced people is not a sufficient calculation: many small gains do not automatically outweigh severe loss of homes or irreversible ecological damage. A consequentialist could support, reject or redesign the project depending on this evidence and the stated outcome standard.
3. **Rights and duties:** examine affected people's rights, participation and treatment, and any argued duty towards other species. Identify conflicting duties and justify priorities; do not assume one framework always ignores consequences.
4. **Virtue, care and ecocentric reasoning:** consider humility under uncertainty, relationships, vulnerable groups, wetland integrity and alternatives such as demand reduction or another site. Institutions and access affect what choices people can make.
5. **A justified judgement:** make the priority and conditions explicit. One defensible answer might reject the proposal because irreversible species loss and displacement outweigh the demonstrated need when less damaging alternatives remain. Another might support a redesigned option if independent evidence establishes necessity, rights are respected and ecological risks are acceptably addressed. Moving frogs

or promising captive breeding is not proof of a viable replacement population or restored habitat.

The 20 % figure cannot decide the question on its own. Different frameworks weigh the same facts differently, and a good answer shows this.



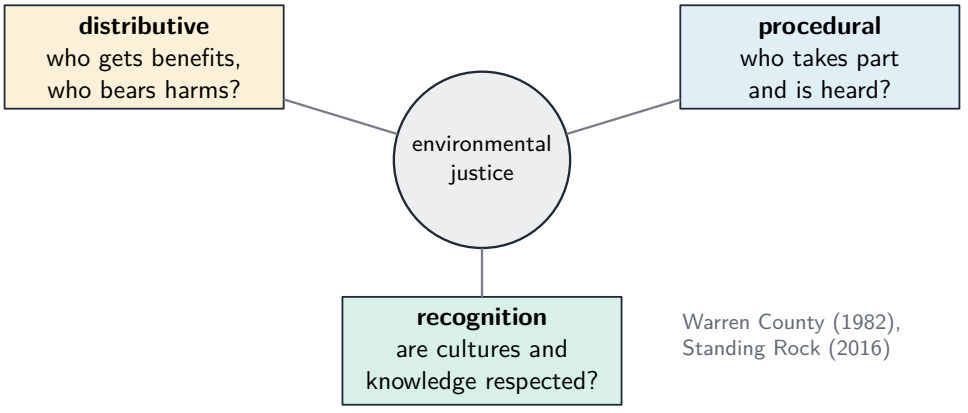
a good answer states its priority and conditions; the 20% alone decides nothing

One set of facts, two defensible judgements, each with its priority and conditions

Justice and responsibility

■ Environmental justice

Environmental justice 环境正义 is the fair sharing of environmental benefits and burdens, and fair involvement in decisions. It has three parts:



The three parts of environmental justice

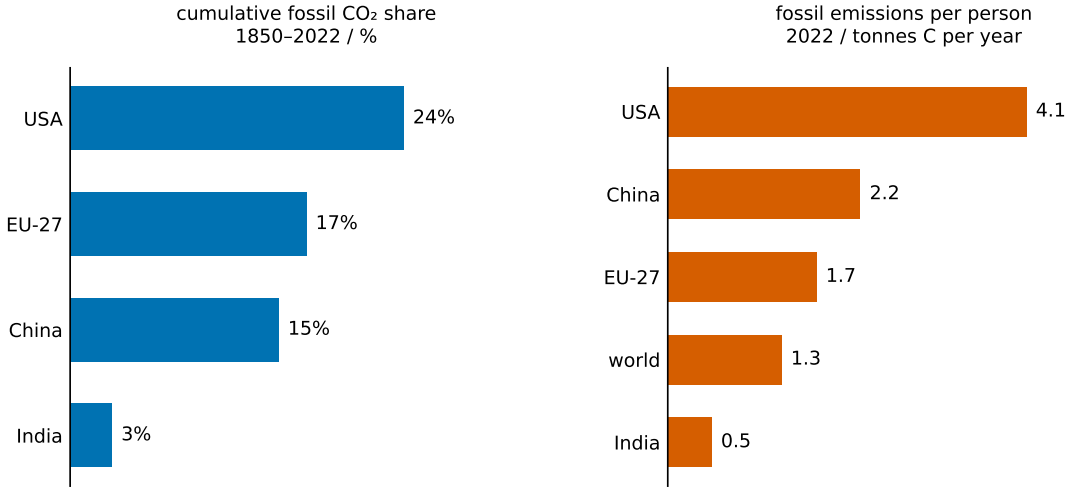
- **Distributive justice** 分配正义: who gets the benefits and who bears the harms? Polluting factories, landfills and incinerators are often sited near poor or minority communities.

- **Procedural justice** 程序正义: who takes part in decisions? Are affected people informed and heard?
- **Recognition**: are different cultures, knowledge and ways of life respected?

The modern movement is often traced to Warren County, North Carolina, in 1982, when a mostly Black community protested against a landfill for toxic PCB waste. In 2016 the Standing Rock Sioux opposed the Dakota Access oil pipeline near their water supply and sacred sites. The philosopher John Rawls suggested a test: choose the rules for a society from behind a "veil of ignorance", not knowing whether you would be rich or poor, live upstream or downstream, or be born now or in 100 years.

Climate justice

Climate change raises sharp questions of justice, because those who caused least of the problem often suffer most from it.



Source: Global Carbon Budget 2023, rounded reported values for selected regions. Historical totals and per-person rates answer different questions.

The paper reports cumulative fossil CO_2 shares for 1850–2022 of 24% for the USA,17% for EU-27,15% for China and 3% for India. The selected shares do not sum to 100%; other regions are not shown. Its 2022 per-person figures are in **tonnes of carbon**, not CO_2:4.1 for the USA,2.2 for China,1.7 for EU-27,1.3 globally and 0.5 for India. Carbon mass converts to CO_2 mass by 44/12; for example the reported rounded 2.2 tonnes C corresponds to about 8.1 tonnes CO_2. Use the source's units and edition, distinguish territorial fossil emissions from all greenhouse gases, land-use emissions and consumption footprints, and do not label these as current 2026 values.

