Course Companion

AP Environmental Science

Every topic handout in one volume

全部专题讲义合集

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Contents 目录

1. The Living World: Ecosystems 2

2. The Living World: Biodiversity 15

3. Populations 28

4. Earth Systems and Resources 40

5. Land and Water Use 54

6. Energy Resources and Consumption 73

7. Atmospheric Pollution 89

8. Aquatic and Terrestrial Pollution 101

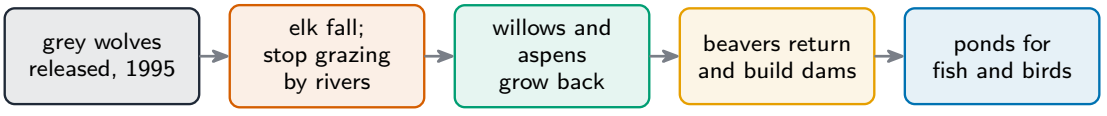
9. Global Change 118

The Living World: Ecosystems

AP Environmental Science

Introduction to Ecosystems

In 1995 fourteen grey wolves were released into Yellowstone National Park, where wolves had been absent for 70 years. Elk numbers fell and elk stopped grazing along rivers; willows and aspens grew back; beavers returned to use them, and their dams created ponds for fish and birds. One predator changed a whole ecosystem. This unit is about how living things are linked to each other, and to the energy and matter that flow through them.



one predator, effects passed down the food web

One predator's effects passed down the food web.

An **ecosystem** 生态系统 is all the living (**biotic** 生物的) and non-living (**abiotic** 非生物的) parts of an area and the interactions among them. Abiotic factors include sunlight, temperature, water, soil and nutrients.

Species in an ecosystem interact in several ways:

Interaction	Effect on species A	Effect on species B	Example
Predation 捕食	predator gains (+)	prey loses (−)	wolf eats elk; herbivores eating plants work the same way
Competition 竞争	loses (−)	loses (−)	lions and hyenas for the same prey
Mutualism 互利共生	gains (+)	gains (+)	bees pollinate flowers and get nectar; coral and algae
Commensalism 偏利共生	gains (+)	unaffected (0)	barnacles riding on a whale
Parasitism 寄生	parasite gains (+)	host loses (−)	ticks on a deer; tapeworms

Symbiosis 共生 is any close, long-term relationship between two species: mutualism, commensalism and parasitism are all types of symbiosis.

Competition happens **within** a species and **between** species when a resource is limited. Over time, competing species often evolve **resource partitioning** 资源分配:

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they use the resource in different ways, in different places or at different times. For example, several warbler species feed in the same spruce tree but in different parts of it; hawks hunt by day and owls by night.

Terrestrial Biomes

A **biome** 生物群系 is a large region with a characteristic community of plants and animals adapted to its climate. **Terrestrial biomes** are set mainly by **average temperature** and **precipitation** 降水, which in turn depend on latitude and altitude.

Biome	Climate	Plants and soil
Tropical rainforest	hot, very wet all year	tall layered forest; thin, nutrient-poor soil (nutrients are held in the plants)
Temperate rainforest	mild, very wet (coastal)	giant conifers, mosses
Temperate seasonal forest	warm summers, cold winters, moderate rain	deciduous trees that lose leaves; rich soil
Taiga (boreal forest)	long cold winters, short summers	conifers; acidic, slow-decaying soil
Tundra	very cold, dry; **permafrost** 永久冻土	mosses, lichens, low shrubs; no trees
Temperate grassland	hot summers, cold winters, too dry for forest	grasses; deep, very fertile soil
Savanna	warm all year, wet and dry seasons	grasses with scattered trees
Shrubland (chaparral)	hot dry summers, mild wet winters	drought-adapted shrubs; fire common
Desert	very dry (under 25 cm rain a year)	cacti and succulents with deep or wide roots

The two images below sit at opposite ends of the precipitation scale, which is why their life looks so different:

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A tropical rainforest 热带雨林*: hot and wet all year, giving dense layered plant life and the richest biodiversity of any land biome*



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

Natural resources on land, such as fresh water and timber, are unevenly spread because of climate, geography, latitude, altitude, nutrients and soil. Biome boundaries are not fixed: as the climate warms, biomes are shifting toward the poles and up mountains, and species that cannot move fast enough are at risk.

Aquatic Biomes

Aquatic biomes are divided by **salinity** 盐度 (salt content), depth, water flow, temperature and **turbidity** (cloudiness).

- **Freshwater biomes:** streams and rivers (flowing water, high oxygen), ponds and lakes (still water), and freshwater wetlands. They are a vital source of drinking water.
- **Marine biomes:** the open ocean, **coral reefs** (warm, clear, shallow tropical water), salt marshes, and **estuaries** 河口, where rivers meet the sea and fresh water mixes with salt water.
- **Wetlands** 湿地 (marshes, swamps, mangroves) are land covered by water for at least part of the year. They filter pollutants, store floodwater and provide nurseries for fish.

Estuaries and salt marshes are highly productive because nutrients are supplied by rivers and tides, and shallow water receives sunlight. Coral reefs are also highly productive, but usually grow in nutrient-poor water: corals and their symbiotic algae recycle nutrients efficiently. In the open ocean, tiny **algae** 藻类 (phytoplankton) produce a large share of Earth's oxygen and take in carbon dioxide from the atmosphere.



A coral reef 珊瑚礁*: warm, sunlit, shallow water makes it one of the most productive and biodiverse of all biomes*

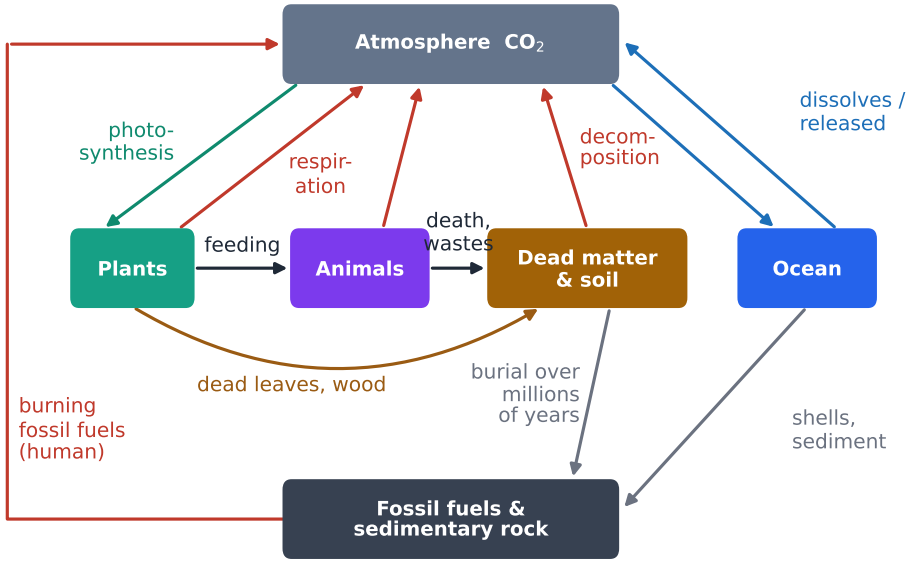
The Carbon Cycle

A **biogeochemical cycle** 生物地球化学循环 is the movement of an element between **reservoirs** 储库 (stores). A reservoir that takes in more of the element than it releases is a **sink** 汇; one that releases more than it takes in is a **source** 源. Some reservoirs hold the element briefly (the atmosphere, living things), others for millions of years

(rocks, fossil fuels).

The **carbon cycle** 碳循环 moves carbon between the atmosphere, living things, the ocean, soil and rocks:

- **Photosynthesis** 光合作用 takes CO_2 from the air and stores the carbon in sugars: $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$.
- **Cellular respiration** 细胞呼吸 by plants, animals and decomposers releases it again as CO_2.
- **Decomposition** 分解 of dead matter returns carbon to the air and soil.
- The **ocean** absorbs CO_2 from the air (it is the largest active carbon sink); marine organisms build shells of calcium carbonate, which settle and form limestone.
- **Burial** of dead plants and plankton under sediment, over millions of years, formed **fossil fuels** 化石燃料 (coal, oil, natural gas).



The carbon cycle: reservoirs and the processes that move carbon between them

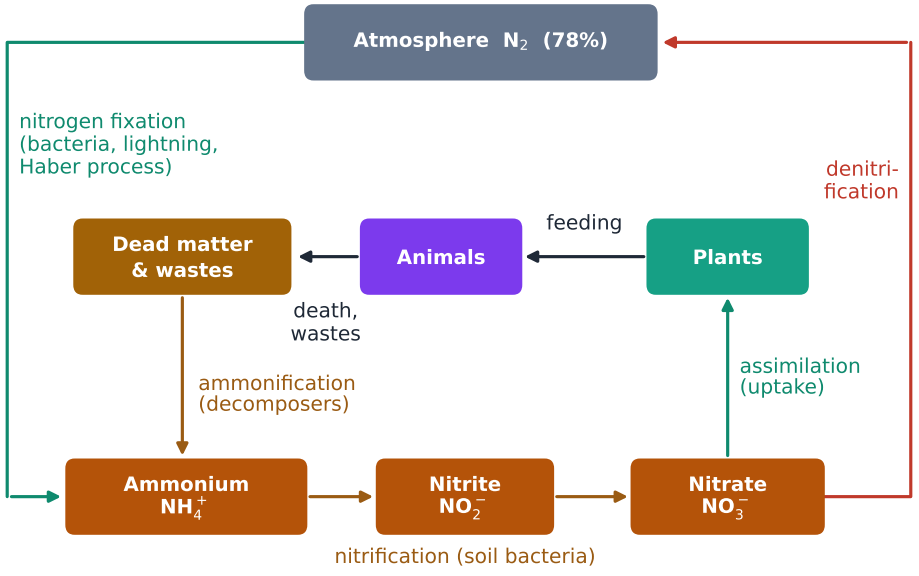
Human impact. Burning fossil fuels moves carbon that was stored for millions of years into the atmosphere in a few decades, much faster than photosynthesis and the ocean can remove it. **Deforestation** 森林砍伐 adds more: burning forests releases carbon, and fewer trees remain to absorb CO_2. The result is rising atmospheric CO_2 and climate change.

The Nitrogen Cycle

Nitrogen is needed to make proteins and DNA. The atmosphere is the largest nitrogen reservoir (78% N_2), but plants and animals cannot use N_2 gas directly. Most nitrogen reservoirs (soil, living things) hold it only for a short time.

The **nitrogen cycle** 氮循环 has five main steps:

1. **Nitrogen fixation** 固氮作用 converts atmospheric N_2 into biologically usable nitrogen. Bacteria in soil and in root nodules of legumes (beans, clover) form ammonia (NH_3) or ammonium (NH_4^+). The industrial Haber process makes ammonia for fertilizer. Lightning forms nitrogen oxides that reach soil mainly as nitrate.
2. **Nitrification** 硝化作用: soil bacteria turn ammonium into nitrite (NO_2^-) and then nitrate (NO_3^-).
3. **Assimilation** 同化作用: plants take up nitrate and ammonium through their roots and build them into proteins; animals get nitrogen by eating plants.
4. **Ammonification** 氨化作用: decomposers break down dead matter and wastes, releasing ammonium back to the soil.
5. **Denitrification** 反硝化作用: bacteria in waterlogged, low-oxygen soil turn nitrate back into N_2 (and some N_2O, a greenhouse gas), which returns to the air.



The nitrogen cycle: fixation, nitrification, assimilation, ammonification and denitrification

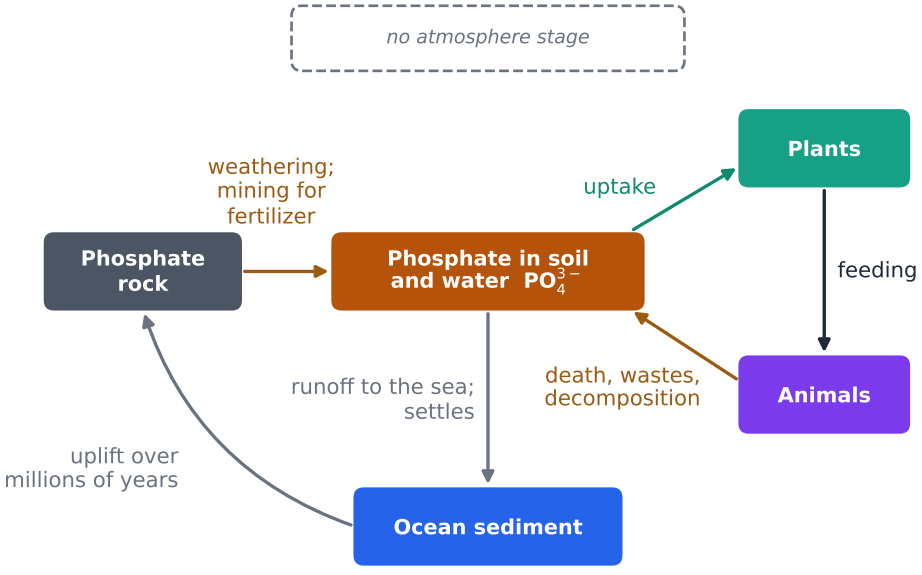
Human impact. Synthetic fertilizer and manure add large amounts of nitrogen. Nitrate dissolves easily, so excess fertilizer leaches into groundwater (unsafe for drinking) or runs off into rivers, where it causes algal blooms. Burning fuels releases nitrogen oxides, which cause smog and acid rain.

The Phosphorus Cycle

Phosphorus is needed for DNA, ATP (the cell's energy molecule), cell membranes, and bones and teeth.

The **phosphorus cycle** 磷循环 is unusual: it has **no atmospheric stage**. Its main reservoirs are rocks and sediments containing phosphate minerals.

1. **Weathering** of rock slowly releases phosphate (PO_4^{3-}) into soil and water.
2. Plants take it up; animals get it by eating plants.
3. Decomposers return phosphate to the soil from wastes and dead organisms.
4. Runoff carries phosphate to lakes and the ocean, where it settles into sediment.
5. Over millions of years, sediments form rock through compaction and cementation; geologic uplift can expose that rock on land.



The phosphorus cycle: rock, soil and water, organisms and sediment, with no gas phase

Phosphorus has no major gas phase, although wind can carry phosphate in dust. It returns from ocean sediments to land mainly through slow geologic processes. So it is naturally scarce in most ecosystems and is often the **limiting nutrient** 限制性养分 for plant and algae growth.

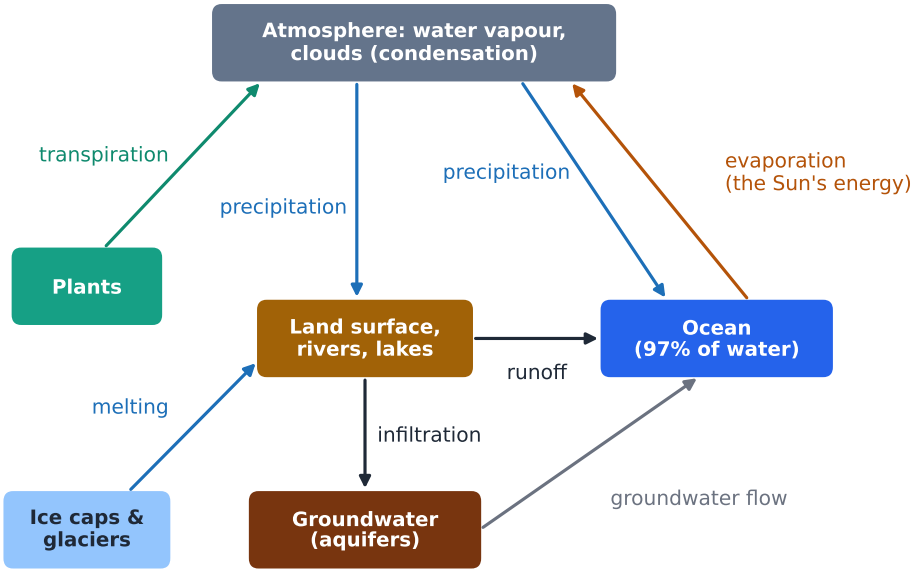
Human impact. Phosphate rock is mined for fertilizer, and phosphates were common in detergents. Runoff from farms and sewage adds phosphorus to lakes and rivers, which causes **eutrophication** 富营养化: algae grow rapidly, then die and decompose, and the decomposers use up the dissolved oxygen, killing fish.

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The Hydrologic (Water) Cycle

The **water cycle** 水循环 (hydrologic cycle) moves water between its solid, liquid and gas forms. It is powered by energy from the **Sun**.

- **Evaporation** 蒸发: the Sun heats surface water, which turns into water vapour.
- **Transpiration** 蒸腾作用: plants release water vapour from their leaves.
- **Condensation** 凝结: vapour cools and forms clouds.
- **Precipitation**: water falls as rain, snow or hail.
- **Runoff** and **infiltration** 下渗: water flows over the land into rivers, or soaks into the soil to become groundwater in **aquifers** 含水层.



The water cycle: evaporation, transpiration, precipitation, runoff, infiltration and groundwater flow

The **oceans** are the main reservoir, holding about 97% of Earth's water. Ice caps and glaciers hold about 2%, and fresh groundwater less than 1%; saline groundwater holds much of the remainder, while lakes, rivers and the atmosphere hold only a tiny fraction. So less than 1% of all water is easily available fresh water.

Human impact. Paving surfaces increases runoff and flooding and reduces infiltration; deforestation reduces transpiration and local rainfall; pumping groundwater faster than it refills lowers the water table.

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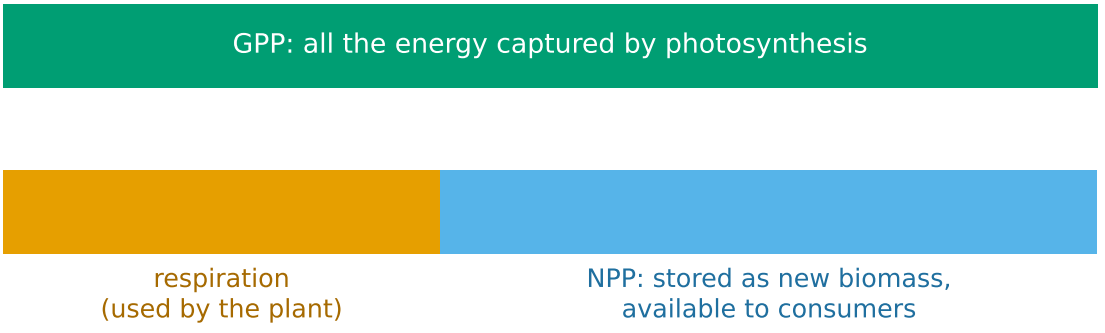
Primary Productivity

Primary productivity 初级生产力 is the rate at which producers convert solar energy into the chemical energy of organic compounds by photosynthesis. It is measured as energy (or biomass) per unit area per unit time, for example kcal/m^2/yr.

- **Gross primary productivity** 总初级生产力 (GPP) is the total rate of photosynthesis in an area.
- **Net primary productivity** 净初级生产力 (NPP) is the energy left after the producers use some for their own respiration (R). NPP is the energy available to consumers.

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

> **Worked example.** Producers in a grassland capture 20,000 kcal/m^2/yr (GPP) and use 8,000 kcal/m^2/yr in respiration. NPP = 20,000 − 8,000 = 12,000 kcal/m^2/yr. Only that NPP, not the full GPP, is available to the consumers.



NPP = GPP − respiration

Net primary productivity is what is left of gross productivity after the plant's own respiration

Tropical rainforests, swamps and marshes, estuaries and coral reefs have high productivity per square metre. Coral reefs maintain high productivity in nutrient-poor water through efficient nutrient recycling. Deserts, tundra and the open ocean (few nutrients) have low productivity per square metre.

Light in water. Water absorbs light quickly. Red light is absorbed more quickly than blue light, which penetrates deepest; the depth depends on water clarity. So most aquatic photosynthesis happens near the surface, and deep-water algae have pigments that capture blue light.

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Trophic Levels

Every ecosystem needs a continuous inflow of high-quality energy, almost always from the Sun. Energy flows from the Sun to **producers** 生产者 at the lowest **trophic level** 营养级, then up to higher levels:

1. **Producers** (autotrophs): plants, algae and phytoplankton make their own food by photosynthesis.
2. **Primary consumers** (herbivores) eat producers.
3. **Secondary consumers** eat primary consumers.
4. **Tertiary consumers** eat secondary consumers; **top predators** 顶级捕食者 have no natural predators.

Decomposers 分解者 (bacteria and fungi) and **detritivores** 食腐动物 (earthworms, millipedes) break down dead matter and wastes from every level, returning nutrients to the soil and water. Without them, matter would not cycle.

Energy flows one way, but matter cycles: the biogeochemical cycles show the **conservation of matter**. Atoms are never destroyed; they move between reservoirs.

Energy Flow and the 10% Rule

The **10% rule**: on average only about 10% of the energy at one trophic level is passed on to the next. The other 90% is used for the organisms' own life processes (respiration, movement, keeping warm) and is finally lost as **heat**, or is in parts that are not eaten or digested.

The laws of **thermodynamics** 热力学 explain this. The first law says energy is not created or destroyed, only changed in form. The second law says that every time energy changes form, some becomes heat, which is not useful to the next level. So energy cannot be recycled up the food chain.

> **Worked example.** From 12,000 kcal/m^2/yr of NPP, primary consumers receive about 1200 kcal/m^2/yr, secondary consumers about 120 kcal/m^2/yr, and tertiary consumers only about 12 kcal/m^2/yr. After three transfers the energy has shrunk a thousand-fold.

> **Worked example (backwards).** A hawk population needs 50 kcal per day from snakes. Working down, the snakes need 500 kcal, the mice 5000 kcal and the grass 50,000 kcal. Multiply by 10 for each level you go **down**.

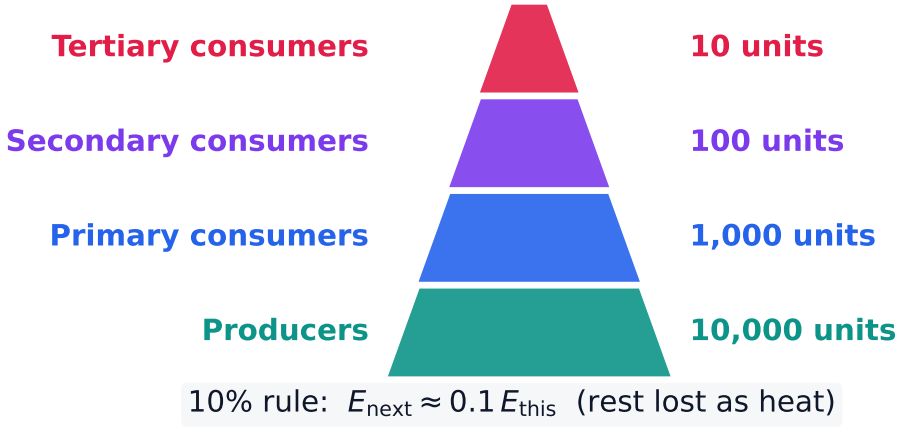
> **Worked example (food needed).** An ocelot needs 720 g of food a day, and 46% of its diet by mass is pocket mice. Each mouse has a mass of 43 g. How many mice does one ocelot eat a day?

1. Mass of mice eaten: $720 \times 0.46 \approx 331$ g per day.
2. Number of mice: $331 \div 43 \approx 7.7$, so about **8 mice** a day.

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3. Show each step with units; FRQs may award a point for the correct set-up; check the rounding and units required by the question.

Why the trophic level of the food matters. Mice eat plants, so they are primary consumers; snakes eat other animals, so they are at least secondary consumers. An ocelot eating snakes gets energy that has passed through one more 10% transfer than energy from mice, so far more primary production is needed to supply the same 720 g of snakes.



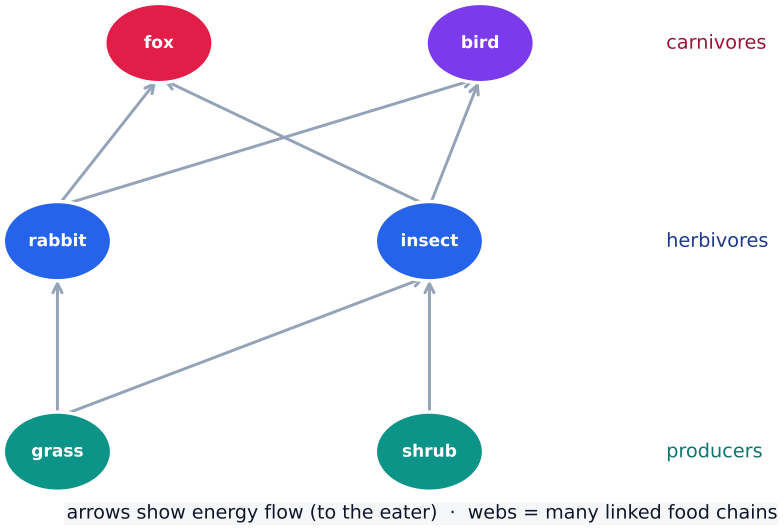
An energy pyramid: only about 10% of energy passes to the next trophic level

This energy loss explains why food chains rarely have more than four or five levels, why top predators are few, and why eating lower on the food chain (plants rather than meat) feeds more people from the same land.