How should the cost of cutting emissions and adapting be shared? Different principles give different answers:

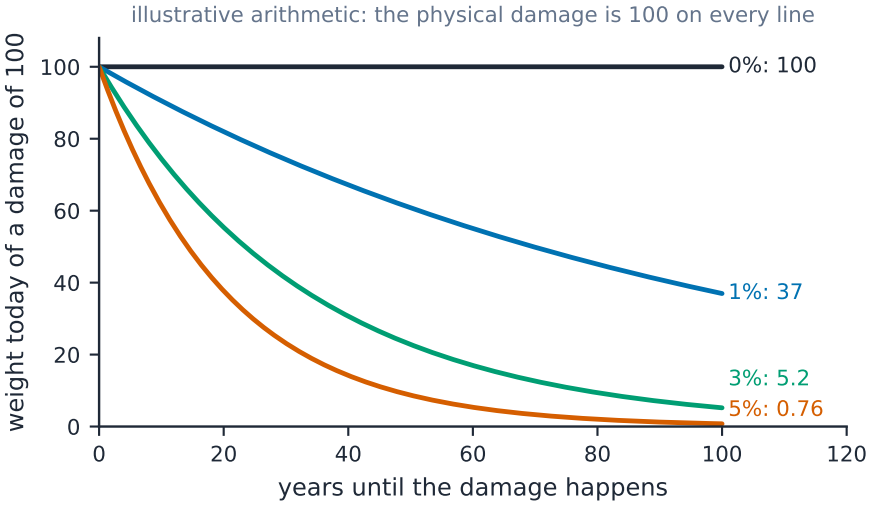
Principle	Who should pay most?	Problem
Polluter pays (historical responsibility)	Those who emitted most in total since industrialisation, such as the USA and Europe	Period, knowledge, benefits, attribution and within-country inequalities require argument
Beneficiary pays	Those who grew rich from fossil fuels	Hard to measure benefits
Ability to pay	The richest countries and people	Ignores who caused the problem
Equal per-person shares	Allocate a specified carbon budget equally per person; implementation determines cuts and transfers	Choice of budget, period, development needs and history matters

The UN climate treaties use **common but differentiated responsibilities** (unit 9), and in 2022 countries agreed to set up a **loss and damage** 损失与损害 fund to help vulnerable countries that suffer climate harm they cannot adapt to. The UNEP 2020 report, chapter 6, describes a range of studies estimating the global top 10%of income earners at 36–49%of consumption emissions. This is a dated range across methods, not an exact current statistic for every country. Income groups within a country are not interchangeable with a country average.

■ Future generations

Intergenerational equity 代际公平 asks how present decisions should treat future people fairly; different theories debate what obligations follow. They cannot vote, buy or protest, yet they will live with today's choices about climate, extinctions and nuclear waste. The Brundtland definition of sustainable development (Topic 1) is itself an ethical statement: meeting the needs of the present "without compromising the ability of future generations to meet their own needs". A discount rate involves economic assumptions as well as ethical choices about time and distribution (unit 10); it does not change the physical future damage.

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A discount rate shrinks the weight of a future damage, not the damage

Applying ethics to environmental issues

■ Ethical questions in conservation

Conservation is full of choices that facts alone cannot settle:



A wandering albatross on its nest on Prion Island, South Georgia: the island's ground- and burrow-nesting seabirds are what the 2011-2015 rat eradication set out to protect

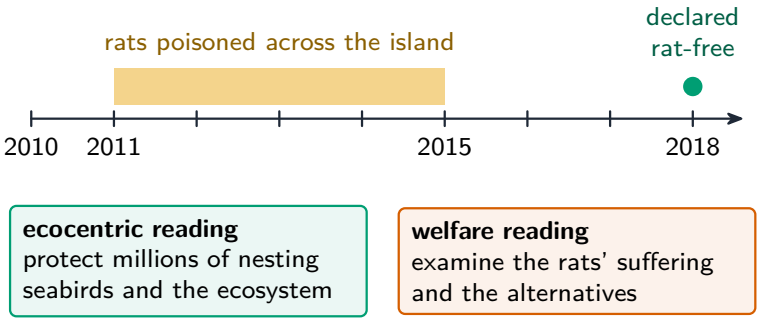
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The giant panda moved from Endangered to Vulnerable in 2016 on wild-population evidence; captive breeding's share in that recovery must be shown, not assumed

- **Culling invasive species:** rats were poisoned across South Georgia island between 2011 and 2015 to save millions of nesting seabirds; the island was declared rat-free in 2018. An ecocentric argument may emphasize seabird and ecosystem protection, while welfare arguments examine suffering and alternatives; do not infer each participant's motive from a label.
- **Zoos and captive breeding:** the giant panda's 2016 IUCN change from Endangered to Vulnerable concerned the wild population and conservation evidence; it is not proof that captive breeding alone caused recovery. Evaluate a particular zoo's demonstrated conservation contribution, welfare and alternatives rather than inferring benefit from the label.
- **Trophy hunting:** fees paid by wealthy hunters can fund conservation and local communities, but many people think killing animals for sport is wrong whatever the outcome.
- **Triage:** with limited money, should conservation focus on species most likely to recover, or the rarest, or the most loved?
- **De-extinction:** should we try to bring back extinct species using genetic technology, or spend the money protecting species that still exist?

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South Georgia: one set of facts, two value positions

Ethics of new technologies

- **Solar radiation modification:** proposals such as stratospheric particle injection aim to alter Earth's radiation balance. Benefits, regional rainfall effects, governance, unequal risk and termination risk require assessment. This is distinct from removing CO_2 and does not by itself address rising atmospheric CO_2 or ocean acidification. Research and deployment are different decisions; neither a claimed benefit nor a fear alone establishes what should be permitted.
- **Genetically modified crops:** compare a specified trait, crop and farming context. Yield and pesticide outcomes are not universal properties of every GM crop. Evaluate gene flow, evidence of benefits and harms, ownership arrangements and the choices available to farmers and consumers.

How to build an ethical argument

1. State the facts clearly and separately from the values (descriptive claims first).
2. Identify the stakeholders, including those with no voice: future generations, other species, distant communities.
3. Apply at least two ethical positions or theories and show how they lead to different conclusions.
4. Consider rights, justice and fairness: who gains, who loses, who decides?
5. Reach a reasoned judgement, stating which principle you weigh most and why, and acknowledge the strongest opposing view.

Practice

1. (a) Distinguish between a descriptive and a normative claim, with an example of each. (b) Distinguish between intrinsic value and instrumental value.

2. (a) Outline what is meant by moral standing, and explain how anthropocentric, biocentric and ecocentric positions differ on it. (b) Explain Aldo Leopold's land ethic.
3. Explain why an ecocentric and an animal-welfare view might disagree about culling invasive rats on an island.
4. Compare consequentialist and deontological approaches to environmental decisions.
5. Outline virtue ethics and apply it to personal consumption.
6. A project will clear 15 hectares of a 50-hectare forest. Calculate the percentage lost, and explain why this number alone does not decide whether the project is right.
7. Explain the three parts of environmental justice, with an example.
8. Using the emissions data, explain why responsibility for climate change can be measured in different ways.
9. Compare the polluter pays and ability to pay principles for sharing the costs of climate action.
10. Explain what is meant by intergenerational equity, and how the discount rate is an ethical choice.
11. Outline how Chinese philosophical traditions view the relationship between humans and nature.
12. Discuss the ethics of keeping endangered animals in zoos.
13. Evaluate geoengineering from two ethical perspectives.
14. Using the ethics lens, evaluate a decision to build a reservoir that floods a wetland and moves a village. Critique an appeal to nature and explain how a stewardship argument could inform the decision.

Answers. Reasoning follows. Several ethical conclusions can be defensible; assess evidence, principles, counterarguments and justification.

1. (a) Descriptive: says what is the case and can be tested, such as "the dam will flood 12 hectares". Normative: says what ought to be done and depends on values, such as "the wetland should be protected". (b) Intrinsic value is value in itself, regardless of usefulness to anyone. Instrumental value is value as a means to an end, such as timber or flood protection that benefit people.
2. (a) Moral standing means an entity's interests count for their own sake. Anthropocentric: only humans (including future generations). Biocentric: every living organism. Ecocentric: also whole species, ecosystems and the biosphere. (b) Leopold (1949) argued that people are members of a biotic community, not its conquerors. An action is right when it preserves the integrity, stability and beauty of that community and wrong when it does not, so the whole ecosystem is the focus of moral concern.
3. An ecocentric reason may emphasize seabird survival and ecosystem integrity; an

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animal-welfare reason assesses suffering and effects on sentient beings, including both rats and birds. Either can consider humane alternatives and uncertain effectiveness. These are possible arguments, not guaranteed verdicts or fixed identities.

4. Consequentialist reasoning evaluates outcomes under a stated account of good, including uncertainty, severity, distribution and alternatives. Deontological reasoning emphasizes rights and duties that constrain choices; approaches differ over conflicting duties and exceptions. Neither a head count nor a policy conclusion uniquely identifies a framework.
5. Virtue ethics emphasizes character and practices such as moderation, humility and care. A reasoned consumption example might reduce avoidable waste and consider effects on others; needs, access and infrastructure constrain choices, so one purchase does not establish a whole character.
6. $15 \div 50 \times 100 = 30$ %. The percentage is a descriptive fact; whether the loss is acceptable depends on values, such as the forest's species, its meaning to local people, who benefits, alternatives and which ethical framework is used.
7. Distributive: fair sharing of benefits and harms, such as incinerators sited near poor communities. Procedural: fair involvement in decisions, such as consultation of affected villagers. Recognition: respect for different cultures and knowledge, such as indigenous rights at Standing Rock.
8. The dated source gives cumulative fossil shares for 1850–2022:USA 24%,EU-27 17%,China 15%,India 3%. Its 2022 per-person data are in tonnes C:4.1 USA,2.2 China,1.7 EU-27,1.3 world,0.5 India. For example $2.2 \times 44/12 \approx 8.1$ tonnes CO_2 from the rounded value. Different periods, boundaries and units answer different factual questions; moving from an emission metric to a duty to pay requires a stated ethical principle, not a label of "most responsible" presented as a pure measurement.
9. Polluter pays: those who emitted most historically should pay, linking cost to responsibility; but people today did not choose past emissions and early emitters did not know the harm. Ability to pay: the richest should pay, because they can bear the cost; but this ignores who caused the problem. Many proposals combine both.
10. Intergenerational equity concerns fair treatment of future people and the environment on which they depend. A high discount rate reduces present monetary weighting of distant harms without reducing their physical severity. Rate choice includes economic, uncertainty and ethical assumptions; explain what obligations and priorities are being argued.
11. Examples include interpretations of Daoist naturalness, Confucian relationships between humanity and heaven, and Mencius's resource-use advice. Traditions and interpretations differ; do not treat all Chinese people or ancient thinkers as holding one modern environmental policy. Ecological civilisation is a modern constitutional goal, distinct from proving ancient and present ideas identical.
12. Possible benefits include demonstrated contributions to conservation, research or

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education; possible harms include restricted behaviour, poor welfare, opportunity costs and ineffective programmes. A 2016 wild-panda status change is not evidence that captive breeding alone produced recovery. A justified answer assesses a specified programme, alternatives and ethical principles rather than endorsing or rejecting every zoo automatically.

13. A consequence-based argument compares uncertain cooling benefits, regional harms, termination risk and alternatives. Rights and justice reasoning asks who decides, who is exposed and whose consent or interests are respected. Research differs from deployment; solar radiation modification does not remove CO_2 or by itself solve ocean acidification. Explain the evidence, priority, strongest objection and conditions behind a judgement.
14. Separate projections from observations; calculate area loss but assess habitat function and species-level risk. Compare expected benefits, severe displacement, rights, participation, uncertainty and alternatives through at least two frameworks. Several reasoned judgements are possible; a large beneficiary count or a promised frog relocation alone is not sufficient justification. Natural origin alone does not prove moral rightness; stewardship requires a justified account of responsible care, not one automatic policy conclusion.

Exam tips

- Separate descriptive facts from normative judgements in every answer.
- Name the ethical position or theory you are using, and contrast it with at least one other.
- Mention voiceless stakeholders: future generations, other species and distant communities.
- Use numbers as evidence, but never as if they settle an ethical question by themselves.
- End with a clear, justified judgement that answers the question.

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Experimental programme

International Baccalaureate · IB Diploma · Environmental Systems and Societies · HL

Scope and prerequisites

This handout teaches the practical programme of the course first assessed in 2026: the skills of planning, fieldwork, data analysis and evaluation that you use in practical work and in your internal assessment (the individual investigation). It is written for both SL and HL students. HL students also apply the three HL lenses (environmental law, environmental and ecological economics, and environmental ethics, units 9 to 11) to these ideas.

Prerequisites: Topic 1 (systems and models), Topic 2 (quadrats, the Lincoln index, Simpson's index and sampling methods) and basic graph skills. Check the current IB guide and your teacher's instructions for the assessment criteria, length and timeline of the internal assessment, which are not repeated here.

Planning an investigation

Counting birds since 1900

Audubon's history of the Christmas Bird Count describes 27 participants and 25 counts on Christmas Day 1900, proposing counting rather than hunting birds. A long-running dataset can reveal patterns beyond a single investigation, but raw totals depend on effort, observers, routes, weather and detectability. Audubon records effort alongside counts. Consistent methods and appropriate adjustment matter; "a long series" does not mean methods and coverage have never changed.

From a question to a plan

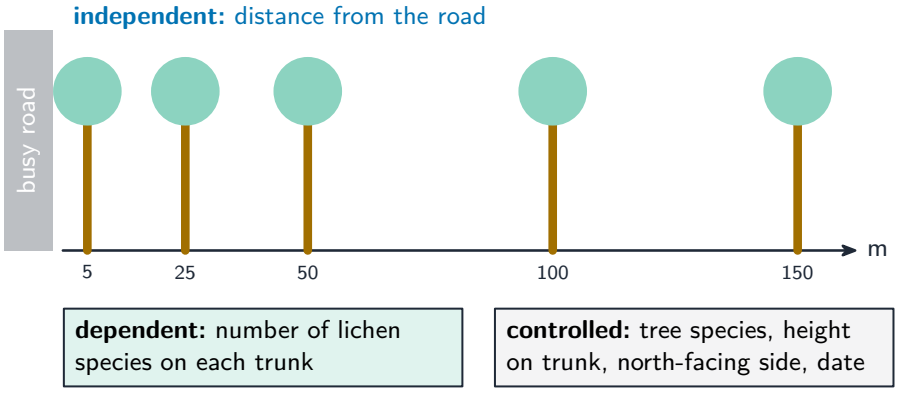
A good investigation starts with a clear, focused **research question** 研究问题 that names what will be changed or compared and what will be measured. Compare:

- Too vague: "How does pollution affect lichens?"
- Focused: "How does the number of lichen species on tree trunks change with distance (5 to 150 m) from a busy road in Hangzhou?"