Food Chains and Food Webs

A **food chain** 食物链 is a single path of who eats whom. A **food web** 食物网 shows many interlocking food chains in an ecosystem. In both, the **arrows point from the food to the eater**: they show the direction in which energy and nutrients flow.

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A food web links many food chains; arrows point the way energy flows

Because species are connected, adding or removing one species affects others:

- Removing a predator lets its prey increase, which may overeat the producers. Removing spiders, for example, can let plant-eating insects multiply and damage crops.
- Adding invasive plankton-eating silver and bighead carp, as in the Mississippi River basin, leaves less food for native fish.
- A **keystone species** 关键种 has a much larger effect on its ecosystem than its numbers suggest. The Yellowstone wolves and sea otters (which eat sea urchins that would otherwise destroy kelp forests) are examples.

Feedback loops 反馈回路 operate in food webs. In a **negative feedback** loop a change produces effects that reverse it: more rabbits feed more foxes, which then reduce the rabbits, keeping both populations stable. In a **positive feedback** loop a change produces effects that amplify it: fewer trees lead to more erosion, which leads to even fewer trees.

Practice

Answer each before reading the answers below.

1. A grassland has a gross primary productivity of 5000 kcal/m^2/yr, and its producers use 3000 kcal/m^2/yr in respiration. Calculate the net primary productivity.
2. Producers in a food web hold 20 000 kcal. Using the 10% rule, how much energy reaches secondary consumers?
3. Describe nitrogen fixation and explain why it matters to plants.

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4. Explain why the phosphorus cycle is much slower than the carbon or nitrogen cycles.
5. Identify one carbon sink and explain how burning fossil fuels changes the carbon cycle.
6. Explain why the tundra has low primary productivity.

Answers

1. NPP = GPP − R = 5000 − 3000 = 2000 kcal/m^2/yr.
2. Producers → primary consumers 2000 kcal → secondary consumers 200 kcal.
3. Bacteria (free-living or in root nodules of legumes) convert atmospheric N_2 into ammonia (NH_3) or ammonium. Plants cannot use N_2 directly, but they can take up these forms to make proteins and nucleic acids.
4. It has no gas phase: phosphorus enters ecosystems mainly through the slow weathering of rock.
5. The ocean (or forests, or sedimentary rock). Burning moves carbon that was stored for millions of years in fossil fuels into the atmosphere as CO_2 far faster than sinks can absorb it.
6. Cold temperatures, a short growing season and little precipitation limit photosynthesis.

Exam tips

- **Energy flows** one way and is lost as heat (the 10% rule); **matter cycles** (carbon, nitrogen, phosphorus, water).
- For symbiosis, state the effect on **both** species (+/+, +/0, +/−).
- Know which cycle has **no gas phase** (phosphorus) and where each element is stored longest (carbon in rocks and fossil fuels, nitrogen in the atmosphere, phosphorus in rock).
- Name the nitrogen cycle steps in order and say which organisms do them: fixation (bacteria), nitrification (bacteria), assimilation (plants), ammonification (decomposers), denitrification (bacteria).
- Use **NPP = GPP − respiration**; only NPP is available to consumers. Give units such as kcal/m^2/yr.
- In a food web, arrows show the direction of energy flow, from food to eater.
- When a species is removed, follow the effects at least two steps through the web.
- Show every step in calculations, with units; the FRQ calculator is allowed but marks need the setup.

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The Living World: Biodiversity

AP Environmental Science

Introduction to Biodiversity

In the 1990s only about 50 Florida panthers were left in the wild. So many were related that kittens were born with heart defects, kinked tails and weak sperm. In 1995 scientists brought in eight female cougars from Texas. Within twenty years the panther population had grown to over 200 and the defects had become rare. The panthers did not need more food or more land first. They needed more **genetic** variety. This unit is about why variety at every level keeps living systems working.

Biodiversity 生物多样性 is the variety of life, measured at three levels:

- **Genetic diversity** – variety of genes *within* a species. More genetic variety means a population can better respond to **environmental stressors** 环境压力 such as a new disease, drought or warmer water: some individuals are likely to carry alleles that help them survive.
- **Species diversity** – the number of species (**species richness** 物种丰富度) and how evenly individuals are spread among them (species **evenness**).
- **Habitat diversity** – the variety of habitats in a region. A landscape with forest, wetland, grassland and streams supports more species than one large wheat field.

A **population bottleneck** 种群瓶颈 is a sharp drop in population size, from hunting, habitat loss or a disaster. Even if the population later recovers, it has lost most of its genetic variety, because the new population descends from only a few survivors. Low variety brings **inbreeding** (harmful recessive traits appear more often) and leaves the whole population open to one new disease. Cheetahs and northern elephant seals both passed through bottlenecks and today show very little genetic variation.

More species-rich ecosystems are more **resilient** 有韧性的: they recover from disruption more readily, because varied species can fill roles when conditions change. If one grass species dies in a drought, a grassland with twenty grass species still has others to hold the soil and feed grazers.

Habitat loss tends to affect some groups more severely than others:

1. **Specialist** 特化 species (narrow needs – one food, one nesting site) go first. The giant panda eats almost only bamboo.
2. Species that need **large territories** decline as their range shrinks and is cut into small pieces (big predators such as tigers and wolves).
3. Hardy **generalist** 广适性 species (broad diets, wide tolerance – raccoons, rats, pigeons) survive longest and may even increase.

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Biodiversity has three levels: genetic, species, and habitat

Worked example (Simpson's Diversity Index). A pond holds 3 fish species with 5, 3, and 2 individuals ($N = 10$). A second pond also has 10 fish of 3 species, split 8, 1, 1.

$$D = 1 - \sum \left(\frac{n}{N}\right)^2$$

Pond 1: $D = 1 - [(0.5)^2 + (0.3)^2 + (0.2)^2] = 1 - 0.38 = 0.62$. Pond 2: $D = 1 - [(0.8)^2 + (0.1)^2 + (0.1)^2] = 1 - 0.66 = 0.34$. Both ponds have the same species richness (3), but pond 1 is more *even*, so it is more diverse. A value near 1 means high diversity; near 0 means one species dominates.



A coral reef: high biodiversity concentrates species and ecosystem services in a small area

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Ecosystem Services

Ecosystem services 生态系统服务 are the free benefits nature gives people, in four categories:

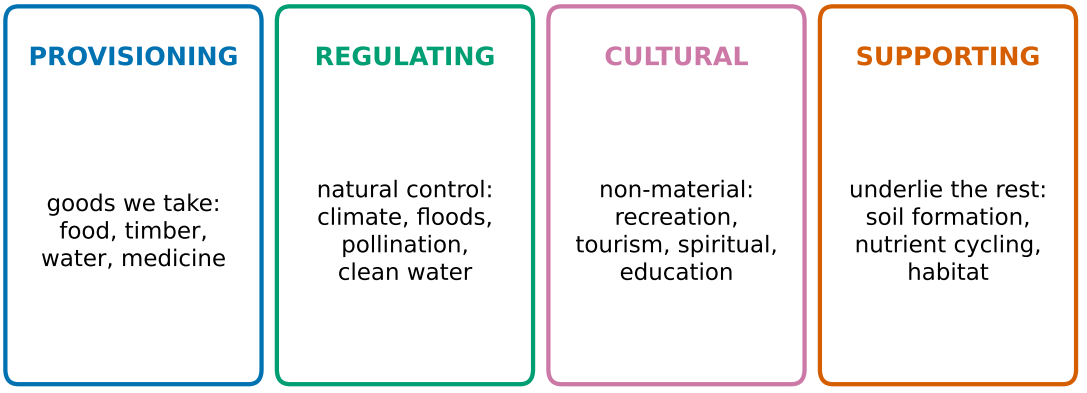
Category	What it means	Examples
Provisioning	products we take from nature	food, fresh water, timber, fibre, medicines
Regulating	processes that keep conditions stable	climate regulation (carbon storage), water filtration, pollination, flood control, erosion control
Cultural	non-material value	recreation, tourism, beauty, spiritual and educational value, scientific research
Supporting	the services that make the others possible	nutrient cycling, soil formation, photosynthesis (primary productivity), habitat

Anthropogenic 人为的 (human-caused) activities can disrupt these services, with real economic *and* ecological costs. AP questions often ask for both, so learn to name each one:

- **Deforestation** removes timber for later harvests (provisioning), releases stored carbon and increases flooding downstream (regulating), and ends ecotourism income (cultural).
- **Clearing mangroves** for shrimp farms removes the young-fish nurseries that support local fisheries (provisioning) and the roots that absorb storm surges (regulating). Towns behind the mangroves then pay for sea walls and storm damage.
- **Losing pollinators** to pesticides and habitat loss forces farmers to rent beehives or pollinate by hand – paying for a service bees once did for free.
- **Draining wetlands** removes natural water filtration, so a city must build a more expensive water treatment plant.

> **Worked example (FRQ style).** *A company plans to clear a forest above a city's drinking-water reservoir. Identify one ecosystem service the forest provides and describe one economic cost of losing it.* The forest provides **water filtration** (a regulating service): roots and soil trap sediment and pollutants before rain reaches the reservoir. Without the forest, more sediment and nutrients enter the water, so the city must spend money on extra treatment or a new filtration plant.

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The four kinds of ecosystem services

Island Biogeography

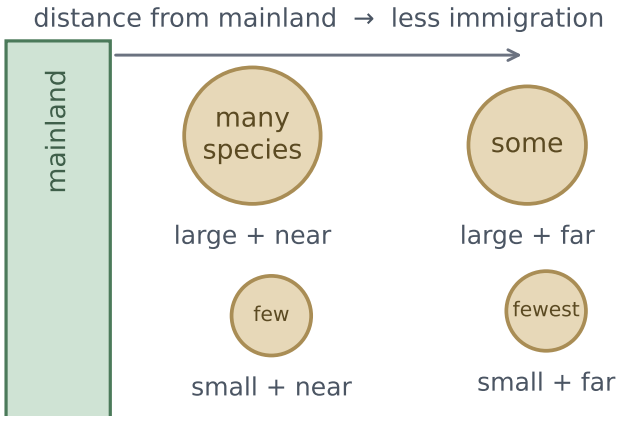
Island biogeography 岛屿生物地理学 studies how many species an island holds. The same ideas apply to any *habitat island*: a lake, a mountaintop, or a park surrounded by farms and roads. The number of species settles at a balance between two rates:

- **Immigration** of new species – higher for islands **closer** to the mainland, because seeds, insects and birds reach them more easily.
- **Extinction** of resident species – lower on **larger** islands, because they have more habitat types, more resources and larger populations that are less likely to die out by chance.

So big, near islands hold the most species; small, remote ones the fewest. Scientists find a rough rule: an island with ten times the area holds about twice as many species.

Isolation also drives evolution. A few colonists reach a remote island and **adaptive radiation** follows: they evolve into many new species, each using a different resource (Darwin's finches in the Galápagos, honeycreepers in Hawaii). Island species often become **specialists** because resources are limited, and many are **endemic** 特有 – found nowhere else. That makes them fragile. When an **invasive species** 入侵物种 (usually a tough generalist with no local predators) arrives, it can outcompete or eat the specialists, which have nowhere else to go. Brown tree snakes, carried to Guam on cargo planes, wiped out most of the island's native forest birds.

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Larger and nearer islands hold more species, balancing immigration against extinction

Applying it to conservation. Roads, farms and towns cut large habitats into small, isolated patches (**habitat fragmentation** 栖息地破碎化). Each patch behaves like a small, remote island: it holds fewer species and loses them faster. Planners respond by:

- protecting **one large reserve** rather than several small ones where possible;
- linking patches with **wildlife corridors** 野生动物廊道 – strips of habitat, or bridges and tunnels over and under highways – so animals can move, find mates and recolonize patches. This raises the "immigration rate" and keeps genetic variety flowing.

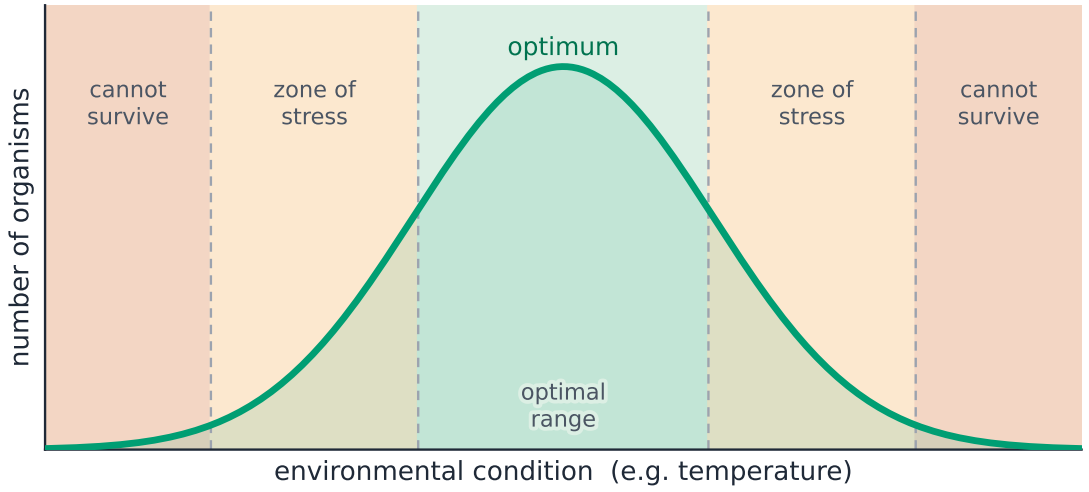
Ecological Tolerance

Every species has a **range of tolerance** 耐受范围 – the span of conditions (temperature, salinity, pH, dissolved oxygen, sunlight) it can survive. Near the middle is an **optimal range** 最适范围 where individuals thrive and reproduce; toward the edges are **zones of stress** 胁迫区 (zones of physiological stress) where they survive but grow slowly, reproduce little and fall sick more easily; beyond the limits they die. **Ecological tolerance** 生态耐受性 applies both to a single individual and to a whole species, and it decides where an organism can live and how it copes with change.

Two ideas make tolerance useful in exam answers:

- **A species is limited by the factor it tolerates least.** A trout stream may have perfect temperature and food, but if dissolved oxygen falls below the trout's range, the trout disappear.
- **Species with narrow ranges are sensitive.** Reef-building corals live within about 1–2 °C of their upper temperature limit. A small rise pushes them into the stress zone, and they expel their algae (coral bleaching).

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range of tolerance: optimum peak · outside = stress or death

Within its optimal range a species thrives; toward the limits it is stressed, then cannot survive

Worked example (reading a tolerance curve). *A fish's optimal range is 18–24 °C and it dies above 30 °C. A power plant raises the river from 22 °C to 27 °C. Predict the effect.* At 27 °C the fish are outside the optimal range but still below the lethal limit, so they are in the zone of stress. They survive, but they grow and reproduce less, so the population declines over time. Warm water also holds less dissolved oxygen, which adds a second stress.

Natural Disruptions to Ecosystems

Natural events disrupt ecosystems across every timescale, and a single natural event can rival or exceed a human-made one. Earth's processes come in three timing patterns:

- **Periodic** 周期性 – regular cycles (seasons, tides, monsoons).
- **Episodic** 偶发性 – occasional, irregular events (fires, floods, droughts, volcanic eruptions, El Niño years).
- **Random** 随机 – no pattern at all (a meteor strike, an earthquake).

Over geological time, Earth's climate has shifted for many reasons (changes in Earth's orbit, volcanic activity, the movement of continents). Sea level has risen and fallen with the amount of **glacial ice**: when ice sheets grow, they lock up ocean water and sea level drops; when they melt, sea level rises. During the last ice age, sea level was about 120 m lower than today, and land bridges joined Asia to North America. Each change reshaped large areas of habitat.

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Wildlife responds by **migration** 迁徙, moving short or long distances to follow food, water or suitable temperatures. Some migrations are seasonal (wildebeest on the Serengeti, geese flying south); others are slow shifts of a whole range – many plants and animals are now moving toward the poles and up mountains as the climate warms.

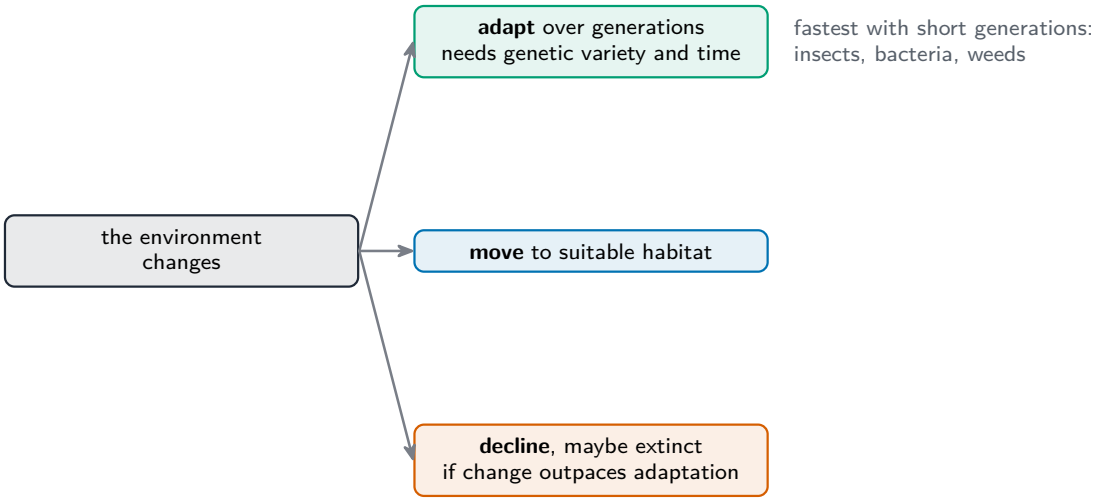


A crown fire sweeping through a forest. Fire is a natural episodic disturbance, and many species are adapted to it

Adaptations

An **adaptation** 适应 is an inherited trait that improves survival and reproduction in an environment. Adaptations arise through **natural selection** 自然选择: individuals vary, some variations help survival, and those individuals leave more offspring, so the helpful trait becomes common. This is incremental genetic change accumulating over generations, not change within a single lifetime – a giraffe cannot stretch its neck and pass the stretch to its calves.

When the environment changes, populations may **adapt** over generations (if they have enough genetic variety and time); individuals may **move** to suitable habitat or **die**. If change comes faster than a population can adapt – for example, rapid warming or a sudden new predator – the population declines and may go extinct. Species with short generation times (insects, bacteria, weeds) adapt fastest; this is why pests evolve resistance to pesticides within a few years.



Three outcomes when conditions change; short generations adapt fastest.

A periodic disturbance such as fire is often part of a healthy cycle, and many species are adapted *to* it. Some pine cones open only in a fire's heat, and thick bark protects mature trees. Putting out every small fire lets dead wood build up, so the fire that finally comes is far larger and hotter.

Ecological Succession

Ecological succession 生态演替 is the gradual, orderly change in the species of a community over time:

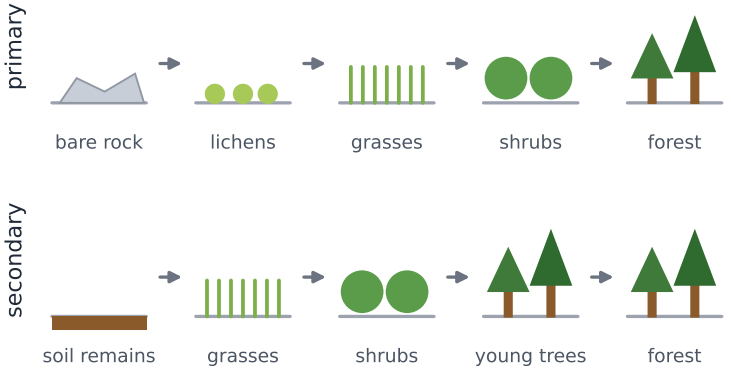
- **Primary succession** 初级演替 starts on bare rock with **no soil** – after a glacier retreats, lava cools, or a new volcanic island rises. **Pioneer species** 先锋物种 such as **lichens** 地衣 and mosses arrive first. They break rock down with acids and add dead organic matter, slowly building a thin soil. It takes hundreds to thousands of years.



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

- **Secondary succession** 次级演替 follows a disturbance that leaves the soil intact – after a fire, a flood, logging, or an abandoned farm field. Seeds and roots are already in the soil, so it is much faster (decades). Grasses and weeds come first, then shrubs, then fast-growing trees, and finally slow-growing, shade-tolerant trees.

Succession tends toward a relatively stable **climax community** 顶极群落, such as a mature oak–hickory forest. Each stage changes conditions (more soil, more shade, more moisture) in ways that help the next set of species and push out the earlier ones.



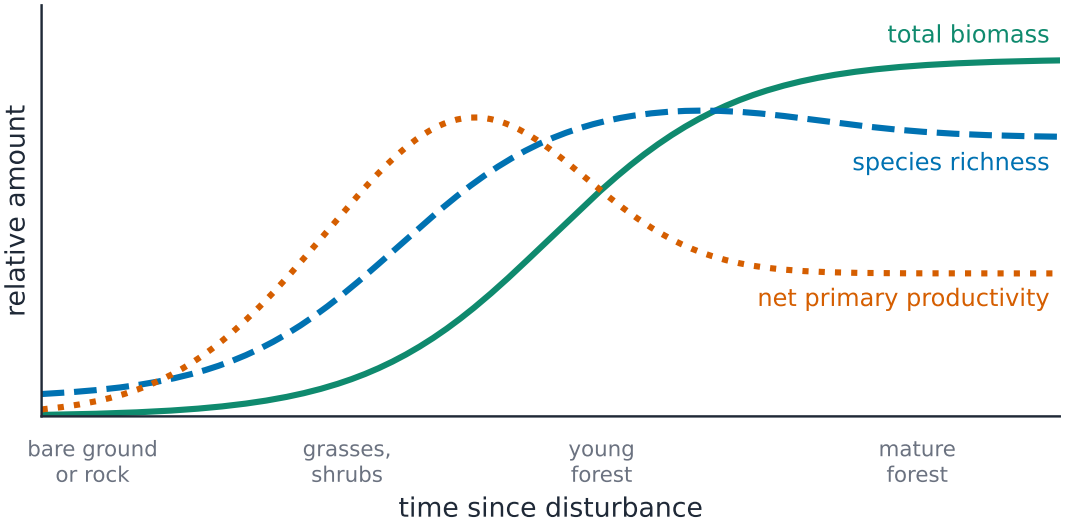
primary: bare substrate (no soil) · secondary: soil remains ⇒ faster recovery

Primary succession builds from bare rock; secondary succession regrows from surviving soil

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How the ecosystem changes during succession. AP questions ask about three quantities:

- **Total biomass** rises steadily and levels off as large, long-lived trees store more and more carbon.
- **Species richness** rises quickly as new habitats appear, then levels off or falls slightly in the mature forest as a few dominant trees shade out other plants.
- **Net primary productivity** (NPP) is highest in the middle stages, when fast-growing plants add new growth quickly. In a mature forest, much of the energy captured is used for the respiration of large trees, so NPP drops.



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

Two special roles shape a community out of proportion to their numbers:

- A **keystone species** 关键种 holds the community structure together; remove it and the community collapses. Sea otters eat sea urchins; without otters, urchins strip kelp forests bare. Beavers build dams that create ponds and wetlands used by fish, birds and insects; remove the beavers and the wetland drains.
- An **indicator species** 指示物种 signals the condition of the whole ecosystem by its presence, absence or health. Lichens vanish where the air holds sulfur dioxide; mayfly and stonefly larvae live only in clean, well-oxygenated streams; frogs, with thin skin, are early warnings of water pollution.

Worked example (FRQ style). *A farm field in Pennsylvania is abandoned. Describe the type of succession that follows, and explain how net primary productivity changes over 150 years.* The soil is still present, so this is **secondary succession**. Annual weeds and grasses arrive first, followed by shrubs and fast-growing trees such as pines, then hardwoods such as oaks. NPP rises during the early and middle stages as plants grow quickly and cover the ground, peaks when young trees are growing fastest, and then falls in the mature forest because large trees use much of their gross productivity for respiration.

Designing an investigation. Many APES FRQs describe a field study and ask about its design. Know these words:

- **Hypothesis**: a testable prediction, often "if … then …". *If grassland is left unmowed, then it will have more ant species than mowed grassland.*
- **Independent variable**: what the investigator changes or compares (mowed or unmowed).
- **Dependent variable**: what is measured (number of ant species, or Simpson's index).
- **Control**: the group or site with no treatment, used for comparison. An untouched zone upstream of a pollution source is a typical control.
- **Constants**: things kept the same in every group, such as sampling time, trap size and weather.

Worked example (changing the method). Students counted ant species in a grassland in May. Explain how the results would change if they (a) sampled a paved playground instead, or (b) sampled in winter.

1. (a) A playground has little food, no plants and no soil for nests, so far fewer ant species would be found. The comparison would then measure habitat loss, not mowing.
2. (b) In winter, many ants are inactive underground, so counts would be lower in **every** plot, and real differences between plots might be hidden.
3. In each answer, name the direction of the change (more or fewer) **and** give the reason.