The plan then identifies the variables:

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Variable	Meaning	Lichen example
Independent variable 自变量	What you manipulate in an experiment or compare as an explanatory variable	Distance from the road
Dependent variable 因变量	What you measure	Number of lichen species on each trunk
Controlled variables 控制变量	What you attempt to standardise; remaining variation must be assessed	Tree species, height on trunk, side of trunk facing north, date

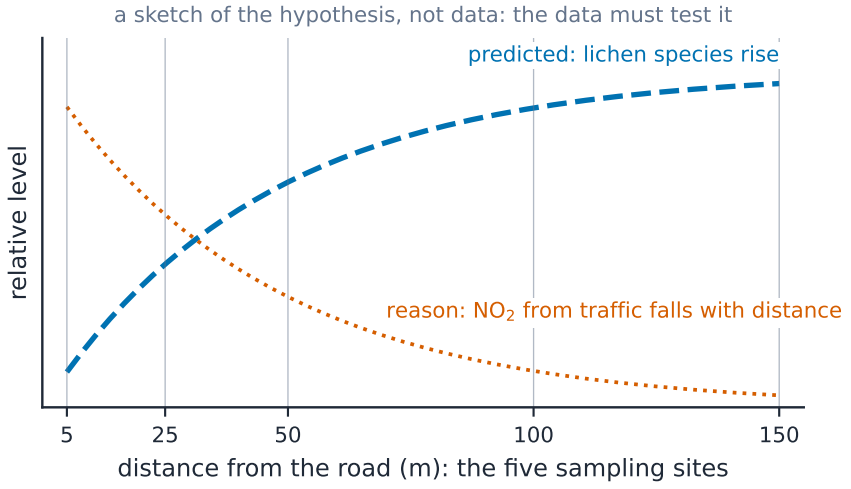


The lichen plan: one variable changed along the transect, one measured, the rest standardised

In fieldwork you often cannot control everything, so you also record **uncontrolled variables** (such as weather or shade) and discuss them later.

A **hypothesis** 假设 is a testable prediction with a scientific reason: "The number of lichen species will increase with distance from the road, because nitrogen dioxide from traffic falls with distance and many lichens are sensitive to it." This is a proposed mechanism to test, not proof that richness always increases with road distance: different lichens respond differently to nutrients, moisture and pollutants. A statistical test checks a **null hypothesis** 零假设, which states that there is no relationship or difference: "There is no correlation between distance from the road and the number of lichen species."

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The hypothesis drawn as a prediction the data can test

Kinds of investigation

ESS investigations can use methods from the natural sciences, the social sciences or both:

- **Experiments** in a laboratory or mesocosm, where variables can be controlled (Topic 2).
- **Field studies** that compare sites or sample along a gradient.
- **Social surveys** that measure attitudes, behaviour or values, such as recycling habits or willingness to pay for a park.
- **Secondary data**: published data from governments, scientists or databases, such as air-quality records or species counts.
- **Models and simulations** that test how a system responds to change.

Safety, ethics and the environment

- **Safety:** risk assessment for water, traffic, slopes, weather, chemicals and working alone.
- **Environmental impact:** minimise trampling and disturbance, return organisms, do not collect protected species, follow site rules.
- **Ethics with people: informed consent** 知情同意, anonymity, the right to withdraw, no questions that cause distress, and permission from a parent or guardian for younger participants.
- **Animal welfare:** handle animals as little as possible and avoid harming them.

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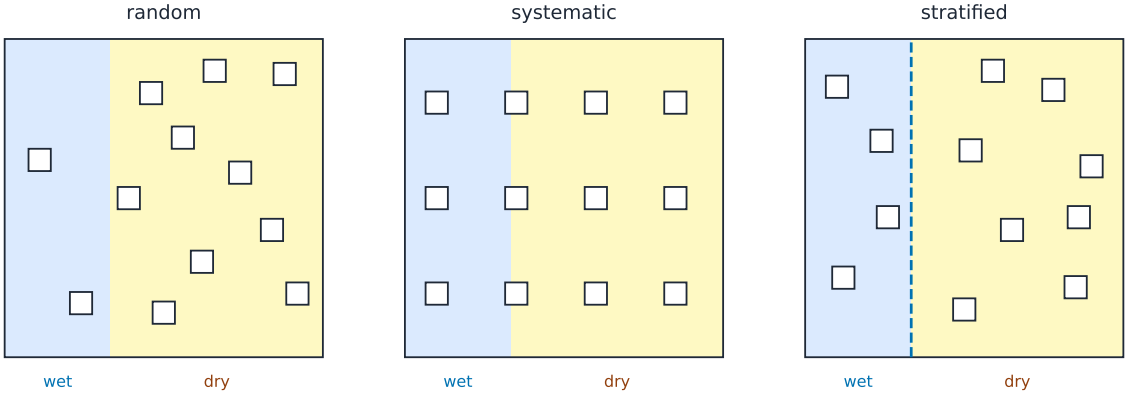
Collecting data in the field

Sampling strategies

You can rarely measure a whole population or habitat, so you take a **sample** 样本 and use it to estimate the whole. The sample must be large enough and **representative** 有代表性的.



A 50 cm quadrat placed on a shore to count organisms in a known area



Random, systematic and stratified sampling

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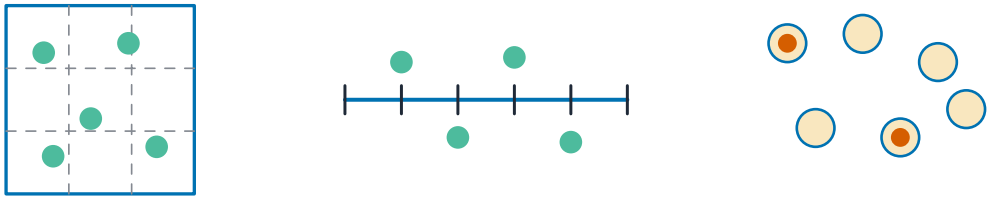
Strategy	How	Best for	Limitation
Random sampling 随机抽样	Use random numbers as coordinates	A fairly uniform area; avoids observer bias	May miss small habitats by chance
Systematic sampling 系统抽样	Sample at regular intervals, often along a **transect** 样带	Showing change along a gradient, such as from shore to dune	May miss patterns between the sampling points
Stratified sampling 分层抽样	Divide into strata and sample randomly within them; proportional allocation or explicit analysis weights can represent their areas	Areas with distinct habitats	Needs a map of the zones first

A **line transect** can record species touching a line continuously or at specified intercept points; name the protocol. A **belt transect** samples a stated-width strip, often using contiguous or interrupted quadrats. Choose a random start where appropriate and check whether regular intervals could coincide with a repeating spatial pattern.

Measuring abundance

- **Quadrats** 样方 measure **percentage cover** (plants), **density** (individuals per m^2) or **frequency** (the percentage of quadrats in which a species occurs). A **species-area curve** helps assess how richness changes with sampled area; a species-accumulation curve concerns additional sampling effort. Use pilot variation and required precision as well as habitat heterogeneity to justify quadrat size and number; an apparent plateau does not prove every habitat is represented.
- **Capture-mark-recapture** for mobile animals, with the Lincoln index (Topic 2).
- **Kick sampling** in streams for invertebrates, and indicator species to assess water quality (Topic 4).
- **Diversity indices** such as Simpson's index (Topic 2).

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quadrat
count species in a square

transect
record along a line

mark-recapture
mark some (red), release, then re-catch

Quadrats and transects sample fixed plants; mark-release-recapture estimates numbers of moving animals

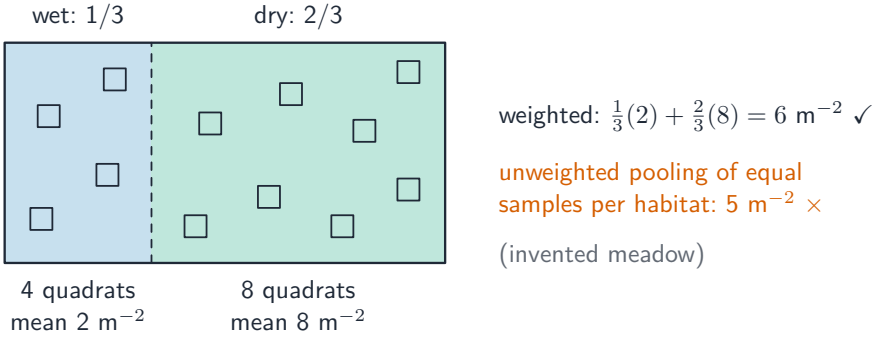
> **Worked example: scaling up.** In a 2500 m^2 meadow, ten 1 m^2 quadrats contain 4, 7, 5, 3, 6, 8, 5, 4, 6 and 2 orchid plants.

1. Mean density $= (4 + 7 + 5 + 3 + 6 + 8 + 5 + 4 + 6 + 2) \div 10 = 50 \div 10 = 5$ plants per m^2.
2. Estimated population $= 5 \times 2500 = 12\,500$ plants.

The estimate assumes that the quadrats are representative of the whole meadow.

■ Strata, weights and independent samples

If one-third of a meadow is wet and two-thirds dry, proportional allocation of 12 equal-area quadrats gives 4 wet and 8 dry. If subgroup mean densities are 2 and 8 plants per square metre, whole-site density is $(1/3) \times 2 + (2/3) \times 8 = 6$ plants per square metre. An equal number of quadrats in each habitat may help compare habitats, but pooling their observations unweighted would give 5 rather than 6. State the target population and use appropriate stratum weights.



Weight strata by area: 6, not 5 plants per square metre

Distinguish an independent sampling unit from repeat readings. Measuring one tree ten times does not provide ten independently sampled trees. Multiple quadrats within

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one stream are not ten independent streams for a between-stream inference. Define spatial and temporal units, repeat at the right level, and discuss clustering or autocorrelation. A larger biased or dependent sample does not automatically produce a representative, independent dataset.

Measuring abiotic factors

Factor	Instrument or method	Notes
Temperature	Thermometer or digital probe	Record time of day and shade
Light intensity	Light meter	Changes quickly with cloud; take readings together
Soil or water pH	pH probe or indicator	Calibrate the probe with buffer solutions
Dissolved oxygen	Oxygen probe or Winkler titration	Warmer water holds less oxygen at saturation; actual readings also depend on mixing, photosynthesis and respiration
Soil moisture and organic content	Tare containers, dry to constant mass, then use an approved loss-on-ignition method	State wet/dry basis for moisture; ignition loss uses dry soil as denominator
Wind speed	Anemometer	Very variable; take several readings
Air pollution	Diffusion tubes, monitors, lichen surveys	Lichens are biological indicators
Turbidity	Secchi disc or turbidity tube	Secchi depth measures visibility under stated conditions; it is not directly a calibrated NTU reading

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A Stevenson screen shades its thermometers the same way at every station, so the readings can be compared fairly

Many probes connect to data loggers that record readings automatically over hours or days.



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Worked soil example: choose the denominator

For net soil masses after subtracting the container, wet mass=30 g, dry-to-constant mass=24 g and residue after approved ignition=21.6 g. Water loss=6 g: wet-basis moisture is $6/30\times100=20\%$, while dry-basis moisture is $6/24\times100=25\%$. Neither is wrong when the basis is stated. Loss on ignition is$(24-21.6)/24\times100=10\%$ of dry mass, an estimate of organic content under the protocol, not a direct measurement of organic carbon. Structural water or carbonate loss can also contribute. Use the teacher-approved laboratory method, equipment and handling procedure; temperature, drying and ignition conditions affect the result.

Social science methods

- **Questionnaires** 问卷 with **closed questions** (yes or no, multiple choice, rating scales, easy to analyse) and **open questions** (richer answers but harder to compare).
- **Interviews** with stakeholders, such as farmers, officials or residents.
- **Observation**, such as counting how many people sort their waste correctly at a set of bins.

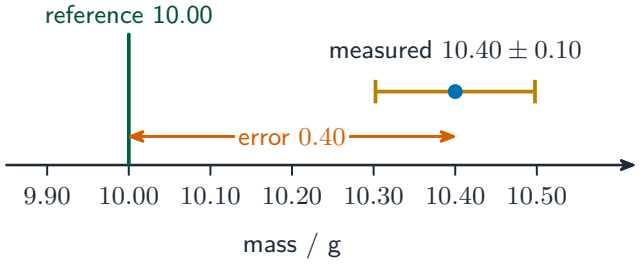
Choose a sample of people that represents the population (by age, location and other relevant groups), avoid **leading questions** that push people towards an answer, and test the questionnaire on a few people first (a pilot study).

Uncertainty and data quality

Errors and uncertainty

Every measurement has some **uncertainty** 不确定度.

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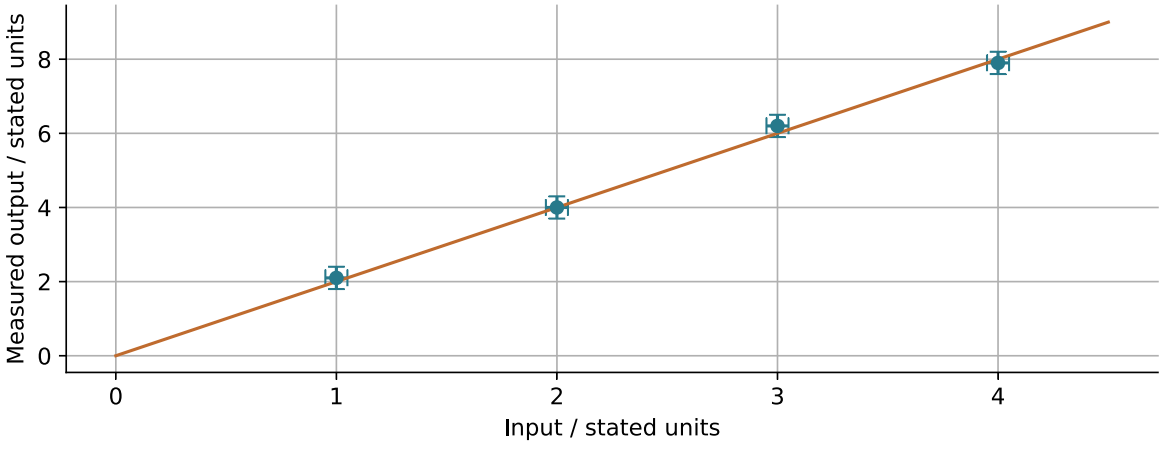


$$\%\ \text{uncertainty} = 100 \times \frac{0.10}{10.40} = 0.96\% \quad \text{(divide by the measured value)}$$

$$\%\ \text{error} = 100 \times \frac{|10.40 - 10.00|}{10.00} = 4.0\% \quad \text{(divide by the reference)}$$