Recovering after a disturbance. In data on restored land, such as old mine spoil, species numbers rise with the age of the site. Areas left to recover by themselves (spontaneous succession) are first colonised by pioneer plants: small, fast-growing, wind-dispersed, and able to live in poor soil. The same recovery is much slower in the tundra, where the cold, short growing season and thin soil slow plant growth and decomposition.

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Practice

Answer each before reading the answers below.

1. According to island biogeography, which island has the most species: a large island near the mainland, or a small island far from it? Explain.
2. Name the four categories of ecosystem services and give one example of each.
3. Distinguish primary and secondary succession, with an example of each, and name a pioneer species.
4. Explain how a rise in ocean temperature beyond corals' range of tolerance causes coral bleaching.
5. Community A has four species with 25 individuals each; community B has four species with 85, 5, 5 and 5. Compare their richness and evenness.
6. Explain why a population with high genetic diversity is more likely to survive a new disease.

Answers

1. The large, near island: it has more habitats and resources (lower extinction rate), and is easier to reach (higher immigration rate).
2. Provisioning (timber, food), regulating (flood control, pollination, climate regulation), supporting (nutrient cycling, soil formation), cultural (recreation, tourism).
3. Primary succession starts on bare rock with no soil (after a lava flow or a glacier retreats); secondary succession starts where soil remains (after a fire or farm abandonment). Lichens and mosses are pioneer species.
4. Heat stress makes corals expel their symbiotic algae (zooxanthellae), which supply most of their food and their colour. The coral turns white and may starve.
5. Same richness (four species), but A is more even, so it is more diverse.
6. Some individuals are more likely to carry alleles that give resistance, so they survive and reproduce, and the population persists.

Exam tips

- Describe biodiversity at three levels: **genetic, species, and habitat**, and link higher diversity to greater **resilience**.
- Explain why a **bottleneck** is harmful *even after* numbers recover: genetic variety has been lost.
- **Specialist** species (narrow needs) are more vulnerable than **generalists** when a habitat changes; large-territory species decline as habitat is fragmented.
- Name the four **ecosystem services** (provisioning, regulating, cultural, supporting) and give an **economic** cost when one is lost.
- Island biogeography: **larger** islands mean lower extinction; **nearer** islands mean higher immigration. Apply it to habitat fragments and **wildlife corridors**.

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- On a tolerance curve, name the **optimal range**, **zones of stress** and the **limits**; a narrow range means a sensitive species.
- Distinguish **primary** succession (bare rock, no soil, slow) from **secondary** (soil intact, faster), and name a **pioneer species**.
- During succession: biomass rises and levels off, richness rises then levels, **NPP peaks in the middle**.
- Explain a **keystone species** (outsized effect) and an **indicator species** (signals ecosystem health) with an example of each.

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Populations

AP Environmental Science

Generalist and Specialist Species

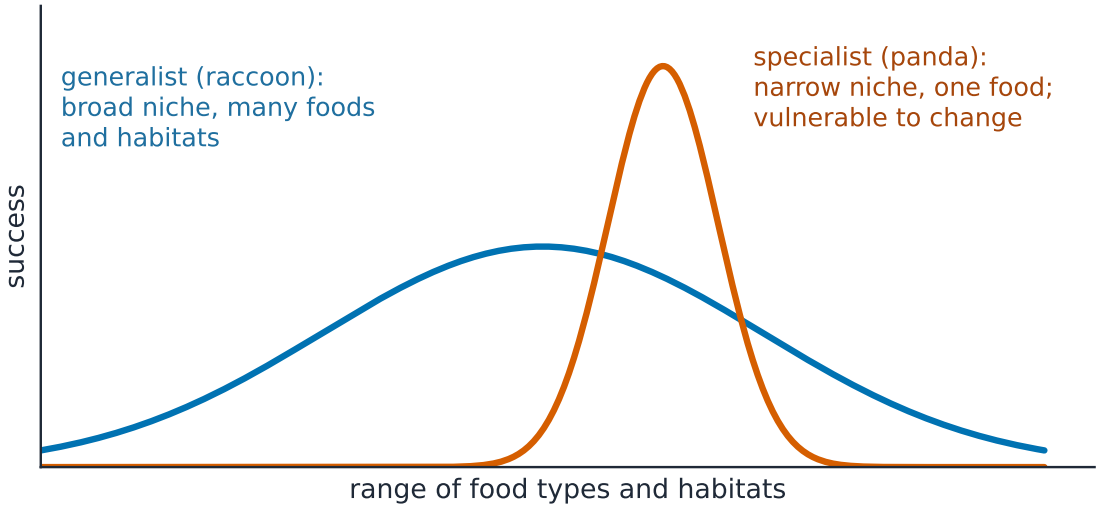
In 1944 the US Coast Guard released 29 reindeer on St. Matthew Island in the Bering Sea. With rich lichen to eat and no predators, they reached about 6000 by 1963. They ate the lichen faster than it could grow back; in one hard winter almost all of them starved, and by 1966 only 42 were left. This unit asks why populations grow, what stops them, and what that means for the eight billion people on Earth.

Every species has a **niche** 生态位: the range of conditions and resources it can use and its role in the ecosystem.

A **generalist** 广适性物种 has a broad niche: it can live in many **habitats** 栖息地 and eat many foods. Examples are raccoons, rats, cockroaches and crows. A **specialist** 狭适性物种 has a narrow niche: it needs a particular food or habitat. Examples are the giant panda (bamboo), the koala (eucalyptus leaves) and many tropical frogs.

- In a **stable** habitat, specialists have the advantage: they use their resource very efficiently and face less competition for it.
- In a **changing** habitat, generalists have the advantage: if one food or habitat disappears, they switch to another.

So specialists are more **vulnerable** 脆弱的 to habitat loss, habitat fragmentation, climate change and invasive species. Generalists often become pests or invasive species themselves.



Generalists have broad niches; specialists have narrow niches and are more vulnerable

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K-Selected and r-Selected Species

Species have different **reproductive strategies** 繁殖对策:

Feature	r-selected	K-selected
Body size	small	large
Number of **offspring** 后代	many	few
Parental care	little or none	a lot
Age to **mature** 成熟	early	late
Life span	short	long
Population	booms and crashes	stays near carrying capacity
Examples	insects, mice, weeds, most fish	elephants, whales, humans, oak trees

Biotic potential 生物潜能 is the maximum rate at which a population can grow in ideal conditions. r-selected species have a high biotic potential, so they **colonize** 定殖 new or disturbed areas quickly. Most **invasive species** 入侵物种 are r-selected.

K-selected species are hurt more by disturbance and invasive species. Because they reproduce slowly, a population that falls (from hunting, habitat loss or disease) takes a long time to recover. This is why many endangered species are K-selected.

Many species are not purely one type. Sea turtles are large and long-lived (K) but lay hundreds of eggs with no care (r).



An elephant with its single calf: a K-selected species has few young but invests heavily in each one, so it recovers slowly if numbers fall

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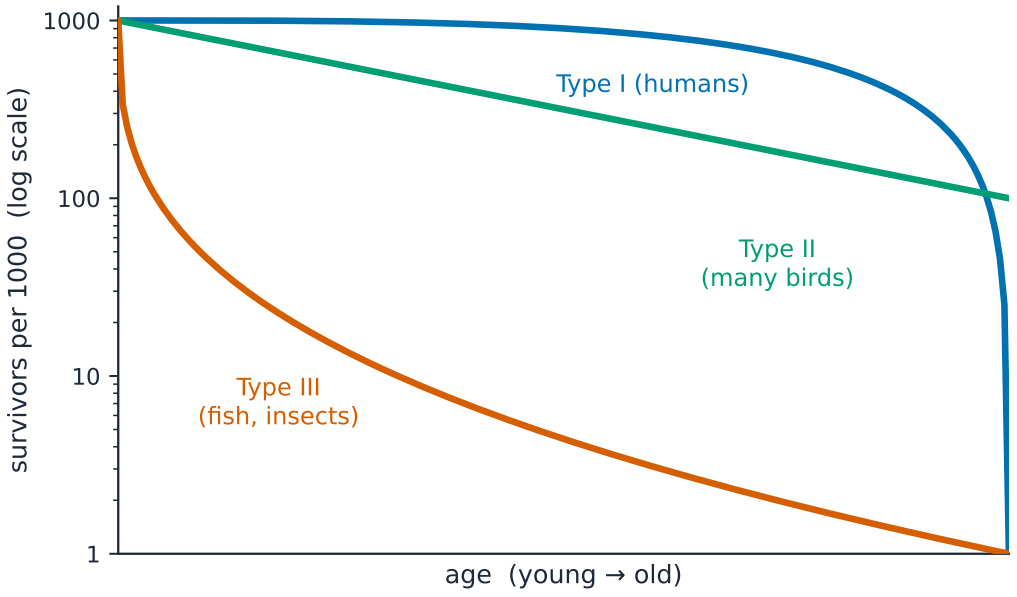
A young rabbit: r-selected species produce many offspring quickly with little parental investment

Survivorship Curves

A **survivorship curve** 存活曲线 shows how many members of a **cohort** 同龄群 (a group born at the same time) are still alive at each age. The number of survivors is plotted on a **log scale** 对数刻度, so a constant death rate gives a straight line.

- **Type I:** most individuals survive to old age, then many die. The curve is flat and then drops steeply. Examples: humans, elephants, whales (K-selected).
- **Type II:** individuals die at a roughly constant rate at all ages, so the curve is a straight line. Examples: many birds, squirrels, some lizards.
- **Type III:** most individuals die very young; the few that survive live a long time. The curve drops steeply at first and then flattens. Examples: fish, insects, oysters, plants (r-selected).

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Type I, II, and III survivorship curves on a log scale

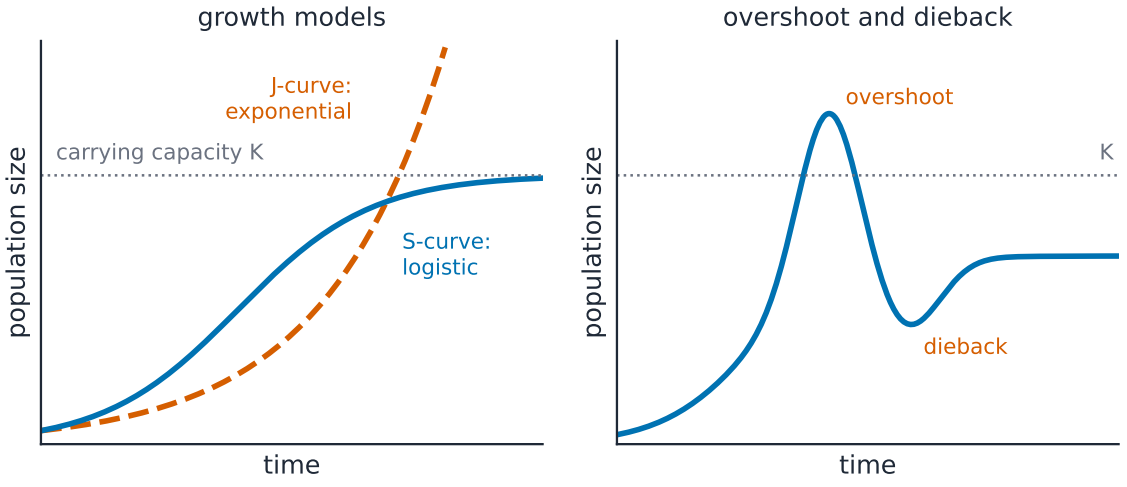
K-selected species usually follow Type I or Type II curves; r-selected species usually follow Type III. To read a curve, look at **when** the steep drop happens: early (Type III), late (Type I) or steady (Type II).

Carrying Capacity

The **carrying capacity** 环境容纳量 (K) is the largest population that an environment can support for a long time with its available food, water, space and other **resources** 资源.

A population can **overshoot** 超出 its carrying capacity for a short time, for example when resources were plentiful or because animals keep breeding before the shortage is felt. The extra individuals use resources faster than they are replaced, so the resource base is damaged (**resource depletion**). The result is **dieback** 种群骤减: a sharp, often catastrophic fall in population from famine, disease or conflict. After dieback the carrying capacity may be **lower** than before, because the habitat was damaged. The St. Matthew reindeer are a classic case.

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Left: J-shaped exponential growth and S-shaped logistic growth up to K. Right: overshoot followed by dieback to a lower level



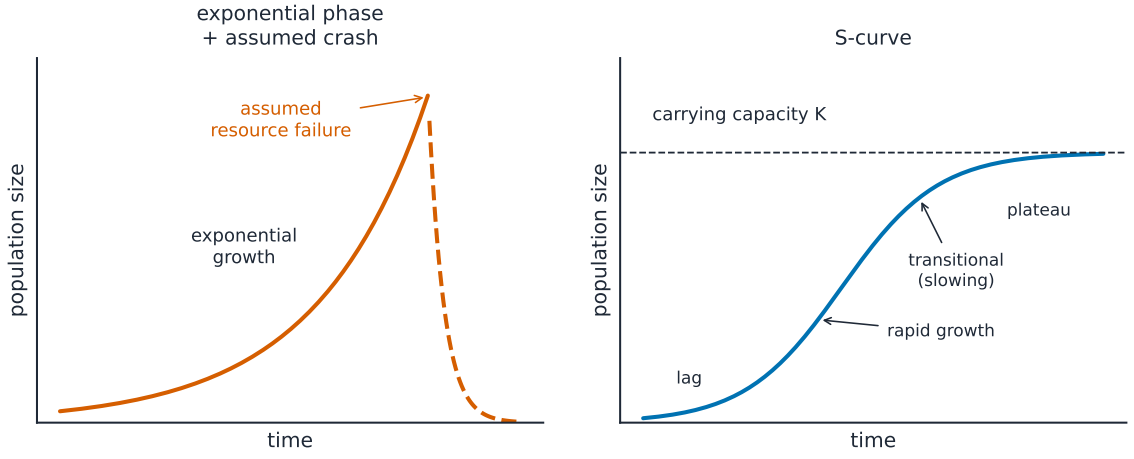
A deer herd: when a population approaches carrying capacity, resources limit further growth

Populations near K tend to **fluctuate** 波动 around it. Predator and prey populations often rise and fall in cycles: more prey supports more predators, which then eat more prey, so prey numbers fall, followed by predator numbers.

Population Growth and Resource Availability

Population growth is limited by the environment, especially by available resources and space. The total resource base is finite at every scale, from a pond to the planet.

- When resources are **abundant**, a population grows faster and faster: **exponential growth** 指数增长, which makes a J-shaped curve.
- As the population gets bigger, resources per individual shrink. Competition increases, growth slows, and the population levels off at K: **logistic growth** 逻辑斯谛增长, which makes an S-shaped curve.
- When the resource base **shrinks**, resources are shared out more unequally. The result is more deaths, fewer births (lower **fecundity** 繁殖力), or both, so the population declines.



J-shaped growth with plentiful resources; S-shaped growth as they run short.

Limiting factors 限制因素 are the resources or conditions that keep a population from growing further. They are of two kinds:

Density-dependent factors 密度制约因素	**Density-independent factors 非密度制约因素**
effect grows as the population gets denser	effect does not depend on population size
food, water and space; competition; predation; disease; clean air and water	storms, fires, floods, droughts, heat waves, cold snaps

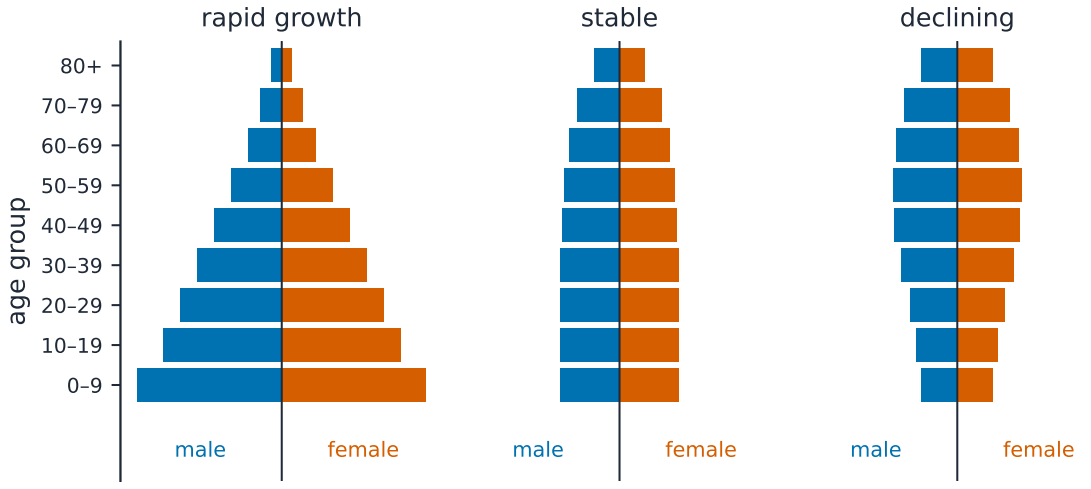
Worked example (area needed). A male wood thrush needs at least 800 m^2 of forest to breed. A planning goal is to keep 275 territories. The forest needed is $275 \times 800 = 220{,}000$ m^2. If a housing plan has 1000 lots of 1100 m^2 each, the fraction of each lot that must stay forest is $\frac{220{,}000}{1000 \times 1100} \times 100 = 20\%$.

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Age Structure Diagrams

An **age-structure diagram** 年龄结构图 (population pyramid) shows the **proportion** 比例 of a population in each age group, with males on one side and females on the other. Its shape predicts how the population will change:

- **Rapid growth:** a wide base and narrow top (a pyramid). Many children will soon be parents, so growth continues. Typical of less developed countries such as Niger.
- **Stable (slow growth):** bars of similar width up to old age (a column). Typical of the USA or France.
- **Declining:** the base is narrower than the middle. Fewer young people than middle-aged, so the population will shrink. Typical of Japan, Italy and Germany.



Age-structure diagrams for a rapidly growing, a stable and a declining population

A population with a wide base keeps growing for decades even if each woman has fewer children, because so many young people are entering their child-bearing years. This is called **population momentum** 人口惯性.

Total Fertility Rate

The **total fertility rate** 总和生育率 (TFR) is the average number of children a woman would have if current age-specific birth rates stayed the same throughout her reproductive life. **Replacement-level fertility** 更替水平生育率 is the TFR at which each generation exactly replaces itself: about **2.1** in developed countries. It is higher than 2 because some children die before they grow up; in countries with high infant mortality it is closer to 2.5 or more.

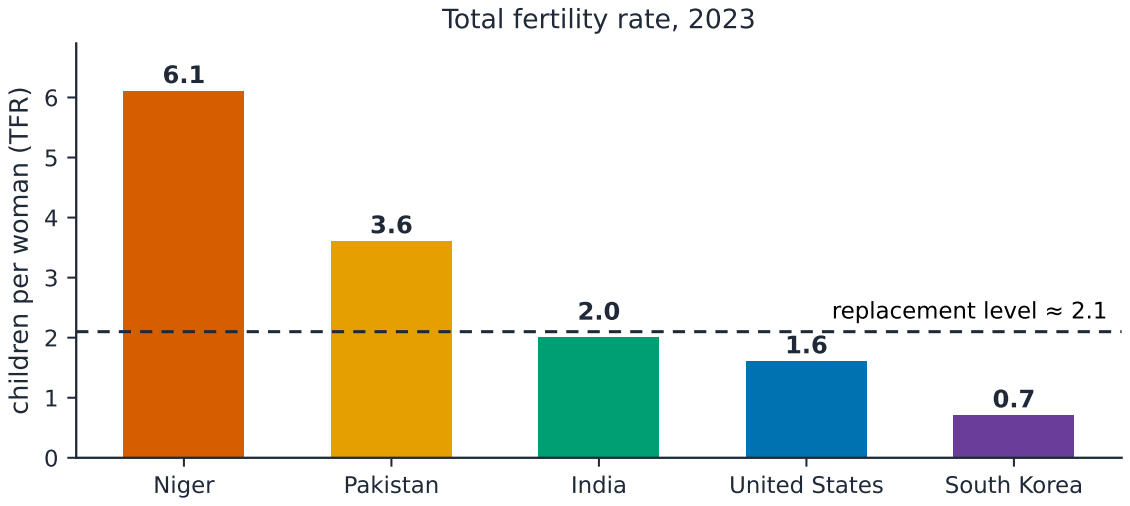
- TFR above replacement level: the population grows.
- TFR at replacement level: the population becomes stable (after a lag, because of momentum).

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- TFR below replacement level: the population eventually declines, unless people migrate in.

Factors that **lower** TFR:

- women having their first child at an older age;
- more **education** and job opportunities for girls and women;
- access to **family planning** 计划生育 and contraception;
- government policies, such as China's one-child policy (1980–2015) or tax benefits for small families;
- lower infant mortality (parents no longer need many births to make sure some children survive).



Total fertility rate in 2023: Niger 6.1, Pakistan 3.6, India 2.0, the United States 1.6 and South Korea 0.7, against the replacement level of about 2.1

Infant mortality 婴儿死亡率 is the number of babies per 1000 live births who die before their first birthday. It falls when mothers have access to good **healthcare** and **nutrition**, clean water, and vaccines.

Human Population Dynamics

A human population changes through births, deaths and **migration** 迁移:

$$\text{growth rate (\%)} = \frac{(\text{births} + \text{immigration}) - (\text{deaths} + \text{emigration})}{\text{population}} \times 100$$

Birth and death rates are usually given per 1000 people. The difference between them, without migration, is the rate of natural increase. To turn a rate per 1000 into a percent, divide by 10.

Birth rate 出生率, infant mortality and overall death rate, access to family planning, good nutrition and education, and getting married later all affect whether a population grows or declines.

Malthusian theory 马尔萨斯理论: in 1798 Thomas Malthus argued that population grows exponentially while food supply grows only steadily, so population would outrun food and be checked by famine and disease. Technology (the Green Revolution) has so far raised Earth's carrying capacity for humans, but finite land, water and energy still limit it.

The **rule of 70** 七十法则 estimates the **doubling time** 倍增时间 of anything growing at a constant percentage rate:

$$\text{doubling time (years)} \approx \frac{70}{\text{growth rate (\%)}}$$

> **Worked example.** A country has a birth rate of 30 per 1000 and a death rate of 10 per 1000, with no migration. The growth rate is $\frac{30-10}{10} = 2.0\%$ per year. The doubling time is $\frac{70}{2.0} = 35$ years.

> **Worked example (FRQ style).** A city grew at 1.88% in 2019. Doubling time $= \frac{70}{1.88} \approx 37$ years, so at a constant rate the population would double around $2019 + 37 = 2056$.

> **Worked example (resource use).** A town of 26,250 people uses 90 gallons of water per person per day. Daily use is $26{,}250 \times 90 = 2{,}362{,}500$ gallons; yearly use is $2{,}362{,}500 \times 365 \approx 8.6 \times 10^8$ gallons.

Rapid growth increases demand for water, food, energy and land, and so increases the total **ecological footprint** 生态足迹. Development, **urbanization** 城市化 and **economic development** 经济发展 usually lower birth rates over time.

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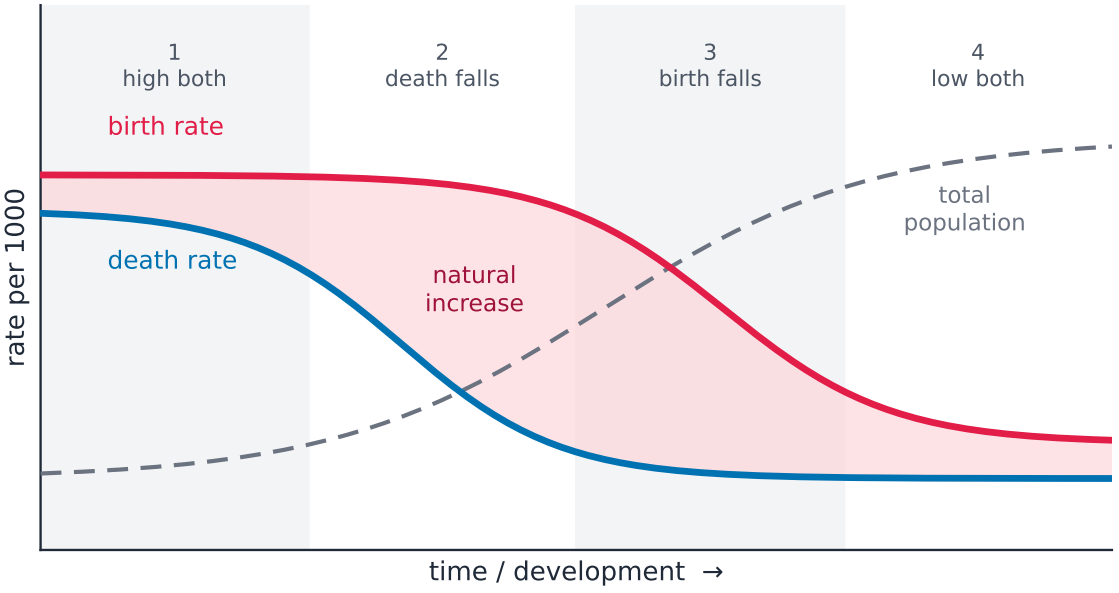
A crowded city crossing: human population dynamics depend on birth rates, death rates and migration

Demographic Transition

The **demographic transition** 人口转变 is the change from high birth and death rates to low birth and death rates as a country develops from a pre-industrial to an industrial economy.