Percentage uncertainty divides by the measured value; percentage error divides by the reference

- **Random errors** 随机误差 produce unpredictable measurement scatter. Biological variation between quadrats is real sampling variation, not necessarily an instrument error. Independent repetition can improve precision of an estimated mean, but does not erase true population variability or establish accuracy.
- **Systematic errors** 系统误差 shift every reading in the same direction, such as an uncalibrated pH probe that always reads 0.3 too high, or always sampling the sunny side of trees. Repeating does not remove them; better calibration or method does.



Every point lies within its uncertainty of the line of best fit

The uncertainty can be given as an absolute value, in the same unit as the measurement, or as a percentage:

$$\text{percentage uncertainty} = \frac{\text{absolute uncertainty}}{\text{measured value}} \times 100$$

Worked example. Five readings of dissolved oxygen at one site are 8.2, 8.6, 8.0, 8.4 and 8.3 mg/L.

1. Mean = $(8.2 + 8.6 + 8.0 + 8.4 + 8.3) \div 5 = 41.5 \div 5 = 8.3$ mg/L.
2. A descriptive spread estimate for this exercise is half the range: $(8.6 - 8.0) \div 2 = 0.3$ mg/L, so report mean 8.3 mg/L with an observed half-range 0.3 mg/L. This is not automatically a confidence interval, instrument uncertainty or standard error.
3. Percentage uncertainty = $0.3 \div 8.3 \times 100 \approx 3.6$ %.

When you combine measurements, uncertainties combine too: for a sum or difference, add the absolute uncertainties; for a product or quotient, add the percentage uncertainties (a simple maximum estimate). A length of 50 ± 1 mm has a 2 % uncertainty; dividing it by a reading with a 3 % uncertainty gives a result with about 5 % uncertainty.

Reliability and validity

- **Reliability** 可靠性: would you get the same results if you repeated the investigation? Improve it by repeating measurements, taking more samples and using a consistent method.
- **Validity** 有效性: does the method actually measure what it claims to measure, and does it test the research question fairly? Different tree species at each distance can confound a causal pollution interpretation, even if the observed richness is measured correctly.
- **Accuracy** means close to the true value; **precision** means repeated readings close to each other. A miscalibrated probe can be precise but inaccurate.

Report data to a sensible number of significant figures: do not quote more digits than your instruments can measure.

Analysing and presenting data

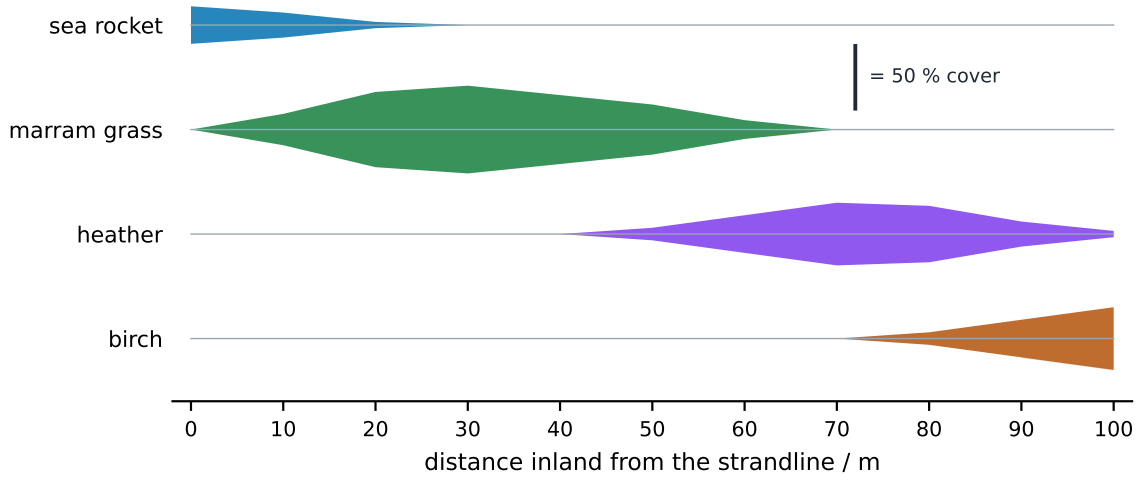
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Choosing a graph

Data	Graph	Example
Two numerical variables	Scatter graph, with a line of best fit if appropriate	Lichen species count against distance from a road
Categories compared	Bar chart, with error bars if means are plotted	Mean invertebrate count at three streams
Parts of a whole	Pie chart or stacked bar	Composition of household waste
Change in abundance along a transect	**Kite diagram** 风筝图	Plant cover across sand dunes
Change over time	Line graph	PM 2.5 by year (Topic 8)

Species richness is a discrete count: a sample can contain three or four species, not 3.5 species. Distance can be measured on a continuous scale. A scatter plot can display these paired numerical observations.

Every graph needs a title, labelled axes with units and a sensible scale.



A kite diagram: the width of each kite shows percentage cover

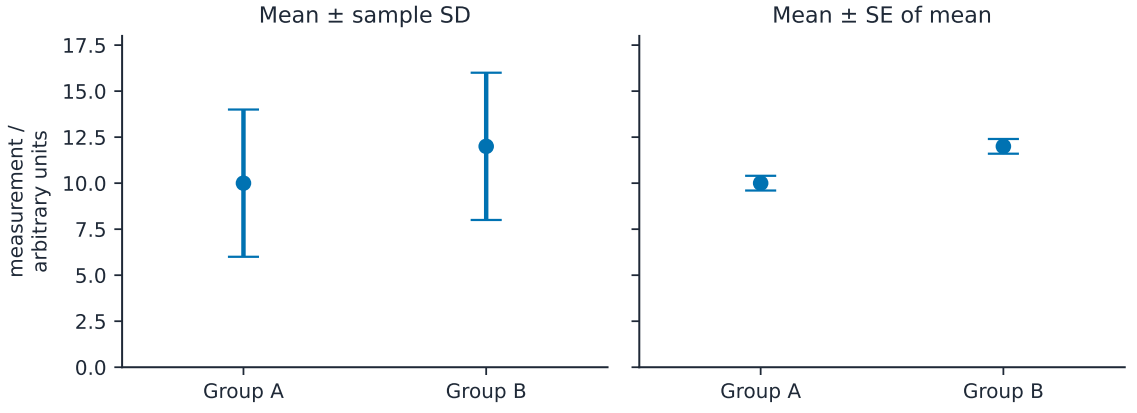
The kite diagram shows spatial zonation, not a direct time series proving succession. A space-for-time interpretation needs evidence about dune history, soils and comparable conditions. Suggested explanations such as salt, disturbance, moisture and pH must be tested rather than inferred uniquely from distance.

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Describing spread: the standard deviation

The mean hides variation. The **standard deviation** 标准差 describes spread of observations; for a normal distribution about 68% of values lie within one population SD of its mean. Sample SD is an estimate and the normal rule is not universal. With independent observations targeting one population, the **standard error** of the mean is estimated by $s/\sqrt{n}$; it concerns mean precision rather than observation spread.

For the oxygen readings, squared deviations from mean 8.3 sum to 0.20. Sample SD=$\sqrt{0.20/4} \approx 0.224$mg/L, and SE=$0.224/\sqrt{5} \approx 0.100$mg/L if the independence assumptions are suitable. Half-range 0.3, SD 0.224 and SE 0.100 describe different things. State exactly what error bars represent. A confidence interval additionally needs a confidence level and appropriate model; a sample mean with an SD bar is not automatically a 95%confidence interval.

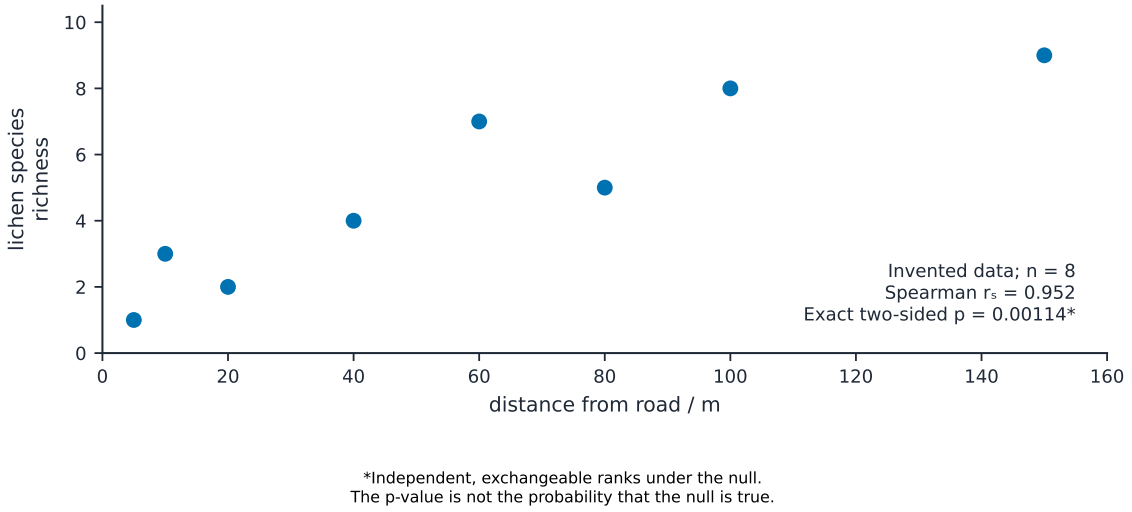


Same summaries, different error-bar definitions. Overlap alone is not a general test of significance.

One-SD bars can overlap even when a properly designed test supports a difference in means. Conversely, selecting a bar style does not replace checking independence, sampling, distributions and the test hypothesis. Statistical significance, effect size, uncertainty and environmental importance are different judgements.

Correlation and Spearman's rank

A **correlation** 相关 is a relationship between two variables: positive (both rise together), negative (one falls as the other rises) or none.



Observations, not measured road-pollution evidence.

Spearman's rank correlation coefficient 斯皮尔曼等级相关系数 measures how strongly two variables are linked by rank. It ranges from -1 (perfect inverse rank order) to $+1$ (perfect matching rank order); zero means no rank association, not necessarily no relationship of any kind. The shortcut below applies to untied ranks; assign average ranks for ties and use a suitable correlation-of-ranks method or tie correction:

$$r_s = 1 - \frac{6\sum D^2}{n(n^2-1)}$$

where D is the difference between the two ranks of each pair and n is the number of pairs.

Worked example. Using the lichen data:

Distance / m	**5**	**10**	**20**	**40**	**60**	**80**	**100**	**150**
Species	1	3	2	4	7	5	8	9
Rank of distance	1	2	3	4	5	6	7	8
Rank of species	1	3	2	4	6	5	7	8
D	0	-1	1	0	-1	1	0	0
D^2	0	1	1	0	1	1	0	0

1. $\sum D^2 = 4$, and $n = 8$.
2. $r_s = 1 - \dfrac{6 \times 4}{8 \times (64-1)} = 1 - \dfrac{24}{504} = 1 - 0.048 = 0.95$.
3. For the stated two-sided 5% test with 8 untied pairs, a commonly supplied critical value is 0.738. The observed $r_s = 20/21 \approx 0.95238$ exceeds it in magnitude. Under an independent exchangeable-rank null model, exact enumeration of 8!=40

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320 permutations gives 46 at least as extreme in either direction: $p = 46/40320 \approx 0.00114$. Thus reject that null at the preselected $\alpha = 0.05$, subject to the design assumptions.

A **significance level** α is a decision threshold chosen before inspecting results. A p-value is the probability, under the null model, of a test statistic at least as extreme as observed. It is not the probability that the null is true, that the result was "caused by chance", or that the conclusion is correct. Failing to reject is not proof of no effect. State whether a test is one- or two-sided, and report effect direction and size, uncertainty and design limitations alongside the test decision.

Correlation is not causation

A significant correlation does not prove that one variable causes the other. Lichen numbers may rise with distance from the road because of less pollution, but also because trees further away are older, or shadier, or of different species. A good conclusion distinguishes an observed association from a proposed mechanism, examines confounders and limits the causal claim to the evidence.

Evaluating and applying

Writing a conclusion

A conclusion:

1. answers the research question directly;
2. describes the pattern in the data with numbers (such as "species rose from 1 at 5 m to 9 at 150 m; $r_s = 0.95$");
3. states whether the null hypothesis is rejected;
4. explains the pattern with environmental science;
5. compares the result with published studies or data where possible.

Evaluating the method

Identify the main weaknesses, explain how each affected the results, and suggest a realistic improvement:



Improve the method: replicate trees of one species at each distance

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Weakness	Effect on results	Improvement
Only one tree sampled at each distance	Natural variation may hide or exaggerate the pattern	Sample five trees at each distance and use means
Different tree species at different sites	Tree species, not pollution, may explain lichen numbers	Sample one tree species only
Sampled on one day	Results may not represent other seasons	Repeat in different seasons
No direct pollution measurement	The cause is inferred, not measured	Place diffusion tubes for nitrogen dioxide at each site

Separate the limitations of the method from the limitations of the conclusion: a perfect method on one road still cannot show what happens on all roads.