Stage	Birth rate	Death rate	Growth	Why
1 Pre-industrial	high	high	slow	poor food supply, disease, no medicine
2 Transitional	high	falling fast	very rapid	better food, clean water, vaccines
3 Industrial	falling	low	slowing	education, jobs for women, cities, contraception
4 Post-industrial	low	low	stable or declining	high cost of raising children, women's careers

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The four stages of the demographic transition

Growth is fastest in stage 2 and early stage 3, where the gap between a still-high birth rate and an already-low death rate is widest. That lag is why a country's population keeps climbing long after its death rate falls.

Less developed countries tend to have higher infant mortality, younger populations and more children in the workforce. Children there help on farms and support parents in old age, which keeps birth rates high. Developed countries tend to be in stage 4.

Practice

Answer each before reading the answers below.

1. A country's population grows at 2% per year. Use the rule of 70 to estimate its doubling time.
2. A country has a crude birth rate of 20 per 1000 and a crude death rate of 8 per 1000, and no migration. Calculate the growth rate as a percentage, and the doubling time.
3. An age-structure diagram has a very wide base that narrows quickly. What does it predict about future growth?
4. Explain why population grows fastest in stage 2 of the demographic transition.
5. Match each survivorship curve to an example and a strategy: Type I, Type III.
6. Give three factors that lower a country's total fertility rate.

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Answers

1. $70 \div 2 = 35$ years.
2. $(20 - 8) \div 10 = 1.2\%$; doubling time $70 \div 1.2 \approx 58$ years.
3. Rapid growth: many young people will soon reach reproductive age (population momentum).
4. Death rates fall (better food, sanitation, medicine) while birth rates stay high, so the gap between them is largest.
5. Type I: humans or elephants, K-selected (most survive to old age). Type III: oysters, r-selected (most die young).
6. Any three: education and employment for women; access to family planning; urbanization; lower infant mortality; pension systems; higher cost of raising children.

Exam tips

- Use the **rule of 70**: doubling time $\approx 70 \div$ growth rate (%). Convert a rate per 1000 to a percent by dividing by 10.
- Generalists win in **changing** habitats; specialists win in **stable** habitats and are more vulnerable to habitat loss.
- Contrast **r-selected** (many offspring, little care, Type III) with **K-selected** (few offspring, much care, Type I or II) species. Most invasive species are r-selected.
- Overshoot leads to resource depletion and **dieback**; the carrying capacity may then be lower.
- Read **age-structure diagrams** from the base: wide base, rapid growth; even bars, stable; narrow base, declining.
- Replacement-level fertility is about 2.1; give **specific** reasons TFR falls (education of women, family planning, lower infant mortality).
- Classify limiting factors: density-dependent (disease, food, competition) or density-independent (storms, fires, drought).
- In the demographic transition, the death rate falls **before** the birth rate, which causes rapid growth in stage 2.
- A falling **growth rate** 增长率 still means growth: the population only shrinks when deaths and emigration exceed births and immigration.

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Earth Systems and Resources

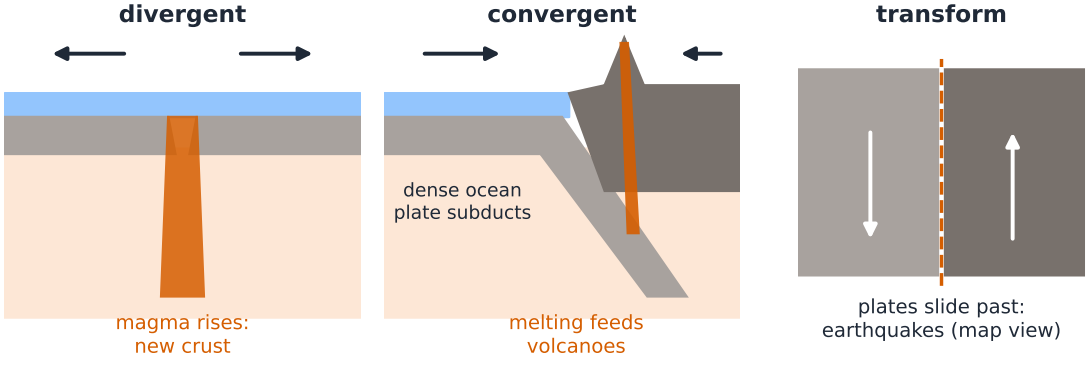
AP Environmental Science

Plate Tectonics

On 26 December 2004 the sea floor off Sumatra jumped upward by several metres. The earthquake lasted almost ten minutes, and the tsunami it raised killed about 230,000 people in fourteen countries. It happened where one plate slides under another. This unit is about the physical Earth that every ecosystem sits on: its moving plates, its soil, its air, its winds and water, and the sunlight that drives them.

Earth's outer layer (the **lithosphere** 岩石圈) is broken into rigid **plates** 板块 that move a few centimetres a year on the hot, slowly flowing mantle below. This is **plate tectonics** 板块构造. Most earthquakes and volcanoes happen at the edges of plates, the **plate boundaries** 板块边界.

Boundary	Plate motion	What forms
Divergent 离散型	plates move apart	seafloor spreading, rift valleys, volcanoes, earthquakes
Convergent 汇聚型	plates move together	mountains, island arcs, trenches, volcanoes, earthquakes
Transform 转换型	plates slide past each other	earthquakes



Divergent, convergent and transform plate boundaries

- **Divergent:** magma rises into the gap and cools into new crust. On the ocean floor this is **seafloor spreading** (the Mid-Atlantic Ridge); on land it makes a rift valley (East Africa). Iceland sits on the Mid-Atlantic Ridge.
- **Convergent:** when an ocean plate meets a continental plate, the denser ocean

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plate sinks under it. This is **subduction** 俯冲. As the sinking plate goes deep, water released from it lowers the melting point of the mantle rock above, which melts; the magma rises to form volcanoes (the Andes). When two ocean plates meet, subduction forms a chain of volcanic islands, an **island arc** (Japan, the Philippines). When two continents meet, neither sinks, so the crust crumples into high mountains (the Himalayas).

- **Transform:** the plates grind past each other, like the San Andreas Fault in California.

Why earthquakes happen. Between earthquakes, friction locks the two sides of a **fault** 断层 together while the plates keep moving, so stress builds up in the rock. When the stress overcomes the friction, the fault slips suddenly and the stored energy is released as an earthquake.

Hot spots 热点 are places where a plume of hot mantle rises under the middle of a plate, as under Hawaii. The plate moves over the fixed hot spot, leaving a line of volcanoes that get older away from the hot spot.

On a map of plate boundaries you can predict where volcanoes, earthquakes, island arcs and faults will be. Plate boundaries bring hazards, but they also bring fertile volcanic soils and mineral deposits.



A volcano erupting at a plate boundary in Iceland. Molten rock rising between spreading plates builds new crust

> **Worked example (rate).** A plate moves 5 cm per year. In 1 million years it moves $5\ \text{cm/yr} \times 10^6\ \text{yr} = 5 \times 10^6\ \text{cm}$. Convert: $5 \times 10^6\ \text{cm} \div 100 = 5 \times 10^4\ \text{m} = 50\ \text{km}$. Small yearly motions open oceans over geologic time.

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Soil Formation and Erosion

Soil 土壤 is a mix of weathered rock, organic matter, water, air and living things. It forms as **parent material** 母质 (local rock or deposited material) is broken down by **weathering** 风化 and mixed with organic matter; transport is not required.

- **Physical weathering:** rock is broken into smaller pieces without changing its chemistry, for example by ice expanding in cracks, roots, or wind and water.
- **Chemical weathering:** rock is changed by chemical reactions, for example by acid rain dissolving limestone.
- **Biological activity:** plants, fungi, worms and bacteria add organic matter and mix the soil. Dead matter breaks down into dark **humus** 腐殖质.

Soil forms very slowly: about 2–3 cm in a few hundred years or more. It forms faster in warm, wet climates, where weathering and decomposition are quicker, and slower in cold or dry places. On a new volcanic landscape, **primary succession** starts with lichens and mosses, which break down rock and add organic matter until enough soil exists for grasses, then shrubs and trees.

Soil horizons. As soil develops it forms layers called **horizons** 土层:

Horizon	Name	Contents
O	organic layer	leaf litter and partly decomposed matter
A	topsoil	humus mixed with minerals; most roots and life
B	subsoil	minerals and nutrients washed down from above
C	weathered parent material	broken rock
R	bedrock	solid rock

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Soil horizons form over time as parent rock weathers; erosion can strip topsoil and reverse that progress

Erosion 侵蚀 is the removal of soil by wind or water. It is natural, but people speed it up by removing plant cover: farming bare fields, cutting forests, **overgrazing** 过度放牧 and building. Eroded soil ends up in streams as **sediment**, which makes the water cloudy (high **turbidity** 浊度), blocks light for water plants and buries fish eggs. Healthy soil also filters and cleans water that moves through it, so protecting soil protects water quality.

Because soil forms far more slowly than it can erode, topsoil lost in a few years may take centuries to replace.

Soil Composition and Properties

Soil particles are sorted by size into three groups:

Particle	Size	Feel	Water
Sand	largest (0.05–2 mm)	gritty	drains fast, holds little
Silt	medium	smooth like flour	middle
Clay	smallest (under 0.002 mm)	sticky when wet	holds a lot, drains slowly

The mix of sand, silt and clay is the soil's **texture** 质地. Texture controls three properties:

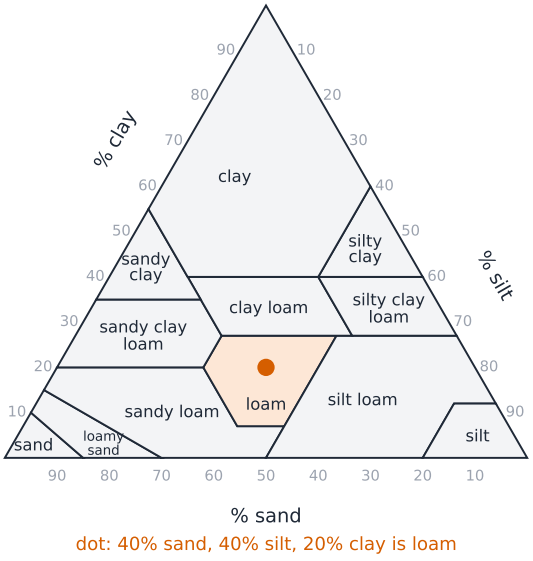
- **Porosity** 孔隙度: the fraction of the soil that is empty space.
- **Permeability** 渗透性: how fast water moves through the soil. Sand has large, connected pores and high permeability; clay has tiny pores and low permeability.

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- **Water holding capacity** 持水能力: the total water the soil can hold. Clay and humus hold the most; sand the least.

Clay also holds nutrients well, because its tiny particles have a huge surface area. **Loam** 壤土, a mix of about 40% sand, 40% silt and 20% clay, is best for most plants: it drains well but still holds water and nutrients.

The soil texture triangle. A **soil texture triangle** 土壤质地三角图 names a soil from its percentages of sand, silt and clay. Find the clay percentage on the left side, the silt on the right side and the sand along the bottom, follow the lines in from each side, and read the class where they meet. The three percentages always add up to 100.



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

> **Worked example.** A soil sample is 10% sand and 60% clay. The silt is $100 - 10 - 60 = 30\%$. Reading the triangle, the point is in the **clay** class. It will hold a lot of water but drain slowly, so it may waterlog.

Testing soil. Farmers test soil to decide on irrigation and fertilizer:

- **Chemical:** pH, and nutrients such as nitrogen, phosphorus and potassium.
- **Physical:** texture (by settling a sample in a jar of water: sand settles first, then silt, then clay), water holding capacity, and how fast water soaks in.
- **Biological:** the number of earthworms and microorganisms, and the amount of organic matter.

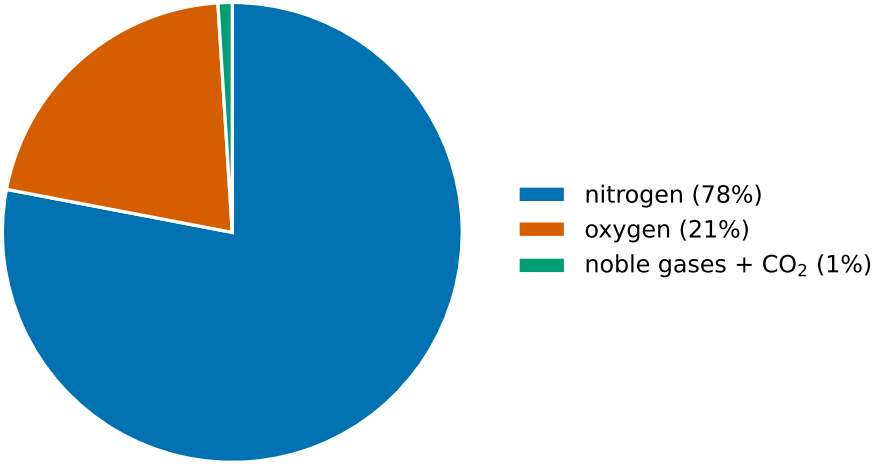
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A pit dug through soil shows its horizons: dark organic topsoil on top, then paler mineral layers, over broken rock (tape for scale)

Earth's Atmosphere

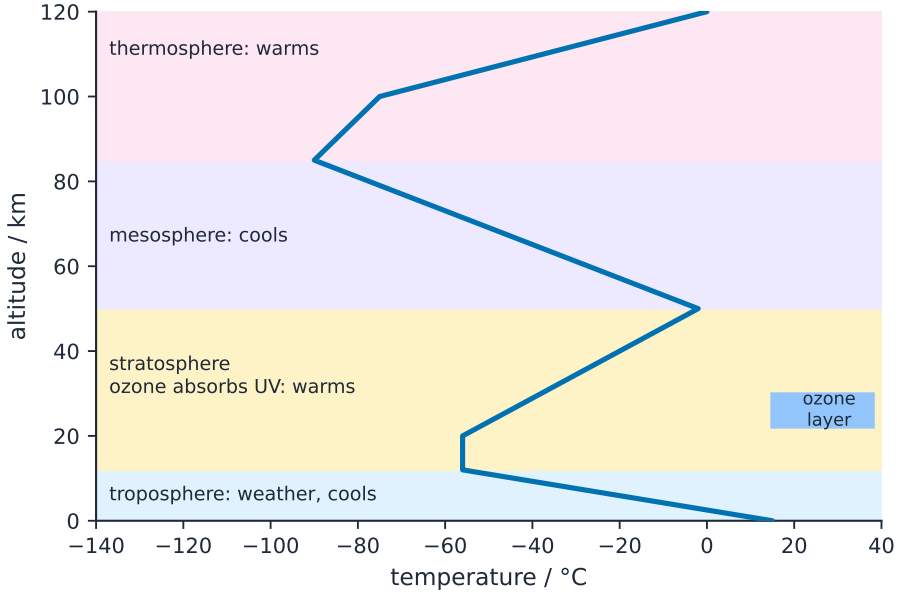
The **atmosphere** 大气层 is the layer of gases around the Earth. Dry air is about 78% nitrogen (N_2), 21% oxygen (O_2), 0.93% argon, and about 0.04% carbon dioxide, plus traces of other gases. Water vapour varies from 0 to about 4%. The trace gases are small in amount but large in effect: CO_2, water vapour and methane trap heat (the greenhouse effect).



Clean dry air is about 78% nitrogen, 21% oxygen, and 1% other gases

The atmosphere has layers, defined by whether the temperature falls or rises with height:

1. **Troposphere** 对流层 (0 to about 12 km): temperature falls with height. It holds about 75% of the air's mass and almost all the water vapour, so all weather happens here.
2. **Stratosphere** 平流层 (about 12 to 50 km): temperature rises with height, because the **ozone layer** 臭氧层 here absorbs the Sun's ultraviolet (UV) light. This ozone protects life from harmful UV.
3. **Mesosphere** 中间层 (about 50 to 85 km): temperature falls again; it is the coldest layer. Meteors burn up here.
4. **Thermosphere** 热层 (about 85 to 600 km): temperature rises steeply as gases absorb high-energy solar radiation. The auroras happen here.
5. **Exosphere** 外逸层: the thin outer edge, merging into space.



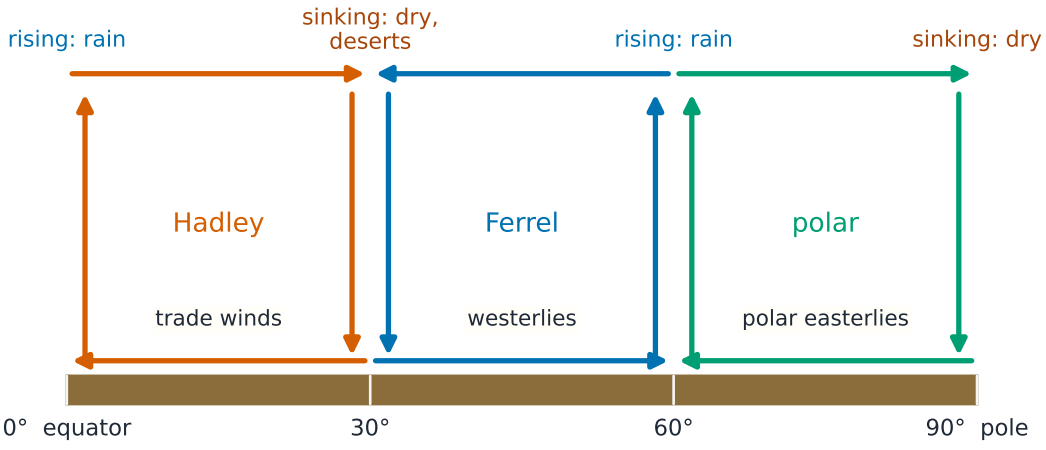
Temperature against altitude defines the layers of the atmosphere

Global Wind Patterns

Global wind patterns 全球风带 are driven by uneven heating. The most intense sunlight arrives at the equator, so the air there is heated most. Warm air is less dense, so it rises. As it rises it cools, and its water vapour condenses and falls as heavy rain: this is why tropical rainforests lie on the equator.

The rising air spreads toward the poles high up, cools, becomes denser and sinks at about 30° north and south. Sinking air warms and is dry, so the world's great deserts (the Sahara, the Australian deserts) lie near 30°. The air then flows back along the

surface toward the equator. This loop is a **convection cell** 对流环流, the **Hadley cell**. Two more cells (Ferrel and polar) carry the pattern to the poles, with rising air (rain) at about 60° and sinking air (dry) at the poles.



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

Because the Earth spins, moving air is deflected: to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. This is the **Coriolis effect** 科里奥利效应. It turns the surface winds into the **prevailing winds** 盛行风:

- **Trade winds** 信风 (0–30°): blow from the east toward the equator.
- **Westerlies** 西风带 (30–60°): blow from the west. They carry weather across the USA from west to east.
- **Polar easterlies** (60–90°): blow from the east.

Watersheds

A **watershed** 流域 (also called a drainage basin) is all the land that drains into one river, lake or other body of water. High ground called a **divide** 分水岭 separates one watershed from the next. Every watershed is described by its area, length, slope, soil and vegetation.

These features control how water moves:

- **Slope:** steep slopes make water run off faster, with more erosion and flooding.
- **Soil:** permeable soils let rain soak in and refill groundwater; clay or paved surfaces increase **runoff** 径流.
- **Vegetation:** plant roots hold soil, and leaves slow the rain, so forested watersheds have clean water and steady flow.

Anything on the land ends up downstream: fertilizer from farms, oil from roads,

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sediment from building sites. So deforesting a watershed raises sediment and turbidity in its streams, and also water temperature (less shade). Natural flooding is useful: when a river floods its **floodplain** 洪泛区, it deposits fertile sediment and refills wetlands and groundwater.

Removing riverbank vegetation. The strip of trees and plants along a river is its **riparian zone**. If it is cleared, banks erode faster, so the channel widens and moves; more sediment and nutrients reach the water; and with less shade the water warms and holds less oxygen. Fish that lay eggs in clean gravel lose their spawning sites when sediment covers it.

> **Worked example (watershed water budget).** A watershed delivers an average of 9.60 million acre-feet (maf) of water to a reservoir each year. One maf is 3.26×10^{11} gallons, and a household uses 5.0×10^4 gallons a year. How many households could this water supply for a year?

1. Convert to gallons: $9.60 \times 3.26 \times 10^{11} \approx 3.13 \times 10^{12}$ gallons.
2. Divide by use per household: $\dfrac{3.13 \times 10^{12}}{5.0 \times 10^4} \approx 6.3 \times 10^7$ households, about 63 million.
3. In a drought year when the river flows at only 36% of average, the same water supplies $0.36 \times 63 \approx 23$ million households.

Keep the units on every line, and divide the powers of ten by subtracting exponents ($10^{12} \div 10^4 = 10^8$).

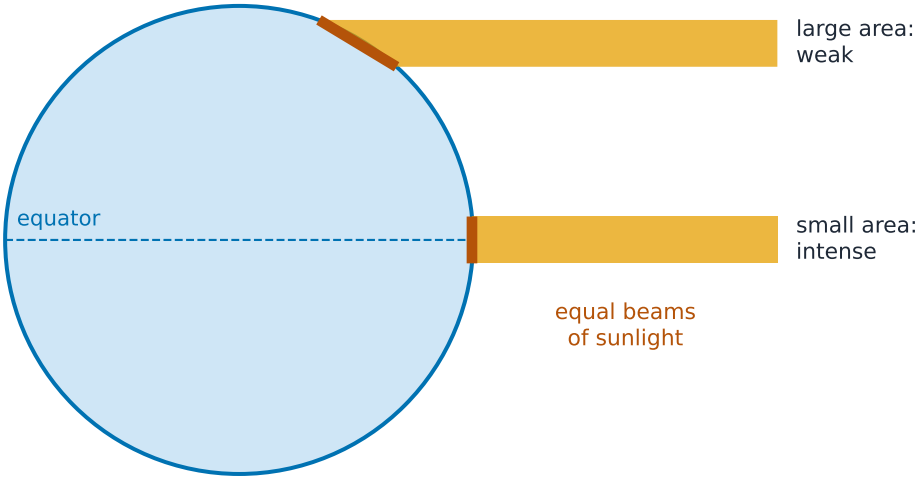


A waterfall in a river basin: a watershed is the land that drains into a stream or lake

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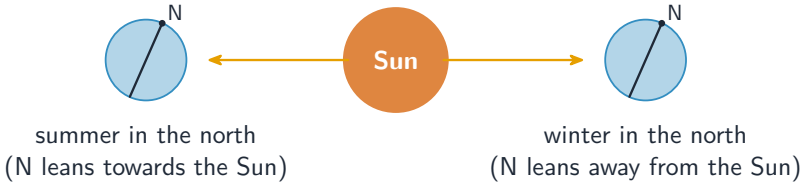
Solar Radiation and Earth's Seasons

Insolation 日射 (incoming solar radiation) is the Earth's main source of energy. How much a place receives depends on the angle of the Sun's rays. Near the equator, the rays hit the surface almost head-on, so a beam's energy falls on a small area. Near the poles the same beam hits at a low angle and spreads over a much larger area, so each square metre gets less energy. It also passes through more atmosphere. This is why insolation is highest at the equator and falls toward the poles.



The same beam of sunlight is concentrated at the equator and spread out near the poles

Seasons 季节 are caused by the **tilt of the Earth's axis** 地轴倾斜 (about 23.5°), **not** by the Earth's distance from the Sun. The axis always points the same way in space. In June the Northern Hemisphere is tilted toward the Sun: the Sun is higher in the sky, its rays are more direct, and the days are longer, so the north has summer. At the same time the Southern Hemisphere is tilted away and has winter. In December the situation reverses.



The tilt of the Earth's axis causes the seasons

A place gets the most solar radiation on its longest summer day and the least on its shortest winter day. Near the equator, day length and insolation change little through the year, so temperature changes little, although wet and dry seasons can be strong.

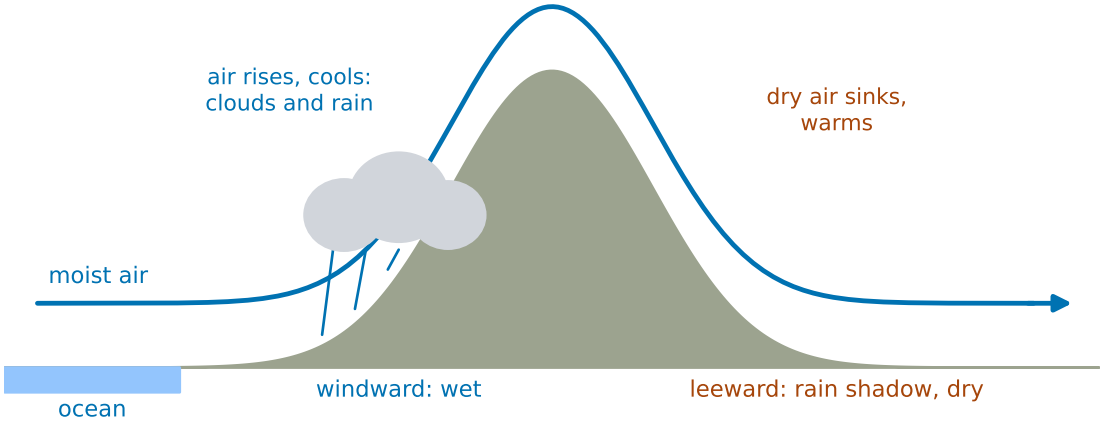
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Earth's Geography and Climate

Weather is the condition of the air on a given day; **climate** 气候 is the average pattern over 30 years or more. Climate depends on the Sun's energy, but also on geography:

- **Latitude:** higher latitude, less insolation, colder.
- **Altitude:** air cools by about 6.5 °C for every 1000 m of height, so mountains are colder.
- **Oceans:** water heats and cools slowly, so coastal places have milder climates than inland places. Ocean currents carry heat: the Gulf Stream keeps western Europe warmer than its latitude suggests.
- **Mountains:** they block winds and create rain shadows.

A **rain shadow** 雨影 forms when moist wind meets a mountain range. The air is forced up the **windward** 迎风 side, cools, and its water vapour condenses and falls as rain. The air that crosses the top has lost its moisture; it sinks down the **leeward** 背风 side and warms, so that side is dry. Death Valley in California lies in the rain shadow of the Sierra Nevada.



A rain shadow: rain falls on the windward side; the leeward side stays dry

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Desert dunes: latitude, altitude and ocean currents shape Earth's climate regions

El Nino and La Nina

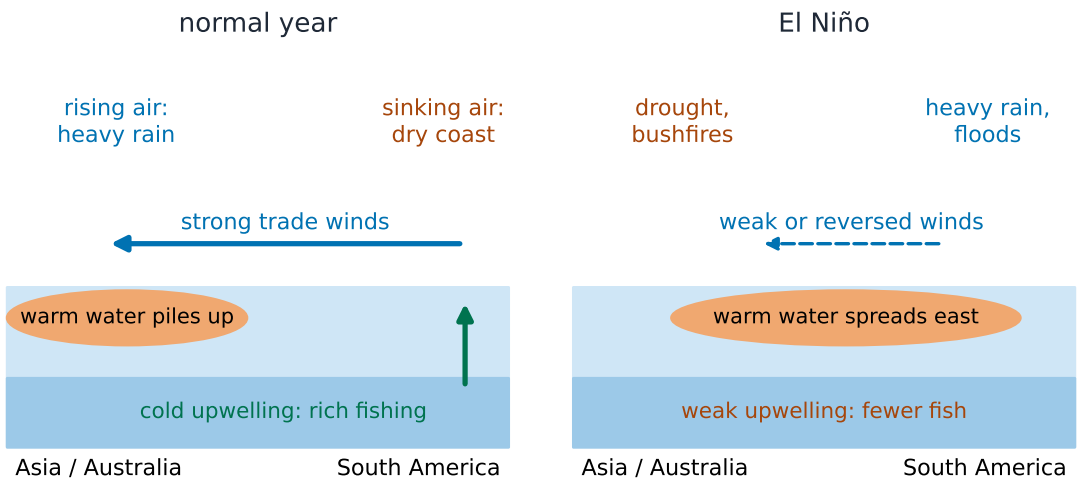
El Niño 厄尔尼诺 and **La Niña** 拉尼娜 are changes in the surface temperature of the tropical Pacific Ocean, and in the winds above it, that recur every few years. Together they are called the El Niño–Southern Oscillation (ENSO).

A normal year. Strong **trade winds** blow from east to west across the Pacific. They push warm surface water west, toward Indonesia and Australia, where the warm water heats the air, which rises and brings heavy rain. Off the coast of Peru, the winds push surface water away, and cold, nutrient-rich water rises from below. This **upwelling** 上升流 feeds plankton and supports one of the world's richest fisheries.

El Niño. The trade winds weaken or even reverse. Warm water spreads east across the Pacific to South America. Upwelling off Peru weakens, so plankton and the fish catch fall. Rain moves east with the warm water: Peru and Ecuador have floods, while Indonesia and Australia have drought and bushfires. The effects spread worldwide: the southern USA usually has a wetter winter.

La Niña is the opposite: the trade winds become stronger than normal, the eastern Pacific becomes cooler than normal, upwelling increases, and the west gets even more rain. The southern USA usually has a drier winter, and Atlantic hurricanes are more common.

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Normal conditions and El Niño across the equatorial Pacific

The same event affects places differently, depending on where they are and their geography.

Practice

Answer each before reading the answers below.

1. Describe what happens where an oceanic plate meets a continental plate, and name two features that form.
2. A soil is 40% sand, 40% silt and 20% clay. Name its texture, and say which soil type drains fastest.
3. Name the layer of the atmosphere where weather happens and the layer that contains the ozone layer.
4. Explain how a mountain range creates a rain shadow.
5. Describe how an El Niño event affects the fisheries off Peru.
6. Explain what causes Earth's seasons.

Answers

1. The denser oceanic plate is subducted under the continental plate (a convergent boundary), forming a deep ocean trench and volcanoes, with earthquakes.
2. Loam. Sandy soil drains fastest: its large particles leave large pores.
3. The troposphere; the stratosphere.
4. Moist air rises up the windward side, cools and drops its rain. The air that descends on the leeward side is dry and warms, so that side is a desert.
5. Trade winds weaken, warm water spreads east, and the upwelling of cold, nutrient-rich water off Peru decreases. Plankton decline, and so do the fish (anchovy) catches.

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6. Earth's axis is tilted about 23.5°, so as Earth orbits the Sun each hemisphere receives more direct sunlight and longer days for part of the year. Distance from the Sun is not the cause.

Exam tips

- Match each plate boundary to what it makes: divergent (spreading, rift valleys), convergent (subduction, volcanoes, mountains, island arcs, trenches), transform (earthquakes only).
- To explain subduction volcanoes: the denser plate sinks and releases water, lowering the melting point of mantle rock above it; that rock melts and magma rises.
- Know the soil horizons (O, A, B, C, R) and use the texture triangle: the three percentages add to 100.
- Sand drains fast and holds little water; clay holds a lot but drains slowly; loam is best for crops.
- Atmosphere layers: troposphere (weather), stratosphere (ozone layer absorbs UV, so it warms with height).
- Global winds: rising air at the equator (rain), sinking air at 30° (deserts); the Coriolis effect deflects winds.
- **Seasons come from the Earth's tilt**, not its distance from the Sun.
- A rain shadow is dry on the **leeward** side. Say which side gets the rain and why: rising air cools and condenses.
- El Niño: weaker trade winds, warm water moves east, upwelling weakens off South America, fisheries decline.

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Land and Water Use

AP Environmental Science

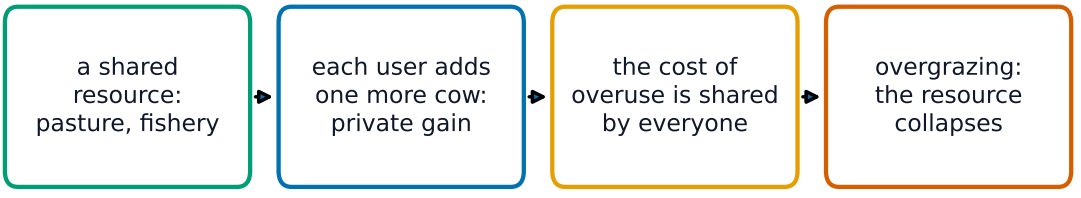
The Tragedy of the Commons

For 500 years, the Grand Banks off Newfoundland held so many cod that sailors said you could walk across the sea on their backs. Then large factory trawlers arrived, each boat catching as much as it could before the others did. In 1992 the cod stock collapsed, Canada closed the fishery, and about 35 000 people lost their jobs in a single year. Thirty years later the cod have still not fully recovered. This unit is about how we use land and water to feed and house eight billion people – and how to do it without using up the resources we depend on.

The **tragedy of the commons** 公地悲剧 suggests that individuals will use a shared resource in their **own self-interest** rather than for the common good, and so deplete it. Each user gains the full benefit of taking a little more (one more cow on the shared pasture, one more boatload of fish), while the cost – a damaged pasture or a smaller fish stock – is shared by everyone. Examples: open-ocean fisheries, the atmosphere (as a dump for CO_2), groundwater pumped by many farmers, and public grazing land.

Solutions change the rules so that users carry the cost of their actions:

- **Regulation** – catch quotas, fishing seasons, limits on how many animals may graze;
- **Fees or taxes** – grazing fees, a carbon tax;
- **Private or community ownership** – a group that owns a resource has a reason to protect it for the long term;
- **International agreements** for resources no single country owns.



The tragedy of the commons: private gain, shared cost

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Clearcutting

Clearcutting 皆伐 removes all the trees from an area at once. It is **economically advantageous** – it is the fastest and cheapest way to harvest timber, and it suits trees such as pines that need full sun to regrow. But it leads to:

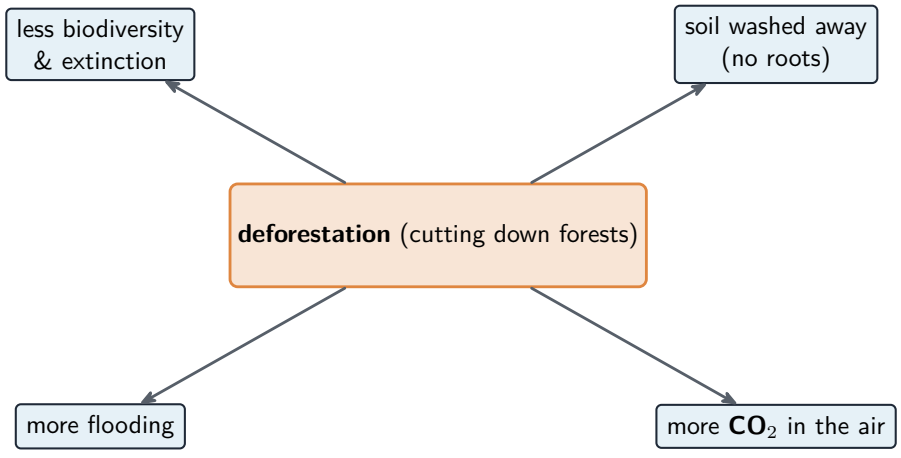
- **soil erosion** 土壤侵蚀 – no roots hold the soil, and rain washes it into streams;
- **higher soil and stream temperatures** – no shade, so soil dries out and streams warm, holding less dissolved oxygen for fish;
- **flooding** – without trees to soak up and transpire water, more rain runs straight off the land;
- **loss of habitat and biodiversity**.

Forests contain trees that **absorb pollutants and store carbon**. Cutting and burning trees releases that carbon as CO_2 and contributes to climate change. Deforestation causes roughly a tenth of global CO_2 emissions.



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

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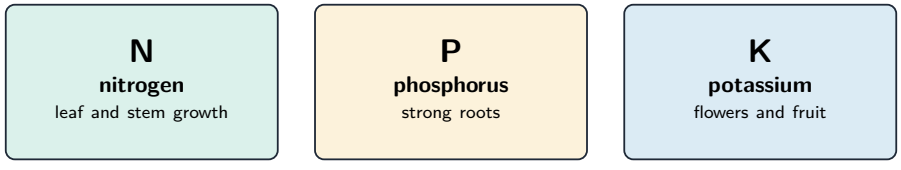
Deforestation lowers biodiversity and causes erosion, flooding, and higher CO2

The Green Revolution

The **Green Revolution** 绿色革命 (from the 1940s to the 1970s) shifted farming to new strategies that greatly increased food production. Its methods:

- **mechanization** – tractors and combine harvesters;
- **high-yield crop varieties** and, later, **genetically modified organisms (GMOs)**;
- **synthetic fertilizers** 化肥;
- **irrigation**;
- **pesticides** 农药.

The results were both positive and negative. World grain production roughly tripled, and famine became far rarer even as the population doubled. Mechanization **increases profits and efficiency** – one farmer can work far more land – but it also **increases reliance on fossil fuels** for machinery, fertilizer manufacture and transport. Other costs include soil degradation, water pollution from fertilizer and pesticide runoff, falling water tables, and loss of crop diversity as farmers plant a few high-yield varieties in **monoculture** 单一栽培.



NPK fertilisers supply nitrogen, phosphorus and potassium, three major mineral nutrients

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Impacts of Agricultural Practices

Three practices named by the course cause most of the environmental damage:

- **Tilling** (ploughing) loosens the soil and buries weeds, but leaves the topsoil bare and loose, so wind and water erode it. It also speeds up decomposition, releasing soil carbon as CO_2. During the 1930s Dust Bowl in the US Great Plains, ploughed and drought-dried soil blew away in storms that reached the Atlantic coast.
- **Slash-and-burn farming** clears tropical forest by cutting and burning it; the ash fertilizes the soil for a few years, then the nutrients are used up and the farmer moves on to clear more forest. It causes deforestation, air pollution and CO_2 release.
- **Synthetic fertilizers** – excess nitrogen and phosphorus run off into rivers and lakes and cause **eutrophication** 富营养化; nitrates also leach into groundwater, and making nitrogen fertilizer uses a lot of natural gas. Over time, heavy use without organic matter can leave soil less able to hold water.

Irrigation can also cause **soil salinization** 土壤盐碱化 (see Irrigation Methods).



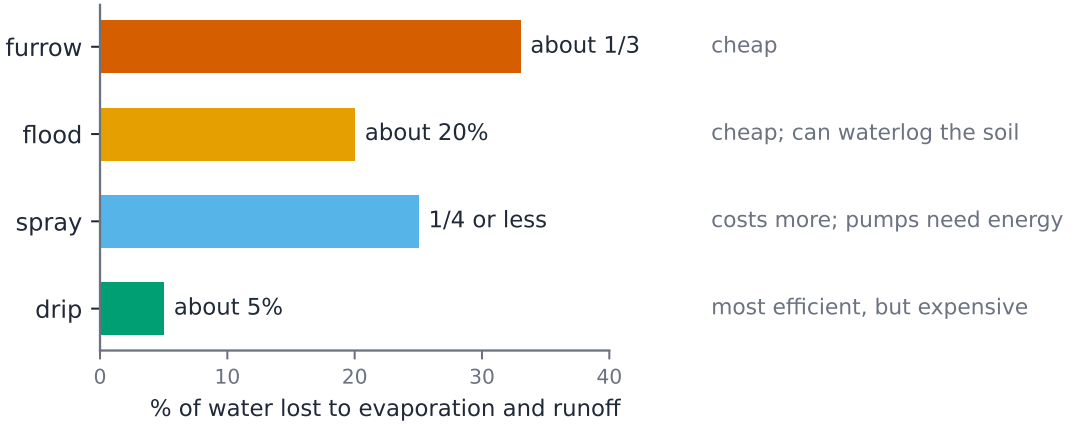
Intensive farmland: tillage, fertilisers and monocultures raise yields but can erode soil and pollute water

Irrigation Methods

Irrigation 灌溉 supplies water to crops, and it is by far the **largest share of freshwater withdrawals – about 70%** worldwide, a figure the exam expects you to know.

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Method	How it works	Water lost to evaporation and runoff	Notes
Furrow	ditches (furrows) are cut between crop rows and filled with water	about **1/3**	inexpensive
Flood	the whole field is flooded	about **20%**	inexpensive; can waterlog the soil
Spray	groundwater is pumped to spray nozzles across the field	**1/4 or less**	efficiency depends on conditions; more expensive and needs energy
Drip	perforated hoses release small amounts of water at the plant roots	about **5%**	the most efficient, but expensive, so not often used



Water lost to evaporation and runoff by irrigation method: furrow about a third, flood about 20%, spray a quarter or less, drip about 5%

Over-irrigation causes two kinds of soil damage:

- **Waterlogging** – too much water sits in the soil, raising the water table so that plant roots cannot absorb oxygen.
- **Salinization** – irrigation water (especially groundwater) contains dissolved salts. When the water evaporates, the salts stay behind in the soil. Over time the soil becomes toxic to plants. Salinization has damaged farmland in Pakistan, Australia and California's Central Valley. Solutions include drip irrigation, flushing the soil with fresh water, and good drainage.

Irrigation also depletes **aquifers** 含水层 (underground stores of freshwater) when water is pumped out faster than rain can refill them. The **Ogallala Aquifer** under

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the US Great Plains supplies about a third of US irrigation water; in parts of Kansas and Texas its water level has dropped more than 30 m, and some wells have run dry.

> **Worked example (irrigation).** A farm applies 1 000 000 L of water a season by furrow irrigation, losing 1/3 to evaporation and runoff. How much water reaches the crops, and how much would a drip system need to deliver the same amount? With furrow irrigation, the crops receive $1\,000\,000 \times \frac{2}{3} \approx 667\,000$ L. Drip loses only 5%, so it needs $\dfrac{667\,000}{0.95} \approx 702\,000$ L. Switching saves about $1\,000\,000 - 702\,000 \approx 298\,000$ L a season – about 30%.

Pest Control Methods

Pest-control chemicals include **pesticides** (the general term), **herbicides** (kill weeds), **fungicides** (kill fungi), **rodenticides** (kill rats and mice) and **insecticides** (kill insects). They decrease crop damage and **increase crop yields**, but:

- they harm **non-target species** – pollinating bees, birds, fish, and the natural predators of the pests;
- they pollute water and soil, and some persist and biomagnify;
- pests develop **pesticide resistance** 抗药性 through **natural selection**: the few pests that survive a spraying carry resistance genes, breed, and pass them on, so the next generation is harder to kill. Farmers then use stronger doses or new chemicals – the "**pesticide treadmill**".

Genetically engineered crops can be made resistant to pests and diseases – for example Bt corn, which produces its own insecticide protein. This reduces spraying, but planting the same engineered variety everywhere leads to a **loss of genetic diversity** in that crop, so a single new pest or disease could damage the whole harvest.



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

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Meat Production Methods

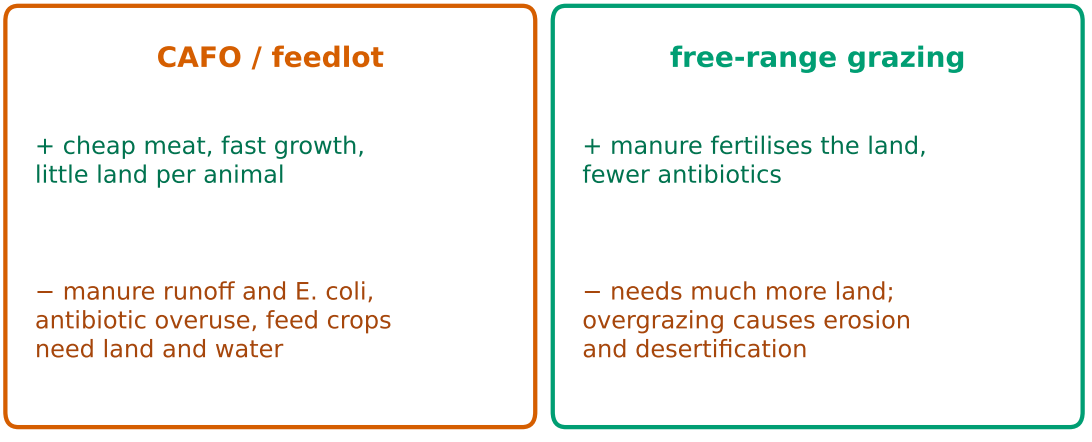
Meat is produced in two main ways:

- **Concentrated animal feeding operations (CAFOs)**, also called **feedlots**, crowd livestock together and feed them grain to get them ready for slaughter quickly. Grain-rich diets speed weight gain in cattle but can cause digestive problems. Antibiotics may be used to treat disease; growth hormones are also used in some beef-production systems. Feedlots generate huge amounts of **organic waste**, which can contaminate groundwater and surface water with nutrients and E. coli bacteria. But they are **less expensive**, which keeps prices down for consumers.
- **Free-range grazing** gives livestock access to pasture, where manure fertilizes the land. Pasture access alone does not guarantee a grass-only diet or meat free of antibiotics and other treatments. But it needs **large areas of land**, and the meat is **more expensive**.

Meat production is much **less efficient** than growing crops for people to eat: producing meat, especially beef, usually requires more land per calorie than growing crops for direct human consumption. The ratio varies with the animal and production system; energy is lost between trophic levels.

Overgrazing 过度放牧 occurs when too many animals feed on one area of land. The vegetation is eaten faster than it regrows, so the soil is left bare and erodes. On dry land this can drive **desertification** 荒漠化: the degradation of low-precipitation regions until they become increasingly arid deserts, as in the Sahel south of the Sahara.

Eating less meat could reduce emissions of CO_2, **methane** 甲烷 (from cattle digestion and manure) and N_2O (from manure and feed-crop fertilizer); conserve water; reduce the use of antibiotics and growth hormones; and improve topsoil.



Feedlots and free-range grazing: benefits and costs

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Worked example (pasture needed). A beef cow eats 11.8 kg of food a day. A hectare of pasture grows 2000 kg of grass a year. How much pasture does one cow need?

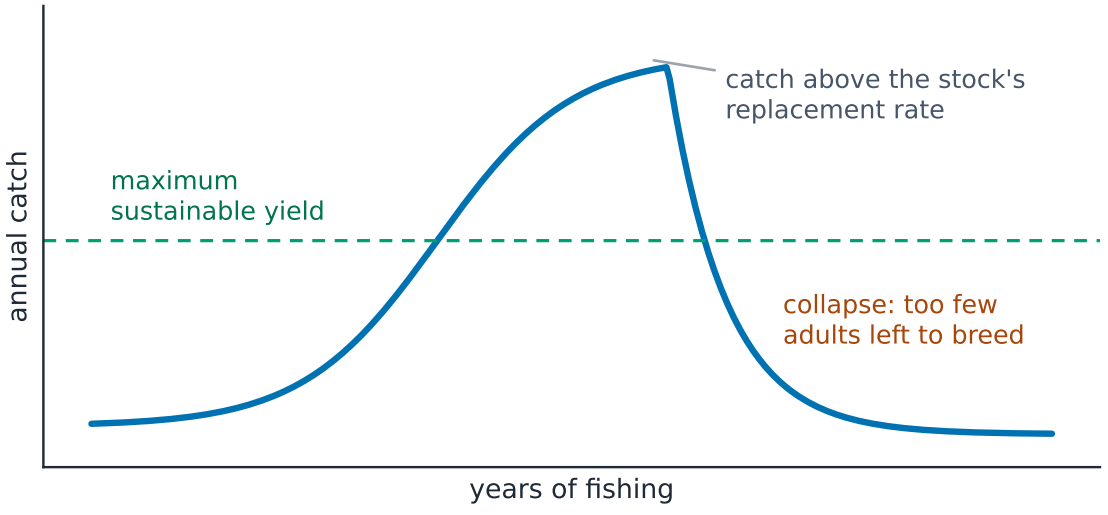
1. Food per year: $11.8 \times 365 \approx 4310$ kg.
2. Area: $4310 \div 2000 \approx 2.2$ hectares per cow.
3. A herd of 500 cattle needs about 1100 hectares, which is why free-range beef uses so much land.

Impacts of Overfishing

Overfishing 过度捕捞 removes fish faster than they can reproduce. It has made some fish species **extremely scarce** – Atlantic cod, bluefin tuna and many sharks – which reduces biodiversity in aquatic systems and harms the people who depend on fishing for **food and commerce**, especially coastal communities in developing countries. About a third of the world's assessed fish stocks are now overfished.

Destructive methods make it worse. **Bottom trawling** drags heavy nets across the seafloor, destroying corals and sponges. **Bycatch** – unwanted species such as dolphins, sea turtles and seabirds caught along with the target fish – is thrown back dead or dying. As large predatory fish are fished out, fleets move to smaller fish lower in the food web ("fishing down the food web").

Overfishing is a classic tragedy of the commons in the open ocean. Solutions include catch quotas set at a **sustainable yield**, marine protected areas where fishing is banned, larger net mesh sizes so young fish escape, and bycatch-reduction devices such as turtle excluders.



Catch rises with fishing effort until the stock collapses

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Impacts of Mining

Mining 采矿 provides the low-cost energy and raw materials needed to make products – metals, coal, sand, phosphate. Its methods:

- **Surface mining** removes large amounts of soil and rock, called **overburden**, to reach the ore beneath. **Strip mining** removes the vegetation and soil in strips, so the area is easily eroded; **open-pit mining** digs a huge stepped pit; **mountaintop removal** blasts off the top of a mountain to reach coal seams and dumps the rock into nearby valleys and streams.
- **Subsurface mining** reaches deep deposits through shafts and tunnels. As the easily reached coal reserves are used up, it becomes necessary to mine underground, which is **very expensive** – and more dangerous for miners (cave-ins, explosions, lung disease).

Mining wastes include the soil and rock moved to reach the ore, plus **slag** (waste from smelting) and **tailings** (the crushed rock left after the mineral is removed). Water draining through these wastes picks up sulfuric acid and heavy metals – **acid mine drainage** 酸性矿山废水. Coal mining can also destroy habitats, contaminate groundwater, and release **dust particles** and **methane**.

As the more accessible, higher-grade ores are mined to depletion, companies turn to **lower-grade ores**. Extracting the same amount of metal from poorer ore needs more digging, energy and water, and produces more waste and pollution.