■ Applying the results

ESS investigations should connect to real environmental issues. Ask what your results suggest for management, policy or behaviour, and what perspectives different stakeholders would take. HL students can apply the HL lenses: could the result support a law (unit 9), a charge or payment (unit 10), or an ethical argument about who bears the harm (unit 11)? Keep claims proportional to the evidence: a small local study can suggest action but cannot prove that a policy will work everywhere.

Practice

Attempt the questions before reading the worked answers. State the denominator, unit, sampling population and statistical assumptions wherever they affect your conclusion.

1. (a) Rewrite the research question "Does pollution harm rivers?" as a focused, testable question, and identify its independent and dependent variables. (b) State three controlled variables for an investigation of lichen species against distance from a road.
2. Distinguish between a hypothesis and a null hypothesis.
3. (a) Explain when stratified sampling is better than random sampling. (b) Explain why systematic sampling along a transect is used to study zonation on a sand dune.
4. Ten 1 m^2 quadrats in a 4000 m^2 field contain 2, 5, 3, 0, 4, 6, 2, 3, 1 and 4 dandelions. Estimate the total population and state one assumption.
5. Describe how to measure the organic content of a soil sample. Explain why loss on ignition is not a direct organic-carbon measurement.
6. Outline three ethical points to consider when using a questionnaire with other students.

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7. Distinguish between random and systematic errors, with an environmental example of each.
8. Repeated mass readings for a sample are 14.2, 14.8, 14.4, 14.6 and 14.5 g. Calculate the mean, the uncertainty (as half the range) and the percentage uncertainty. Explain why the observed half-range is not automatically a standard error.
9. Distinguish between reliability and validity.
10. Using the kite diagram, describe the distribution of marram grass and heather, and suggest a reason for the difference.
11. Six sites have trampling rates of 2, 5, 9, 14, 20 and 30 people per hour and mean plant heights of 12, 10, 11, 7, 5 and 3 cm. Calculate Spearman's rank correlation coefficient and interpret it, given a critical value of 0.886 for six pairs for a preselected two-sided significance level 0.05. State what the test does not establish.
12. Explain why a significant correlation does not prove causation, using an example.
13. Suggest two improvements to an investigation that counted invertebrates in one kick sample at each of three streams.
14. Discuss the strengths and limitations of using secondary data in an environmental investigation.

Answers.

1. (a) For example: "How does the number of invertebrate taxa change with distance (0 to 500 m) downstream of a sewage outlet on a named stream?" Independent variable: distance downstream. Dependent variable: number of invertebrate taxa (or a biotic index). (b) Any three: the same tree species; the same height on the trunk; the same side of the trunk (aspect); similar trunk size or age; the same date; the same identification method and observer.
2. A hypothesis is a testable prediction with a scientific reason, such as "lichen species will increase with distance because pollution falls". A null hypothesis states that there is no relationship or difference, such as "there is no correlation between distance and lichen species"; statistical tests decide whether to reject it.
3. (a) When the area contains distinct habitats or zones (such as wet and dry areas, or woodland and grassland): stratified sampling ensures each defined stratum is sampled; proportional allocation or appropriate weighting represents its area, while a small unstratified random sample might miss a zone by chance. (b) Conditions such as salt spray, wind, soil depth and organic matter change gradually inland, so species change along a gradient. Sampling at regular intervals along a transect records this change in order.
4. Mean count=30/10=3 per square metre; total estimate=3×4000=12 000 plants. The quadrats must represent the target site under a suitable design, with consistent areas and counting. Uniform distribution is not required if the design and any stratum weights account for heterogeneity.
5. Subtract container mass; dry using an approved protocol to constant mass, then use

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an approved ignition procedure and reweigh the dry residue. Ignition loss divided by initial dry soil mass gives a loss-on-ignition estimate, with water/carbonate and method limitations. It is not automatically organic carbon. For the 30 g wet, 24 g dry and 21.6 g residue: wet-basis moisture 20%, dry-basis 25%, ignition loss 10%.

6. Any three: informed consent; anonymity and keeping data private; the right to withdraw; avoiding upsetting or personal questions; parental permission for younger students.
7. Random errors cause readings to scatter in both directions, such as variation in a fluctuating dissolved oxygen reading. Systematic errors shift all readings the same way, such as a pH probe that was not calibrated and always reads too high.
8. Mean=72.5/5=14.5 g; observed half-range=(14.8−14.2)/2=0.3 g; percentage relative to the mean=0.3/14.5×100≈2.1%. Half-range describes this observed spread and is not automatically an instrument specification, SE or confidence interval. For an absolute temperature reading, a relative percentage also depends on the temperature scale; use meaningful ratios or temperature differences rather than silently treating the Celsius zero as absolute.
9. Reliability: whether repeating the investigation would give similar results (consistency). Validity: whether the method measures what it claims and fairly tests the question.
10. Marram has positive illustrated cover 10–60 m, peaking 70% at 30 m; heather 50–100 m, peaking 50% at 70 m. Salt, disturbance, soil and moisture gradients are possible explanations, not uniquely demonstrated causes. This spatial diagram does not alone prove a succession time sequence.
11. Ranks of trampling: 1, 2, 3, 4, 5, 6. Ranks of height (smallest = 1): 6, 4, 5, 3, 2, 1. D: −5, −2, −2, 1, 3, 5; $\Sigma D^2 = 25 + 4 + 4 + 1 + 9 + 25 = 68$. $r_s = 1 - (6 \times 68) \div (6 \times 35) = 1 - 408 \div 210 = -0.94$. Since $0.94 > 0.886$, there is a significant negative correlation: plant height falls as trampling increases. Use the magnitude for a two-sided comparison and retain the negative direction. These observations show rank association under the model, not proof that trampling alone causes height change; check confounding and independent sampling.
12. Another factor may cause both, or the link may be coincidence. For example, lichen numbers rise with distance from a road, but trees further away may also be older or of different species, so the correlation alone does not prove that traffic pollution is the cause.
13. Take independent sampling units at the level of the question, standardise kick effort and area, record habitat and abiotic conditions, and sample additional independent streams if generalising between streams. Repeats within one stream do not by themselves provide independent stream-level replication.
14. Advantages can include long periods, large coverage and documented methods without new collection. Check actual provenance and quality rather than assuming all published data were collected by trained staff or fit the question. Limits include incompatible definitions, effort, missingness, revisions, selection bias and restricted

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inference; methods can often be inspected in documentation even though collection cannot be repeated directly.

Exam tips

- Write a focused research question that names both variables and the place.
- Justify your sampling strategy and sample size, not just name them.
- Distinguish random from systematic errors, and reliability from validity.
- Show working in calculations, give units and round sensibly.
- In Spearman's rank, compare r_s with the critical value and state whether you reject the null hypothesis.
- Never claim causation from correlation alone; suggest other explanations.

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