An open-pit mine 露天矿*: benches are cut ever wider and deeper to reach the ore, destroying habitat and exposing rock that pollutes water*

When the easily reached deposits are gone, mining moves underground to **subsurface mining** 地下开采, which is far more expensive and dangerous – the same pattern applies to coal as its accessible reserves shrink. Mined land can be partly restored

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by **reclamation**: putting back the overburden and topsoil and replanting, as US law requires for coal mines.

> **Worked example (ore grade).** A phone contains 0.034 g of gold. A gold ore holds 5 g of gold per metric ton of ore. How much ore must be mined for the gold in one million phones?

1. Gold needed: $0.034 \times 1{,}000{,}000 = 34{,}000$ g.
2. Ore needed: $34{,}000 \div 5 = 6800$ metric tons.
3. Recycling the phones instead avoids digging up, crushing and treating 6800 tonnes of rock, with all its waste and water use.

Impacts of Urbanization

Urbanization 城市化 – the growth of cities – affects several cycles:

- **Hydrologic cycle** 水循环: cities use large amounts of water and can deplete local supplies. Heavy groundwater pumping near a coast draws seawater into the aquifer – **saltwater intrusion** 海水入侵 – which can ruin a freshwater supply.
- **Carbon cycle**: burning fossil fuels for transport, power and heating, and landfill decomposition, increase the CO_2 in the atmosphere.
- **Impervious surfaces** 不透水面 – roads, buildings, sidewalks and parking lots – do not let water reach the soil. Rain runs off quickly into drains and streams, causing **flooding**, carrying oil, metals and litter into rivers, and leaving less water to recharge groundwater.
- Dark surfaces absorb heat, so cities become **urban heat islands** 热岛, several degrees warmer than the surrounding countryside.

Urban sprawl is the shift of population from high-density cities to low-density suburbs that spread into rural land. It consumes farmland and habitat, fragments ecosystems, increases car use (and so air pollution and CO_2), and needs more roads, pipes and impervious surfaces per person.

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Urban sprawl 城市扩张*: housing spreads over former farmland, sealing the soil so rain runs off instead of soaking in*

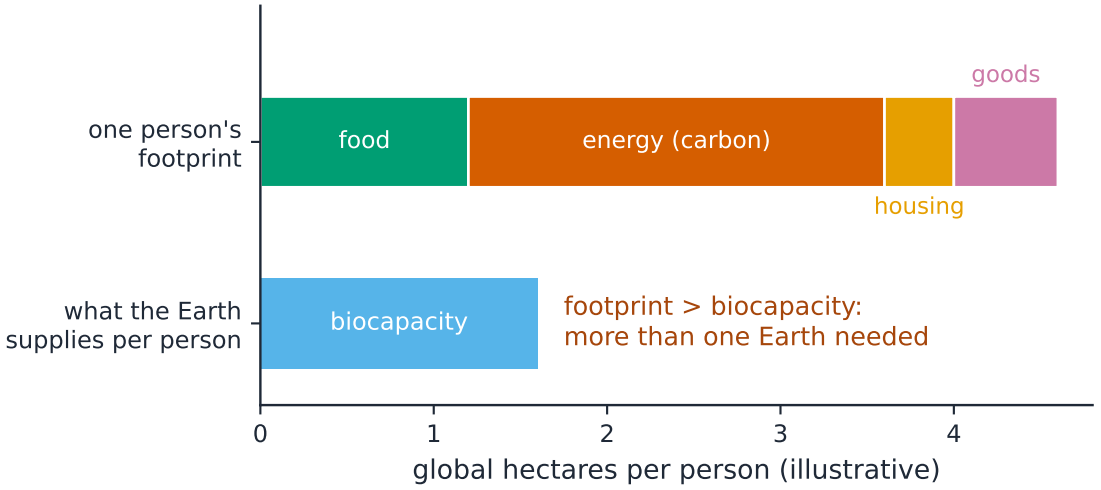
Ecological Footprints

An **ecological footprint** 生态足迹 compares the **resource demands and waste production** of an individual or a society: it measures the area of productive land and water needed to supply the food, energy, timber and space that person or society uses, and to absorb its wastes (especially CO_2). It is measured in **global hectares (gha)**. Wealthy, high-consumption nations have much larger footprints – the carbon from energy use is usually the largest part.

A related measure is the **carbon footprint**: the total greenhouse gases released by a person's or product's activities, measured in tonnes of CO_2-equivalent.

> **Worked example (footprint).** Earth provides roughly 1.6 global hectares (gha) of **biocapacity** per person. If the average person's footprint is 2.7 gha, humanity is demanding about $\frac{2.7}{1.6} \approx 1.7$ Earths – living beyond what the planet can renew. Worse, if everyone consumed like a high-income nation at 8 gha per person, it would take $\frac{8}{1.6} = 5$ Earths – exactly why footprint-per-person is the key sustainability yardstick.

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When the footprint per person exceeds the Earth's biocapacity per person, resources are used faster than they regrow

Introduction to Sustainability

Sustainability 可持续性 refers to humans living on Earth and using its resources **without depleting them for future generations**. It balances environmental health, economic viability and social equity.

Scientists track **environmental indicators** that show whether we are moving toward sustainability:

- biological diversity;
- food production;
- average global surface temperatures and CO_2 concentrations;
- human population;
- resource depletion.

Sustainable yield is the amount of a renewable resource that can be taken **without reducing the available supply** – for example, harvesting no more fish each year than the population adds through reproduction, or cutting no more wood than the forest grows.

> **Worked example (sustainable yield).** A lake holds 10 000 trout. Each year the population adds about 15% through births minus natural deaths. The sustainable yield is about $10\,000 \times 0.15 = 1\,500$ trout a year. If anglers take 2 500, the population shrinks by about 1 000 in the first year. As the stock falls, its 15% net annual increase becomes smaller, so the same catch causes faster decline.

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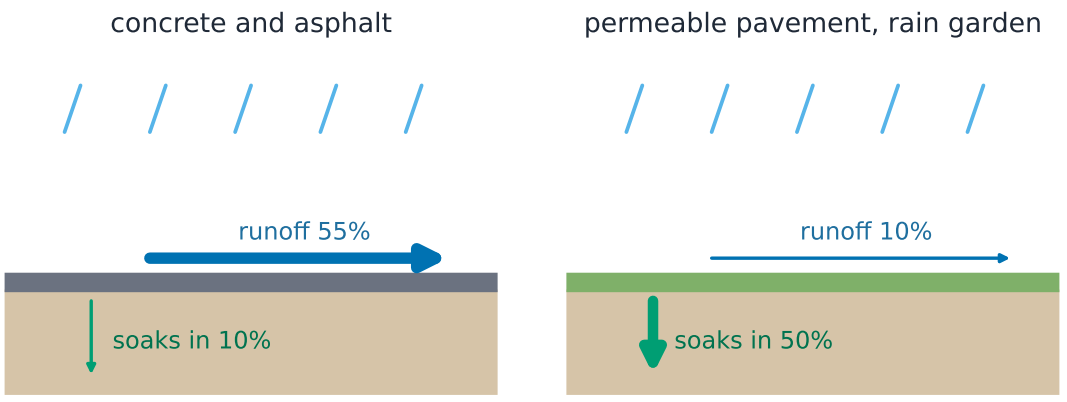
Wind turbines on farmland: sustainable resource use meets present needs without locking out future generations

Methods to Reduce Urban Runoff

Methods that **increase water infiltration** let rain soak into the ground, filtering pollutants and recharging groundwater instead of flooding streams:

- replacing traditional pavement with **permeable pavement** 透水路面, which lets water drain through gaps or pores;
- **planting trees**, whose roots and leaves slow the water and help it soak in;
- **rain gardens**, **green roofs** 绿色屋顶 and retention ponds that catch and hold rainwater;
- **increased use of public transportation**, which means fewer roads and parking lots;
- **building up, not out** – taller, denser buildings cover less ground per person than sprawling suburbs.

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

> **Worked example (runoff volume).** A parking lot is 200 m long and 100 m wide. How much water runs off it in a 5 cm rainfall, if none soaks in?

1. Area: $200 \times 100 = 20{,}000$ m^2.
2. Depth in metres: 5 cm $= 0.05$ m.
3. Volume: $20{,}000 \times 0.05 = 1000$ m^3 of water.

For a whole town of 10 km^2 that is 20% impervious, the paved area is $0.20 \times 10 \times 10^6 = 2 \times 10^6$ m^2, so the same storm sends $2 \times 10^6 \times 0.05 = 1 \times 10^5$ m^3 into the drains. Always convert km^2 to m^2 (1 km^2 $= 10^6$ m^2) and cm to m before multiplying.

Percent change. FRQs often ask for one: percent change $= \dfrac{\text{new} - \text{old}}{\text{old}} \times 100$. If ocelots were once found in 30 Texas counties and now in only 2, the change is $\frac{2-30}{30} \times 100 \approx -93\%$: a 93% decrease. Keep the minus sign, or say "decrease".

Integrated Pest Management

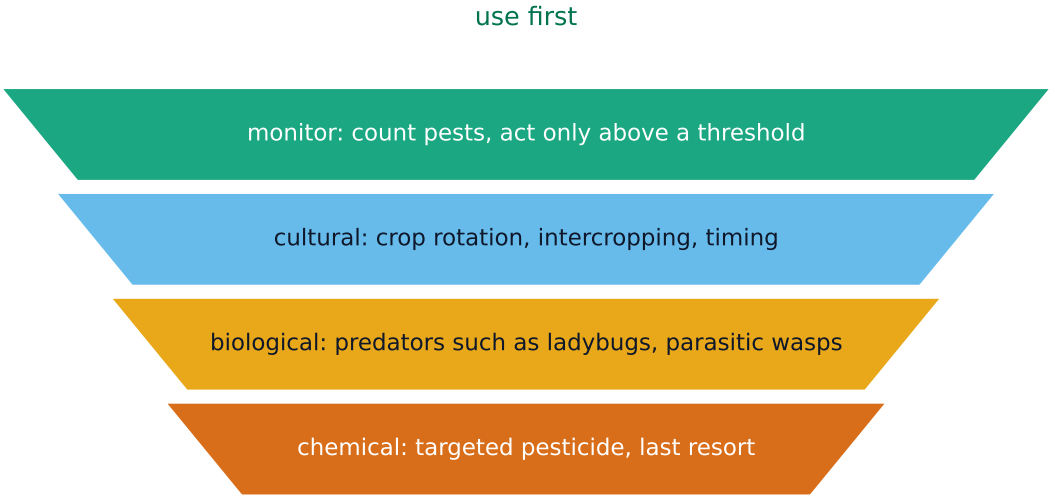
Integrated pest management 病虫害综合治理 (IPM) is a combination of methods used to control pests effectively while minimizing disruption to the environment. It starts by monitoring pest numbers and acts only when they pass a damage threshold. Its methods are biological, physical and only limited chemical:

- **biocontrol** – releasing **natural predators** or parasites of the pest, such as ladybugs that eat aphids;
- **intercropping** – planting two or more crops together, so pests that specialize on one crop spread less easily;
- **crop rotation** 轮作 – changing the crop grown in a field each year, which breaks the life cycle of pests that depend on one crop;
- physical methods – traps, barriers, removing infected plants;

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- targeted pesticides only as a **last resort**.

IPM **reduces the risks** that pesticides pose to wildlife, water supplies and human health, and slows the evolution of resistance. Its drawbacks are that it can be **complex** (farmers need training and time to monitor) and **expensive** at first.



Integrated pest management: monitor first, chemicals last

Sustainable Agriculture

The goal of **soil conservation** is to prevent soil erosion. Methods include:

- **contour plowing** 等高耕作 – ploughing across a slope along its contour lines, so the furrows catch water instead of channelling it downhill;
- **windbreaks** – rows of trees along field edges that slow the wind;
- **perennial crops** – plants that live for many years, so the soil is never left bare;
- **terracing** 梯田 – cutting a steep slope into level steps;
- **no-till agriculture** – planting seeds straight into the remains of the last crop without ploughing;
- **strip cropping** – alternating strips of a row crop (such as corn) with a soil-holding crop (such as grass or clover).

Strategies to **improve soil fertility** include crop rotation (alternating nutrient-hungry crops with **legumes**, which fix nitrogen), adding **green manure** (a cover crop ploughed back into the soil), and adding **limestone** to neutralize acidic soil.

Rotational grazing 轮牧 regularly moves livestock between different pastures so no area is overgrazed, giving the grass time to regrow.



Rice terraces cut a steep slope into level steps, so water and soil stay in place instead of eroding downhill

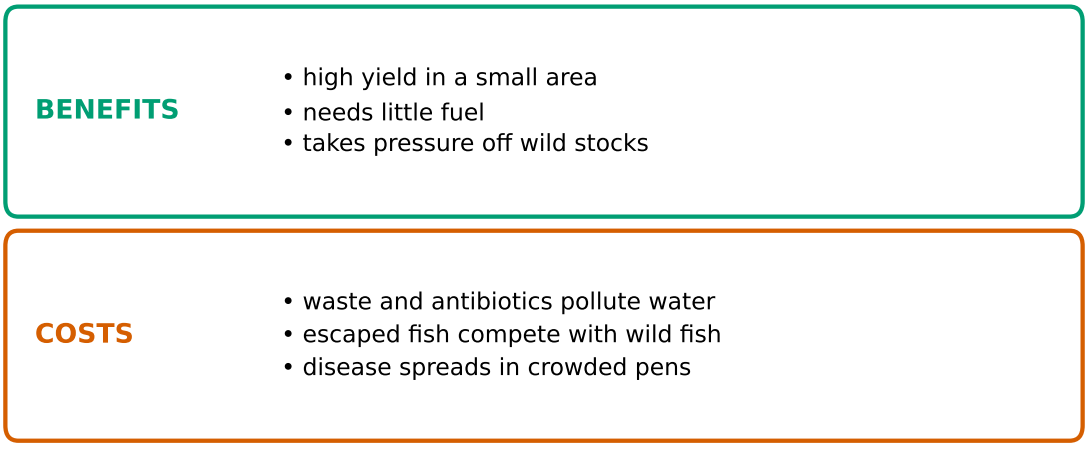
Aquaculture

Aquaculture 水产养殖 – raising fish, shellfish or seaweed in tanks, ponds or ocean pens – now provides about half of the fish people eat. It has expanded because it is **highly efficient**, needs **only small areas of water**, and uses **little fuel** compared with fishing fleets. It also takes pressure off wild fish stocks.

Its problems:

- **contaminated wastewater** – fish waste, uneaten feed and antibiotics pollute nearby water;
- **escaped fish** may compete or interbreed with wild fish, weakening wild populations' genetic adaptations;
- the **high density** of fish increases disease and parasites (such as sea lice on salmon), which can spread to wild fish;
- habitat loss – shrimp farms have replaced large areas of mangroves;
- farming predatory fish such as salmon requires feed made from wild-caught fish.

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Benefits and costs of aquaculture

Sustainable Forestry

Sustainable forestry keeps forests productive for the long term: **selective cutting** 择伐 of mature trees instead of clearcutting, replanting, leaving buffer strips along streams, and long rotation times. It maintains habitat, prevents erosion, and lets forests keep providing ecosystem services.

Ways to **mitigate deforestation** include **reforestation** 重新造林 (replanting), using and buying wood harvested by **ecologically sustainable forestry** techniques (certified wood), and **reusing wood**.

Forests can be protected from **pathogens and insects** (such as the emerald ash borer or bark beetles) by integrated pest management and by **removing affected trees** before the pest spreads.

A **prescribed burn** 计划烧除 sets a forest on fire under controlled conditions to clear dead wood and undergrowth. This reduces the fuel available, so natural wildfires are less frequent and less catastrophic, and it helps fire-adapted species regrow.

Practice

Answer each before reading the answers below.

1. Give an example of the tragedy of the commons and one way to prevent it.
2. Compare drip irrigation with flood irrigation, and explain one soil problem that drip irrigation reduces.
3. Describe integrated pest management (IPM) and give one advantage.
4. Producing 1 kg of beef takes about 15 000 L of water. A family eats 2 kg less beef each week. How much water is saved in a year?
5. Explain why urbanization increases flooding, and give two ways to reduce urban runoff.

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6. Describe two environmental effects of clearcutting.

Answers

1. Overfishing in international waters: each boat gains by catching more, while the cost of the depleted stock is shared. Catch quotas (or tradable permits, or marine protected areas) prevent it.
2. Drip delivers water directly to the roots (over 90% efficient); flood irrigation loses much to evaporation and runoff. Drip reduces waterlogging and soil salinization.
3. IPM combines biological control, crop rotation, monitoring and targeted pesticide use only when needed. It reduces pesticide use, so it slows resistance and harms fewer non-target species.
4. $2 \times 52 \times 15\,000 = 1\,560\,000$ L (about 1.6 million litres).
5. Impervious surfaces stop rain soaking into the ground, so water runs quickly into drains and streams. Permeable pavement, rain gardens, green roofs or retention ponds reduce it.
6. Any two: soil erosion and sediment in streams; habitat loss; higher stream temperatures from lost shade; release of stored carbon.

Exam tips

- Explain the **tragedy of the commons** – individuals overuse a shared resource for self-interest – and give a solution (quotas, fees, ownership).
- Clearcutting is **economically advantageous** but causes erosion, warmer soil and streams, and flooding; burning trees releases CO_2.
- Green Revolution methods: mechanization, GMOs, fertilizers, irrigation, pesticides. Mechanization raises efficiency but increases **fossil-fuel reliance**.
- Know the four irrigation methods and their losses: **furrow ~1/3, flood ~20%, spray ≤1/4, drip ~5%**. Agriculture accounts for about **70%** of freshwater withdrawals, mostly for irrigation. Explain **waterlogging** and **salinization**; name the **Ogallala Aquifer**.
- Pests become resistant through **natural selection**; GE crops can reduce **genetic diversity**.
- CAFOs: cheap meat, but waste contaminates water. Free-range: pasture access, more land, higher price; it does not guarantee no antibiotic use. Meat usually needs more land per calorie, especially beef. Overgrazing → erosion → **desertification**.
- Mining: overburden, slag and tailings; lower-grade ores mean more waste; subsurface mining is expensive.
- Urbanization: saltwater intrusion, more CO_2, **impervious surfaces** → flooding; **urban sprawl** spreads into rural land.
- Compute an **ecological footprint** in "number of Earths" (footprint ÷ biocapacity per person) and a **sustainable yield**.

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- Reduce runoff: permeable pavement, trees, public transport, **build up, not out**.
- IPM: biocontrol, intercropping, crop rotation, natural predators – safer, but complex and expensive.
- Soil conservation: contour plowing, windbreaks, perennial crops, terracing, no-till, strip cropping. Fertility: crop rotation, green manure, limestone.
- Aquaculture is efficient but pollutes water and spreads disease and escaped fish to the wild. Forests: reforestation, sustainable wood, reuse, prescribed burns.

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Energy Resources and Consumption

AP Environmental Science

Renewable and Nonrenewable Resources

Every time you charge a phone in China, there is roughly a 60% chance the electricity came from burning coal. The coal was dug up, carried by train, burned to boil water, and the steam spun a turbine – and about two-thirds of the coal's energy was lost as heat on the way. This unit compares every major energy source by the same questions: where does the energy come from, how is it turned into electricity, and what does it cost the environment?

A **nonrenewable resource** 不可再生资源 exists in a fixed amount and cannot be replaced on a human timescale once it is used; forming more takes millions of years. Fossil fuels (coal, oil, natural gas) and nuclear fuel (uranium) are nonrenewable. A **renewable resource** 可再生资源 is replenished naturally, at or near the rate we use it: sunlight, wind, flowing water, tides, geothermal heat, and biomass.

Two cautions for the exam:

- **Biomass is renewable only if we harvest it no faster than it regrows.** Cutting forests for firewood faster than they regrow turns a renewable resource into a shrinking one.
- **Nuclear power is nonrenewable** even though fission releases no CO_2: uranium ore is mined and is finite.



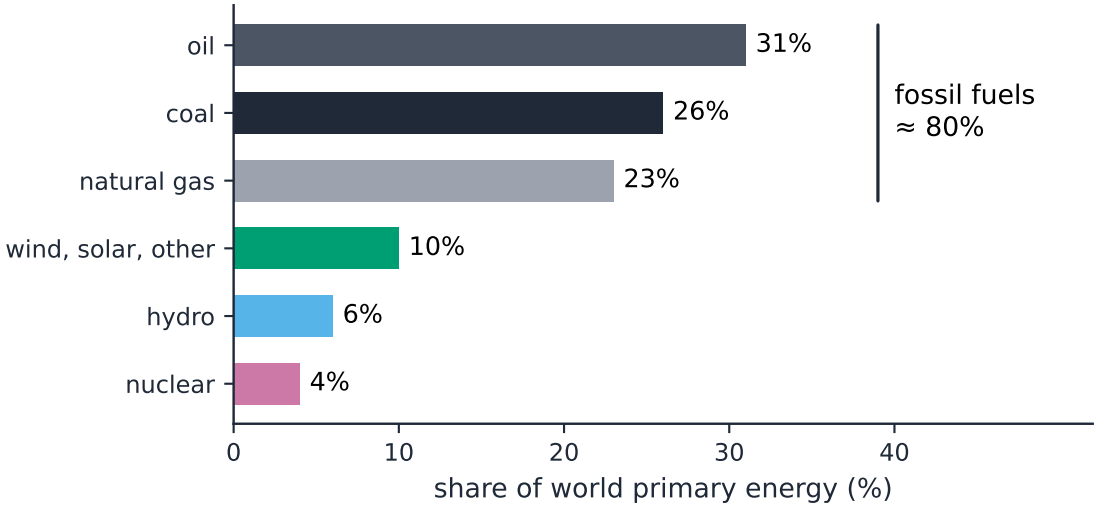
Wind turbines: renewable sources replenish on human timescales; fossil fuels do not

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Global Energy Consumption

The world's most widely used energy sources are **fossil fuels** 化石燃料 – about 80% of primary energy. Energy use is **not evenly distributed**: a person in the United States or Canada uses about ten times as much energy as a person in India, and many times more than a person in most sub-Saharan African countries.

- As the world becomes more **industrialized**, the total demand for energy increases.
- As **developing countries** become more developed, their reliance on fossil fuels usually increases at first – factories, cars and air conditioning arrive faster than renewable capacity is built. China's coal use grew several-fold between 2000 and 2020.
- **Availability, price, and government regulations** decide which sources people use. A country with cheap local coal tends to burn coal; subsidies for solar panels or a carbon tax shift choices toward low-carbon sources; a ban on new petrol cars changes how people travel.



Approximate world primary energy mix: about 80% fossil fuels

Fuel Types and Uses

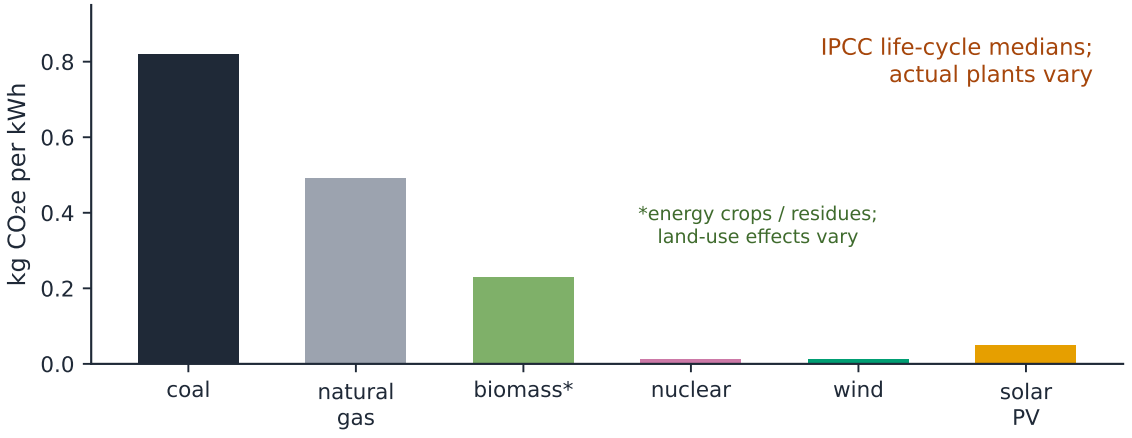
Different fuels suit different needs:

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Fuel	Main uses	Notes
Wood and **charcoal**	cooking and heating	common in developing countries because it is easy to collect; indoor smoke and deforestation
Peat 泥炭	heating, some power plants (Ireland, Finland)	partly decomposed plant material from bogs; burned after drying
Coal	electricity, steel making	four ranks: lignite, subbituminous, bituminous, anthracite
Natural gas (mostly methane)	electricity, heating, cooking	the **cleanest** fossil fuel: fewest pollutants and least CO_2 per unit of energy
Crude oil	refined into petrol (gasoline), diesel, jet fuel, heating oil, plastics	the main transport fuel

Crude oil is refined into specialized fuels: a refinery heats it and separates it by boiling point into gases, petrol for cars, kerosene for jets, diesel for trucks, and heavy oils and asphalt.

Cogeneration 热电联产 (combined heat and power) uses one fuel source to produce **both electricity and useful heat**. An ordinary power plant dumps about two-thirds of its fuel energy as waste heat; a cogeneration plant pipes that heat to nearby buildings or factories, so 70–90% of the fuel's energy does useful work.



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

Distribution of Natural Energy Resources

Energy resources are **unevenly** distributed, and the reason is **geologic history**. Coal formed where swamp forests were buried about 300 million years ago (eastern US, northern China, Germany). Oil and gas formed from marine plankton buried in ancient seas, then collected in traps in sedimentary rock (the Persian Gulf, Texas, Siberia). Metal ores form where magma and hot fluids concentrated minerals.

Renewables depend on local conditions: strong steady winds (coasts, plains), strong sunlight (deserts), large rivers in steep valleys, or hot rock near the surface (volcanic regions). This uneven distribution drives trade, prices and **geopolitics** – countries without their own oil must import it, which can make them vulnerable to supply cuts.

Fossil Fuels

Fossil fuels (coal, oil, natural gas) formed from ancient organisms buried and changed by heat and pressure. They are energy-dense and reliable, but **nonrenewable** and the main source of CO_2 and air pollution. Coal is the dirtiest; natural gas burns cleaner but leaks **methane** 甲烷, a strong greenhouse gas.

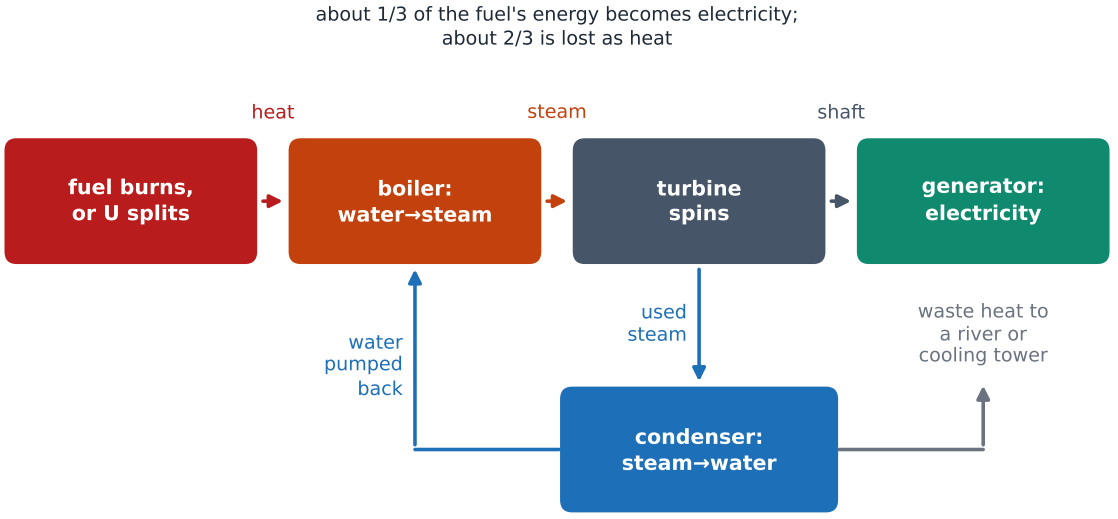
Combustion is a chemical reaction between the fuel and oxygen that releases energy and produces carbon dioxide and water. For methane:

$$CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O + \text{energy}$$

Coal and oil also contain sulfur and nitrogen, so burning them releases SO_2, NO_x, particulates and mercury.

How a power plant makes electricity. Burning fuel heats water into high-pressure steam. The steam turns a **turbine**, the turbine spins a **generator**, and the generator produces electricity. The used steam is cooled back to water and pumped round again. Nuclear, biomass and solar-thermal plants, and some geothermal plants, use this steam-turbine chain. A gas turbine instead uses hot combustion gases directly; a combined-cycle gas plant also uses its exhaust heat to drive a steam turbine.

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A thermal power plant: heat boils water, steam spins a turbine, the turbine turns a generator, and the condenser cools the steam back to water; about two-thirds of the energy is lost as heat



*An open-pit **lignite** 褐煤 (brown coal) mine feeding the power station 发电站 behind it – the fuel is dug from the ground and burned on the spot*

Coal forms in stages, and its **rank** climbs with the heat, pressure, and depth of burial it has endured. Partly decomposed plant matter first becomes peat, then soft brown lignite, then subbituminous coal, then **bituminous** 烟煤 coal, and finally hard **anthracite** 无烟煤 – each step is drier, more carbon-rich, and higher in energy, so anthracite burns hottest and cleanest.

Humans use several methods to extract fossil fuels: **surface (strip) mining** and

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mountaintop removal for shallow coal, **underground mining** for deep coal, and **drilling** wells for oil and gas, on land and offshore.

Oil and natural gas are increasingly reached by **hydraulic fracturing** 水力压裂 ("fracking"): water, sand and chemicals are pumped at high pressure into shale rock to crack it open and release the trapped fuel. It has unlocked huge reserves, but it can **contaminate groundwater** (methane and chemicals reaching drinking-water wells), release **volatile organic compounds** 挥发性有机化合物 into the air, use large amounts of water, and trigger minor earthquakes when waste water is injected underground.

Crude oil can also be recovered from **tar sands** 油砂 – a mix of clay, sand, water, and thick **bitumen** 沥青. Separating the oil is energy- and water-intensive and clears large areas of forest, so its environmental cost per barrel of oil is high.

> **Worked example (power-plant energy).** A coal plant must deliver 1.0×10^9 kWh of electricity a year and is 33% efficient. One kilogram of coal releases about 8 kWh of heat. Heat needed $= \dfrac{1.0 \times 10^9 \text{ kWh}}{0.33} \approx 3.0 \times 10^9$ kWh. Coal needed $= \dfrac{3.0 \times 10^9 \text{ kWh}}{8 \text{ kWh/kg}} \approx 3.8 \times 10^8$ kg, or about 380 000 tonnes a year. Raising the efficiency to 45% would cut that to about 280 000 t – which is why efficiency and cogeneration matter.

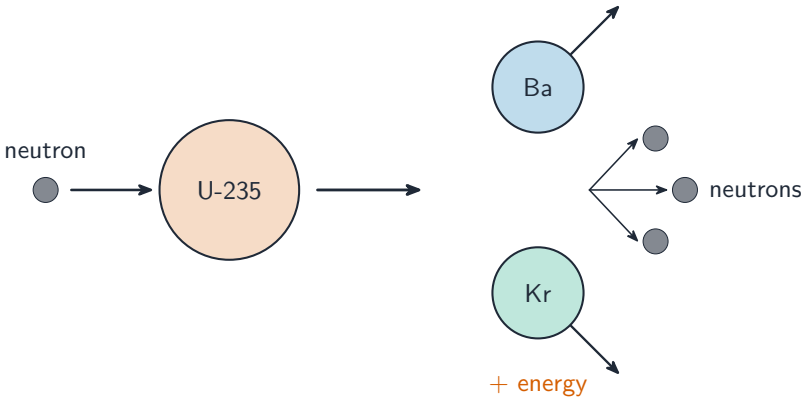
> **Worked example (how long will it last?).** An oil-sands deposit holds 1.7×10^{11} barrels of recoverable bitumen, extracted at 3.0×10^6 barrels a day.

1. Days: $\dfrac{1.7 \times 10^{11}}{3.0 \times 10^6} \approx 5.7 \times 10^4$ days.
2. Years (using the unrounded number of days): $\dfrac{1.7 \times 10^{11}}{3.0 \times 10^6 \times 365} \approx 155$ years.
3. A faster extraction rate shortens this; new discoveries lengthen it. That is why a "reserve lifetime" is an estimate, not a fixed date.

Nuclear Power

Nuclear power 核能 is generated by **fission** 裂变. Atoms of uranium-235, packed into **fuel rods**, are struck by a neutron and split into smaller parts, releasing a large amount of heat and two or three more neutrons, which split more atoms in a chain reaction. **Control rods** absorb neutrons to keep the chain reaction steady. The heat makes steam, which drives a turbine and generator just like a coal plant.

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Nuclear fission of a uranium-235 nucleus releases energy

Radioactivity happens when the nucleus of a radioactive isotope loses energy by emitting radiation (alpha particles, beta particles or gamma rays). Used fuel rods stay radioactive for thousands of years, which makes the disposal of nuclear **waste** 核废料 a long-term problem: it is stored in cooling pools, then dry casks, and deep geologic disposal is intended to isolate high-level waste for the long term; national disposal programmes are at different stages.

Nuclear power is **nonrenewable**. It is considered cleaner than fossil fuels because it produces **no combustion-related air pollutants or direct CO_2** during fission, but it does release **thermal pollution** (warm cooling water returned to rivers or the sea, which lowers dissolved oxygen) and hazardous solid waste.

Accident	Year	What happened	Impact
Three Mile Island (USA)	1979	cooling failure; partial meltdown	small radiation release; no confirmed deaths; ended new US reactor orders for decades
Chernobyl (Ukraine)	1986	a test went wrong; reactor exploded and burned	radiation spread across Europe; 30 km exclusion zone still in place; rise in thyroid cancers
Fukushima (Japan)	2011	earthquake and tsunami knocked out cooling; three meltdowns	radiation released to land and sea; over 100 000 people evacuated



A nuclear power station 核电站. The reactor buildings hold the fuel; the sea supplies cooling water. Notice there is no smoke – fission releases no CO_2

A radioactive element's **half-life** – the time for half of it to decay – lets you calculate how much remains, and how radioactive it is, at any point in time.

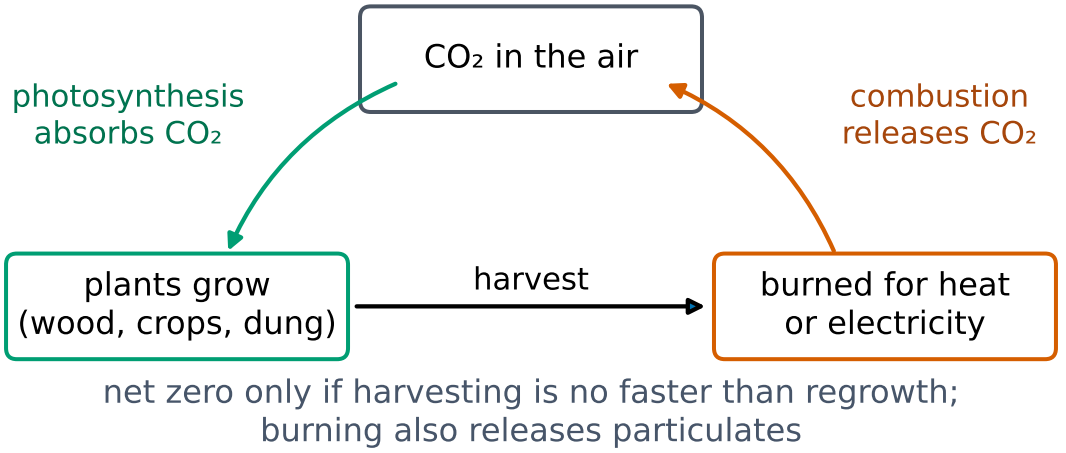
> **Worked example (half-life).** Suppose an isotope has a half-life of 30 years and a reactor leaves 100 g of it. After 30 years 50 g remains; after 60 years 25 g; after 90 years (three half-lives) $100 \times \left(\frac{1}{2}\right)^3 = 12.5$ g. To fall below 1 g needs 7 half-lives ($100 \div 2^7 \approx 0.78$ g), or 210 years. Because the drop is halving, not linear, the waste stays hazardous for many half-lives – the core reason it must be stored safely for centuries.

Energy from Biomass

Biomass 生物质 is energy from living or recently living material: wood, charcoal, crop waste, animal dung, and biofuels such as ethanol and biodiesel. Burning biomass gives heat at a relatively **low cost**, but it releases **carbon dioxide, carbon monoxide, nitrogen oxides, particulates and volatile organic compounds**. Indoor cooking fires are a leading cause of respiratory disease in developing countries, and **overharvesting trees** for fuel causes deforestation.

Ethanol 乙醇, made from crops such as corn or sugarcane, can substitute for gasoline and adds no *new* carbon when burned (the plant absorbed that CO_2 as it grew). Its drawback, especially for corn ethanol, is a low **energy return on energy investment (EROEI)** 能量投资回报率: growing, fertilizing, harvesting, and distilling the corn uses nearly as much energy as the fuel finally delivers. (Sugarcane ethanol returns several times its energy input.) Growing fuel crops also competes with food crops for farmland.

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Biomass energy is carbon-neutral only if regrowth keeps pace with harvest

Solar Energy

Solar 太阳能 energy can be captured in three ways:

- **Photovoltaic (PV) cells** capture light energy and transform it **directly into electricity**, with no turbine. Their use is limited by the availability of sunlight – none at night, less in winter and cloud.
- **Active solar** systems use mechanical and electric equipment (pumps, fans) to heat a liquid in rooftop collectors and **collect and store** the heat, for example in a hot-water tank.
- **Passive solar** design absorbs heat **directly** from the sun with no mechanical or electric equipment – south-facing windows (in the Northern Hemisphere), thick walls and dark floors that soak up heat by day and release it at night. Thermal mass in walls and floors stores the heat for later release without powered pumps or fans.

Solar energy has a low environmental impact and produces clean energy while it runs, but panels can be expensive and their manufacture uses energy and some toxic materials. **Large solar farms** can harm desert ecosystems by clearing land, fragmenting habitat for animals such as desert tortoises, and changing soil and shade.



*A solar farm. Rows of **photovoltaic** 光伏 panels are tilted toward the sun; a big output needs a large area of land*

Hydroelectric Power

Hydroelectric 水电 power uses moving water to spin a turbine. It is generated in several ways:

- **Dams** built across rivers collect water in a **reservoir** 水库; water released through the dam spins turbines. The Three Gorges Dam on the Yangtze is the largest power station in the world.
- **Run-of-the-river** turbines are placed in small rivers, where the flowing water spins them without a large reservoir.
- **Tidal energy** uses the flow of tides in and out of a bay or estuary to turn turbines. Tides are predictable, unlike wind and sun, but few sites have a large enough tidal range.

Hydroelectric power produces **no air pollution or waste** while running, and a reservoir can store energy for when demand peaks. But construction is expensive, and dams change habitats: they flood forests and farmland, displace people, block **fish migration** (salmon cannot reach spawning streams without fish ladders), trap the sediment that would rebuild downstream deltas, and change water temperature and oxygen below the dam. Rotting plants in new reservoirs also release methane.

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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

Geothermal Energy

Geothermal 地热能 energy uses heat stored in Earth's interior to heat underground water, which is brought to the surface as steam. The steam drives a turbine and generator. Geothermal power is renewable and runs day and night, so it is reliable. Its drawbacks: it is **only practical where hot rock lies near the surface** (Iceland, New Zealand, Kenya, California), drilling can be **prohibitively expensive** elsewhere, and it can release **hydrogen sulfide** (H_2S, a toxic gas that smells of rotten eggs).

Small **ground-source heat pumps**, which use the steady temperature a few metres underground to heat and cool buildings, work almost anywhere.

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A geothermal power station in Iceland, a volcanic region. ***Steam*** 蒸汽 *from hot rock below is piped up to drive the turbines*

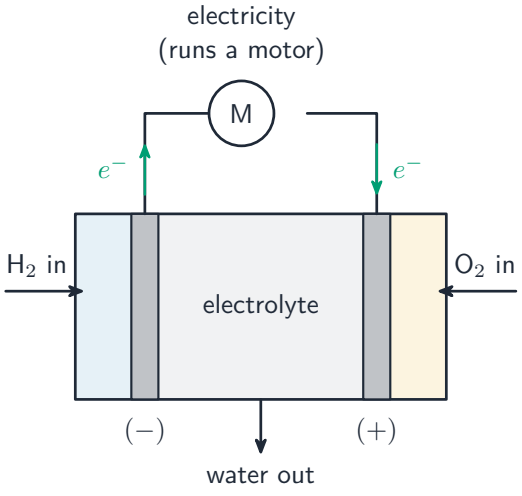
Hydrogen Fuel Cell

A **hydrogen fuel cell** 氢燃料电池 is an alternative to nonrenewable fuels. It combines hydrogen fuel with oxygen from the air to form water, releasing energy as electricity:

$$2\,H_2 + O_2 \rightarrow 2\,H_2O + \text{electricity}$$

Water is the only emission. If the hydrogen is made by splitting water (**electrolysis**) with renewable electricity, the whole system has a low environmental impact and produces no CO_2. However, the technology is expensive, energy is still needed to make the hydrogen gas (today most hydrogen is made from natural gas, which releases CO_2), and hydrogen is hard to store and transport because it is a very light, flammable gas.

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A hydrogen-oxygen fuel cell makes electricity, with water as the only product

Wind Energy

Wind 风能 turbines use the **kinetic energy** of moving air to spin a turbine, which spins a generator, producing electricity. Wind is a renewable, clean source: no fuel, no air pollution and low running costs, and the land between turbines can still be farmed. Its drawbacks are that it is **intermittent** (no wind, no power), turbines can be noisy and change the landscape, and **birds and bats may be killed** if they fly into the spinning blades. Careful siting away from migration routes reduces the harm. The best sites have strong, steady winds – coasts, open plains, ridges and offshore.



Wind turbines 风力涡轮机 *on farmland. They take little ground, so the land between them can still be farmed*

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Worked example (wind farm). A town uses 6.0×10^7 kWh of electricity a year. A wind farm has 20 turbines, each producing 1500 kW when turning. How many hours must they run to supply 80% of the town's demand, and what is that electricity worth at \$0.20 per kWh?

1. Energy needed: $0.80 \times 6.0 \times 10^7 = 4.8 \times 10^7$ kWh.
2. Farm output: $20 \times 1500 = 30{,}000$ kW, so hours $= \dfrac{4.8 \times 10^7 \text{ kWh}}{3.0 \times 10^4 \text{ kW}} = 1600$ hours.
3. Value: $4.8 \times 10^7 \times 0.20 = \$9.6 \times 10^6$, about 9.6 million dollars a year.

Remember: energy (kWh) = power (kW) $\times$ time (h). A year has 8760 hours, so 1600 hours is under a fifth of the year, which suits a wind farm that does not turn all the time.

Energy Conservation

Energy conservation 节能 reduces demand. It is often the cheapest and cleanest option – the energy you do not use needs no fuel and makes no pollution.

Around the home:

- adjust the **thermostat** (a little cooler in winter, warmer in summer) to reduce heating and air conditioning;
- **conserve water**, especially hot water, since pumping and heating water uses energy;
- use **energy-efficient appliances** and LED lighting;
- **conservation landscaping**: plant trees to shade the house in summer and block winter winds, and choose native plants that need little watering.

On a large scale:

- improve the **fuel economy** of vehicles;
- use **battery electric vehicles (BEVs)** and **hybrid vehicles**;
- expand **public transportation**;
- use **green building design**: good insulation, passive solar design, green roofs, natural lighting and efficient heating and cooling.

Worked example (lighting). Replacing a 60 W incandescent bulb with a 10 W LED that gives the same light saves 50 W. Running it 5 hours a day saves 50 W $\times$ 5 h = 250 Wh = 0.25 kWh per day, or about $0.25 \times 365 \approx 91$ kWh per year. At 0.15 US dollars per kWh, that saves about 14 dollars a year for one bulb. Multiply that by every bulb in a city and conservation rivals a new power plant – at far lower cost.

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A solar farm supplies renewable energy; energy conservation reduces energy demand

Practice

Answer each before reading the answers below.

1. A 60 W incandescent bulb is replaced by a 10 W LED, used 5 hours a day for a year. Calculate the energy saved in kWh and the money saved at \$0.12 per kWh.
2. Give one advantage and two disadvantages of nuclear power.
3. A radioactive waste sample of 100 g has a half-life of 30 years. How much is left after 90 years?
4. Classify each as renewable or nonrenewable: geothermal, natural gas, biomass, uranium.
5. Describe two environmental effects of building a large hydroelectric dam.
6. A hydrogen fuel cell's only product is water. Explain why hydrogen cars are not always carbon-free.

Answers

1. $50\ \text{W} \times (5 \times 365)\ \text{h} = 91\,250\ \text{Wh} = 91.25\ \text{kWh}$; $91.25 \times 0.12 \approx \$10.95$.
2. Advantage: no CO_2 released while generating electricity. Disadvantages: long-lived radioactive waste; thermal pollution of cooling water; risk of accidents; mining impacts.
3. Three half-lives: $100 \to 50 \to 25 \to 12.5$ g.
4. Renewable: geothermal, biomass. Nonrenewable: natural gas, uranium.
5. Any two: blocks fish migration; traps sediment upstream; floods habitat; rotting flooded vegetation releases methane; changes water temperature and flow downstream.

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6. Most hydrogen is made from natural gas, which releases CO_2; electrolysis is clean only if the electricity is renewable.

Exam tips

- Separate **renewable** (sun, wind, water, geothermal, biomass if regrown) from **non-renewable** (fossil fuels, **nuclear**) and weigh each source's trade-offs.
- Describe the steam chain: **heat → steam → turbine → generator → electricity**. Coal, nuclear and many biomass and geothermal plants use steam; gas turbines can use combustion gases directly.
- Write the **combustion** equation: fuel + oxygen → carbon dioxide + water + energy.
- Fossil fuels are energy-dense but emit CO_2; **natural gas** is the cleanest fossil fuel. **Nuclear** has no direct CO_2 emissions from fission but leaves long-lived waste and thermal pollution.
- Know the three nuclear accidents: **Three Mile Island, Chernobyl, Fukushima**.
- Do **half-life** math: after n half-lives a fraction $(\frac{1}{2})^n$ remains. Show units and every step in energy calculations.
- Distinguish **PV** (light → electricity directly), **active solar** (pumps, stores heat) and **passive solar** (no powered equipment; heat stored in thermal mass).
- Solar and wind are **intermittent**; tides are predictable; geothermal can release **hydrogen sulfide**.
- Know the **coal ranks** (peat → lignite → subbituminous → bituminous → anthracite) and the problems of **fracking** (groundwater contamination, VOCs) and **tar sands** (bitumen, energy-intensive).
- **Ethanol** adds no new carbon but has a **low EROEI**; **cogeneration** makes both electricity and useful heat from one fuel.
- **Conservation**: thermostats, efficient appliances, conservation landscaping; fuel economy, BEVs and hybrids, public transport, green building design.

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Atmospheric Pollution

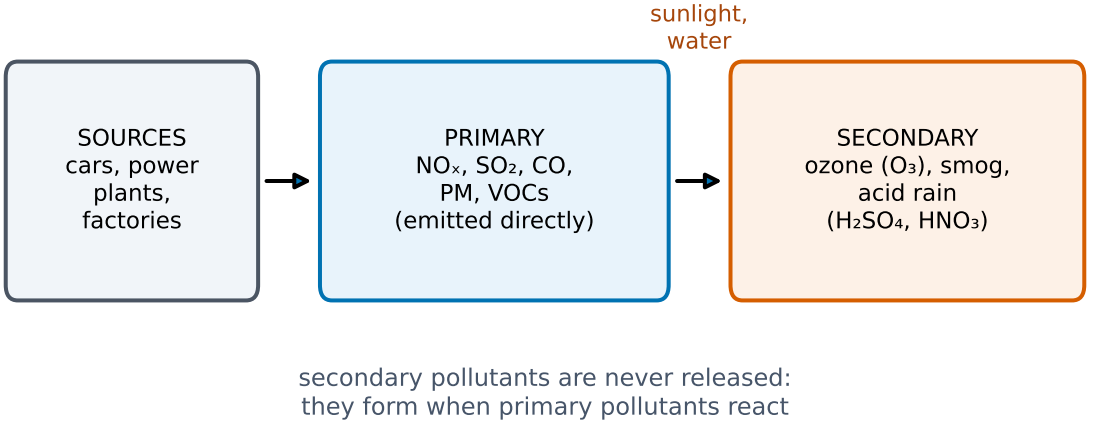
AP Environmental Science

Introduction to Air Pollution

In December 1952 a cold, windless fog settled over London. Smoke from millions of coal fires could not escape, and for five days people could not see their own feet. About 4000 people died that week, and thousands more in the months after. The "Great Smog" led to Britain's Clean Air Act of 1956. This unit explains what was in that air, why it stayed near the ground, and how laws and technology now clean it.

Air pollution 空气污染 is any substance in the atmosphere at a level that harms living things or materials. AP questions ask you to name a pollutant, its source and its effect, so learn them as a set.

Primary pollutants 一次污染物 are emitted directly from a source. **Secondary pollutants** 二次污染物 are not emitted; they form in the air when primary pollutants react with each other, with water or with sunlight.



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

Most outdoor air pollution comes from **combustion** 燃烧 (burning) of fossil fuels:

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Pollutant	Main human source	Main effect
Carbon dioxide (CO_2)	all fossil-fuel burning	greenhouse gas: climate change
Sulfur dioxide (SO_2)	coal burning; diesel fuel	acid rain; breathing problems
Nitrogen oxides (NO_x)	vehicle engines; power plants	smog, ozone and acid rain
Carbon monoxide (CO)	incomplete combustion in engines and stoves	stops blood carrying oxygen
Particulates (PM)	coal burning, diesel, wood fires	lung and heart disease; haze
Hydrocarbons and VOCs	unburned fuel, fuel evaporating	help make smog
Toxic metals (mercury, lead)	coal burning; old leaded fuel	damage nerves and brains

Coal is the dirtiest fuel: it releases CO_2, SO_2 (from sulfur in the coal), particulates and toxic metals such as mercury. Nitrogen oxides form in any very hot flame, because the heat makes nitrogen and oxygen from the air combine.

Lead 铅 is a success story. Lead was once added to gasoline. Under the **Clean Air Act** 清洁空气法, the US **Environmental Protection Agency** (EPA) phased lead out of fuel, and lead in US air fell by more than 90%.

> **Worked example (percent change).** In one national park the visibility was 25 miles in 1990 and 45 miles in 2015. Find the percent change.

$$\text{percent change} = \frac{\text{new} - \text{old}}{\text{old}} \times 100 = \frac{45 - 25}{25} \times 100 = +80\%$$

Always subtract old from new, divide by the old value, and keep the sign: a fall gives a negative answer.

Photochemical Smog

Photochemical smog 光化学烟雾 is a brown haze that forms when **nitrogen oxides** and **volatile organic compounds** 挥发性有机化合物 (VOCs) react in **sunlight** and heat. Its main harmful product is ground-level **ozone** 臭氧 (O_3), a secondary pollutant.

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Photochemical smog over Los Angeles: on a sunny day, car exhaust reacts in the light to make a brown haze that hides the skyline

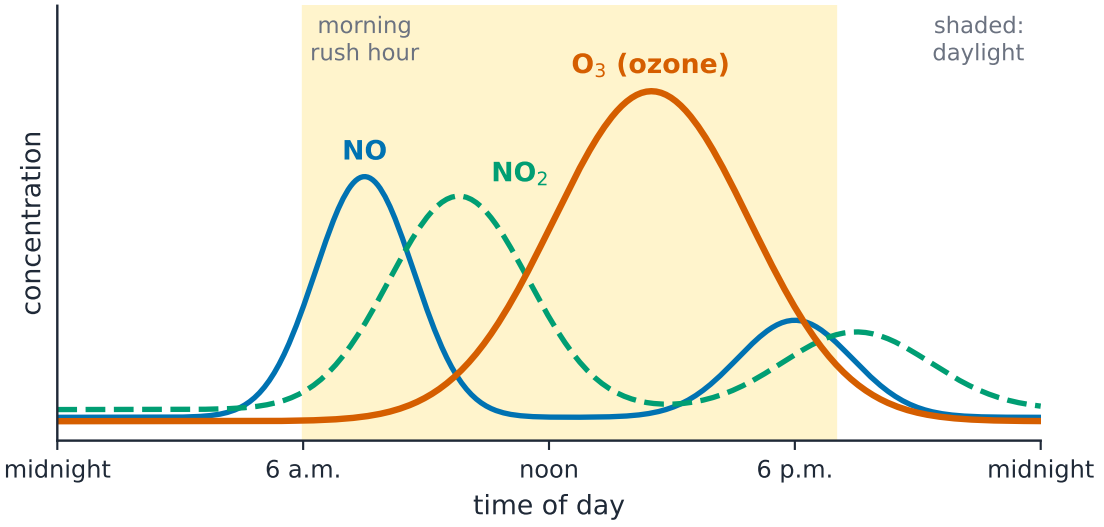
The chemistry follows the clock:

1. **Morning rush hour.** Car engines emit nitrogen monoxide (NO) and VOCs.
2. **Mid-morning.** NO reacts with oxygen to make nitrogen dioxide (NO_2), a brown gas.
3. **Afternoon.** Sunlight splits NO_2 into NO and a single oxygen atom (O). That atom joins an O_2 molecule to make ozone. Ozone peaks in mid-afternoon, when sunlight is strongest.
4. **Evening.** Without sunlight, ozone is not made, and NO destroys some of it.

$$NO_2 \xrightarrow{\text{sunlight}} NO + O \qquad O + O_2 \rightarrow O_3$$

VOCs make things worse: their oxidation produces radicals that convert NO to NO_2 without using up ozone. Sunlight then splits the NO_2, so more ozone builds up.

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A typical daily smog cycle in a sunny city: NO peaks at morning rush hour, NO2 about two hours later, and ozone in mid-afternoon

Conditions that favour smog: many cars (cities), strong sunlight and high temperatures (summer), little wind, and land shapes such as valleys that hold air still. VOCs come from gasoline, paints and solvents, and also naturally from trees.

Effects: ozone irritates the eyes and lungs and makes asthma worse. It also damages plant leaves, lowering crop yields and slowing forest growth.

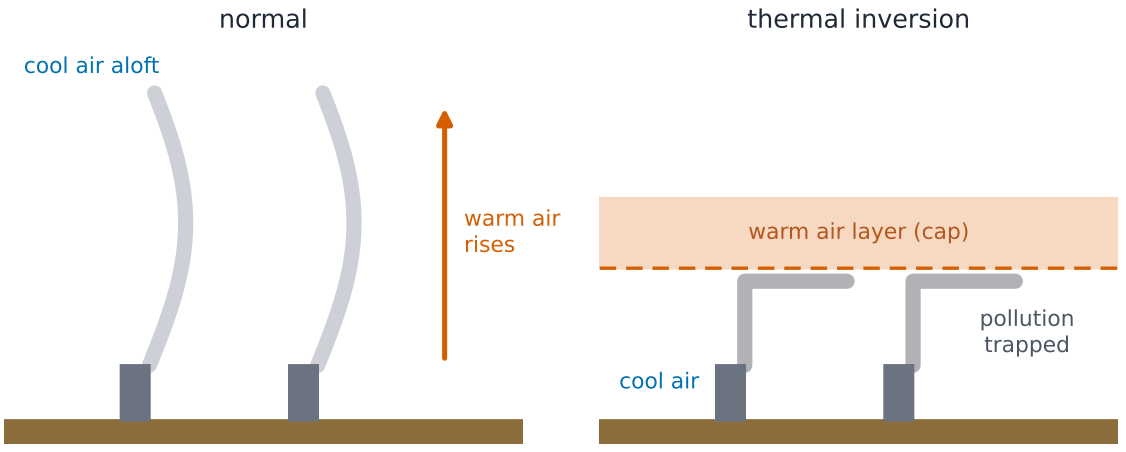
Reducing smog: cut NO_x and VOCs, for example with catalytic converters, vapor recovery nozzles at gas pumps, public transport, and electric vehicles.

> **Worked example (explain a graph).** "Explain why ozone peaks after nitrogen dioxide." Ozone is made when sunlight splits NO_2. NO_2 builds up first, from morning traffic. Ozone needs both that NO_2 and strong sunlight, so its peak comes later, in the afternoon.

Thermal Inversion

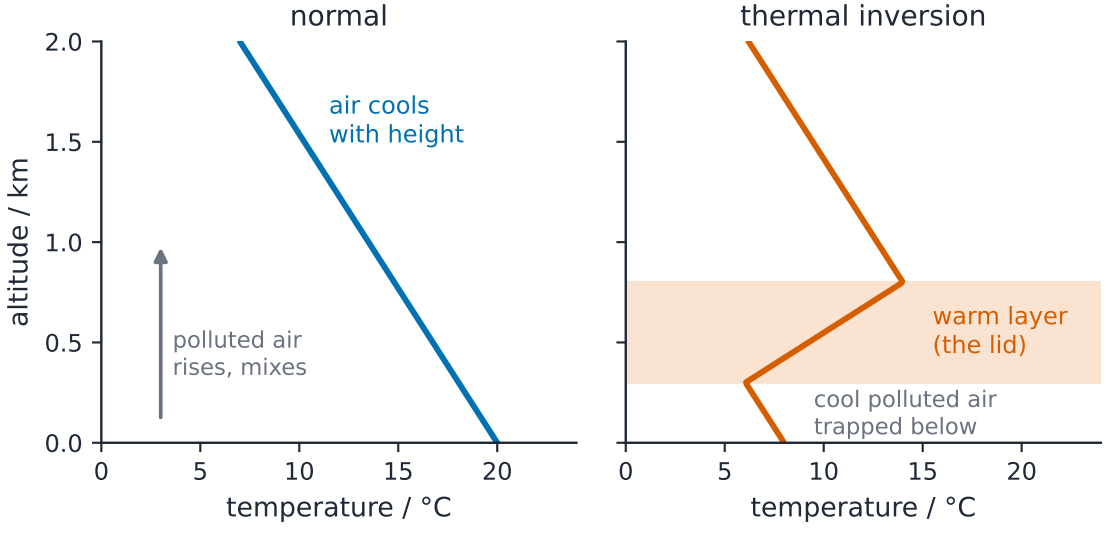
Normally the air is warmest at the ground and gets cooler with height (about 6.5 °C cooler per kilometre). Warm air near the ground is less dense, so it rises, carrying pollutants up and mixing them into a large volume of air.

In a **thermal inversion** 逆温, a layer of **warm air sits above cooler air** near the ground. The cool surface air is denser than the warm layer above it, so it cannot rise. The warm layer acts like a lid, and pollutants (especially smog and particulates) build up underneath.



thermal inversion: warm air aloft traps cool polluted air near the surface

Normally warm air rises and disperses pollution; an inversion caps it near the ground



Temperature against altitude: normally air cools with height; in an inversion a warm layer sits above cool surface air

Inversions are common on clear, calm winter nights, when the ground loses heat fast and cools the air touching it. They are also common in valleys and in coastal cities such as Los Angeles, where cool sea air slides under warmer air. The London smog of 1952 was trapped by an inversion. An inversion does not make new pollution; it stops existing pollution from spreading out, so concentrations rise.

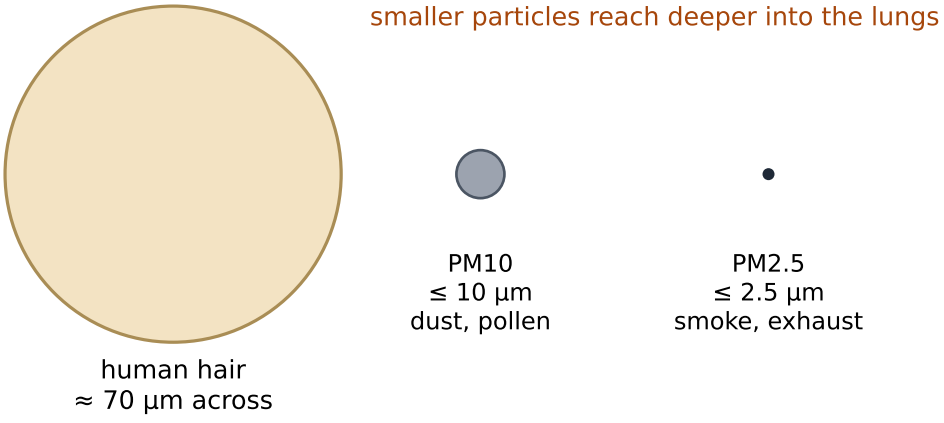
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Atmospheric CO2 and Particulates

Carbon dioxide and particulates have **natural sources** as well as human ones. AP questions often ask you to name one of each.

- **Natural CO_2:** respiration by living things, **decomposition** 分解 of dead matter, volcanic eruptions and natural forest fires.
- **Human CO_2:** burning fossil fuels and clearing or burning forests. Natural sources are roughly balanced by natural uptake (photosynthesis and the oceans). Human emissions add extra CO_2 on top, so the level keeps rising and enhances the greenhouse effect.

Particulate matter 颗粒物 (PM) is tiny solid or liquid particles in the air. Size matters: **PM10** is smaller than 10 micrometres; **PM2.5** is smaller than 2.5 micrometres, about 30 times thinner than a human hair. PM2.5 reaches deep into the lungs and even into the blood, causing asthma, lung disease and heart disease. Particulates also scatter light, which causes **haze** and reduces visibility.



PM10 and PM2.5 compared with a human hair

- **Natural particulates:** dust storms, volcanic ash, sea salt, pollen, smoke from wildfires.
- **Human particulates:** coal power plants, diesel engines, construction, farming, burning wood or crop waste.

> **Worked example (rate per area).** Trees remove 2.3 kg of PM2.5 per hectare each year. Logging removes 400 hectares of forest. The yearly loss of PM2.5 removal is $2.3 \times 400 = 920$ kg. Write the units at every step: kg per hectare per year times hectares gives kg per year.

Indoor Air Pollutants

Indoor air is often more polluted than outdoor air, because pollutants build up in closed rooms. Learn the three source groups:

Group	Examples	Effect
Combustion	carbon monoxide (CO), NO_x, particulates, tobacco smoke, smoke from cooking fires	CO is an **asphyxiant** 窒息剂: it stops the blood carrying oxygen
Natural	**radon** 氡, mold, dust	radon causes lung cancer; mold triggers allergies and asthma
Human-made materials	**asbestos** 石棉 insulation, VOCs and **formaldehyde** 甲醛 from furniture, carpets and glues; **lead** paint in old houses	asbestos fibres scar the lungs; VOCs irritate the eyes and lungs; lead harms children's brains



An indoor cookstove: biomass smoke is a major indoor air pollutant in many homes worldwide

Biomass smoke. About two billion people cook on open fires of wood, crop waste or dung. The smoke contains particulates and CO, and causes lung disease, especially in women and children who spend most time near the fire. Realistic fixes are cleaner cookstoves with chimneys, better ventilation, or switching to cleaner fuels such as liquid gas.

Radon. **Radon-222** is a radioactive gas made by the decay of uranium in some rocks and soils. It moves up through the soil and enters homes through cracks in

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the foundation, basement walls and well water. Breathing it in exposes the lungs to radiation; radon is the second leading cause of lung cancer in the USA, after smoking. Fixes: test the home, seal cracks, and fit a ventilation fan that pulls air from under the floor to the outside.

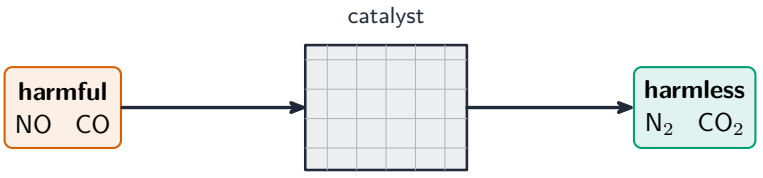
Carbon monoxide has no colour or smell. Faulty gas heaters, stoves and generators used indoors produce it. A CO detector, regular servicing and good ventilation prevent poisoning.

Reduction of Air Pollutants

Pollution can be reduced in three main ways: **regulation** (laws and limits), **conservation** (using less energy, so less is burned) and **alternative fuels** (natural gas, renewables). The best methods stop the pollutant at its source.

Device	Where	What it removes	How it works
Catalytic converter 催化转化器	car exhaust	CO, NO_x, hydrocarbons	a metal catalyst turns them into CO_2, N_2, O_2 and H_2O
Vapor recovery nozzle 油气回收喷嘴	gasoline pump	VOCs (fuel vapor)	a sleeve on the nozzle sucks fuel vapor back into the underground tank
Wet scrubber 洗涤器	smokestack	SO_2, particulates	exhaust passes through a spray of water and lime, which reacts with SO_2
Dry scrubber	smokestack	SO_2	a powder of lime reacts with the gas
Electrostatic precipitator 静电除尘器	coal power plant	particulates	particles are given an electric charge and stick to charged plates
Baghouse filter 袋式除尘器	factories	particulates	fabric bags filter out dust

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$$2NO + 2CO \rightarrow N_2 + 2CO_2$$

A catalytic converter turns harmful NO and CO into N2 and CO2, reducing toxic exhaust; CO2 remains a greenhouse gas

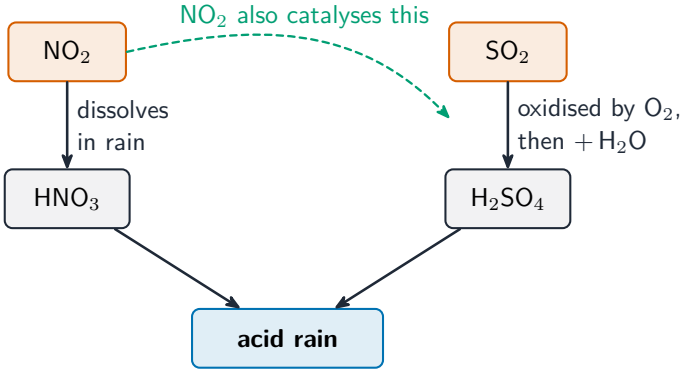
Other methods: burning low-sulfur coal, **fluidized bed combustion** (burning coal at a lower temperature mixed with limestone, which makes less NO_x and traps SO_2), switching from coal to natural gas (almost no SO_2 or particulates), public transport and car-sharing, and emissions trading under the Clean Air Act.

> **Worked example (justify a solution).** "Propose a government action to cut oil use and justify it." Claim: give tax credits for electric vehicles. Justification: fewer petrol cars means less NO_x and VOCs, so less photochemical smog and ground-level ozone in cities. Always link the action to a named pollutant and a named effect.

Acid Rain

Acid rain 酸雨 (more fully, **acid deposition** 酸沉降, which includes dry particles) forms when sulfur dioxide and nitrogen oxides react with water and oxygen in the air to make sulfuric acid and nitric acid. Clean rain is already slightly acidic, pH about 5.6, because CO_2 dissolves in it; acid rain is below that.

$$SO_2 \rightarrow H_2SO_4 \qquad NO_x \rightarrow HNO_3$$



Nitrogen and sulfur oxides form nitric and sulfuric acid in rain

Sources: SO_2 comes mainly from coal-burning power plants. NO_x comes from coal

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power plants and motor vehicles. Volcanoes and lightning are natural sources. Tall smokestacks send the gases high, so the acid falls hundreds of kilometres **downwind**, often in another state or country.

Effects:

- **Water:** lakes become acidic; fish eggs and young fish die below about pH 5. Acid also releases toxic **aluminium** 铝 from rocks into the water.
- **Soil:** acid washes calcium and magnesium out of the soil (**leaching** 淋溶) and releases aluminium, which damages roots. Trees weaken and die.
- **Buildings:** acid dissolves limestone and marble statues and corrodes metal.



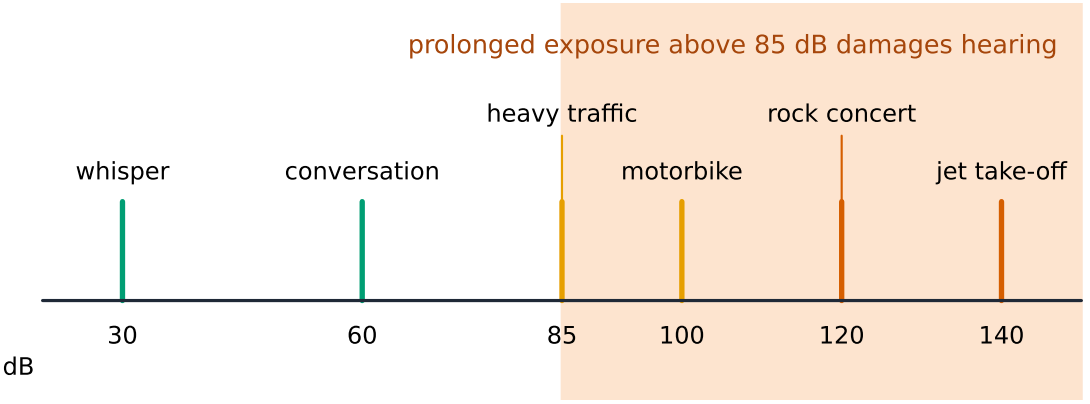
Forest dieback: acid deposition from SO2 and NOx can damage trees far downwind of the source

Bedrock matters. Lakes on **limestone** 石灰岩 bedrock are protected: calcium carbonate neutralizes the acid (it acts as a **buffer** 缓冲剂). Lakes on granite have no buffer, so they acidify quickly. Farmers and lake managers can add crushed limestone (**liming**) to neutralize acidic soil and water.

> **Worked example (pH).** Normal rain has pH 5.6; a sample of acid rain has pH 3.6. pH is a logarithmic scale: each unit is a 10-times change in acidity. The sample is $10^{5.6-3.6} = 10^2 = 100$ times more acidic than normal rain.

Noise Pollution

Noise pollution 噪声污染 is sound at a level high enough to cause physiological stress or hearing loss. Sound level is measured in **decibels** 分贝 (dB). The scale is logarithmic: every 10 dB is ten times the sound intensity, so 90 dB is ten times as intense as 80 dB. Long exposure above about 85 dB damages hearing.



The decibel scale: prolonged exposure above 85 dB damages hearing

Sources in cities: transportation (road traffic, aircraft, trains), construction, and domestic and industrial activity.

Effects on people: hearing loss 听力损失, **stress** 压力, poor sleep and higher blood pressure.

Effects on animals: noise causes stress, **masks** the sounds animals use to communicate, find mates or hunt, damages hearing, and can change migration routes. Birds in noisy areas sing louder or at a higher pitch, or leave. Ship engines and sonar are especially harmful to whales and dolphins, which use sound to navigate.

Reducing noise: sound barriers along highways, quieter engines and mufflers, limits on night flights, and land-use planning that keeps homes away from airports and factories.

> **Worked example (percent change).** Near a new power plant, bird species richness fell from 7.5 to 6.0 species per hectare. Percent change $= \frac{6.0-7.5}{7.5} \times 100 = -20\%$, a 20% decrease.

Practice

Answer each before reading the answers below.

1. Describe how photochemical smog forms, and explain why tropospheric ozone peaks in the afternoon.
2. Explain how a thermal inversion traps air pollution.
3. Classify each as a primary or secondary pollutant: CO, O_3, SO_2, sulfuric acid.
4. Rain of pH 4 is how many times more acidic than rain of pH 6? Explain why lakes on limestone are less affected.
5. Name the source of indoor radon and one way to reduce it.

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6. Describe one technology that reduces each: SO_2 from power plants; NOx and CO from cars.

Answers

1. Cars emit NOx and VOCs in the morning; sunlight breaks down NO_2 to form ozone. Ozone builds up through the day with sunlight and peaks in the afternoon.
2. A warm layer of air sits above cooler air near the ground. The cool air cannot rise, so pollutants stay near the surface.
3. Primary: CO, SO_2. Secondary: O_3, sulfuric acid.
4. $10^2 = 100$ times. Limestone ($CaCO_3$) neutralizes acid (buffering).
5. The decay of uranium in rock and soil under buildings; seal cracks in the foundation and ventilate the basement.
6. Scrubbers remove SO_2 from smokestacks; catalytic converters convert NOx and CO to N_2 and CO_2.

Exam tips

- Distinguish **primary** pollutants (emitted directly: CO, NO_x, SO_2, particulates, VOCs) from **secondary** pollutants (formed in the air: ground-level ozone, sulfuric and nitric acid).
- Ground-level ozone is a **pollutant**; the ozone **layer** in the stratosphere protects us. Do not mix them up.
- For a smog graph: NO peaks in the morning, NO_2 next, and ozone in the afternoon, because ozone needs sunlight. Smog is worse in summer.
- For a thermal inversion, say which air is warm and which is cool: warm air **above** cool air stops the cool polluted air rising.
- Match each control device to its pollutant: catalytic converter (CO, NO_x, hydrocarbons), scrubber (SO_2), electrostatic precipitator (particulates), vapor recovery nozzle (VOCs).
- Acid rain falls **downwind** of coal power plants; limestone bedrock buffers it.
- In a calculation, write the formula, substitute with units, and give the sign of a percent change.
- When asked to "propose a solution", name a realistic action, the pollutant it reduces and the effect that improves.

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Aquatic and Terrestrial Pollution

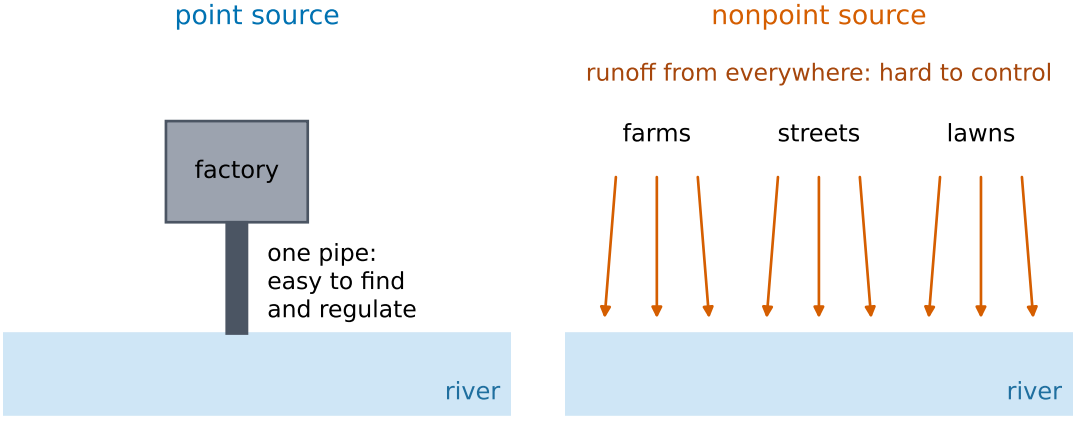
AP Environmental Science

Sources of Pollution

In the 1950s and 60s, cats in the fishing town of Minamata, Japan began to stagger, convulse and die – the locals called it "dancing cat disease". Then people fell ill too: numb hands, slurred speech, and babies born with brain damage. A chemical factory had been releasing wastewater containing methylmercury into the bay for decades. Fish and shellfish accumulated it, and the people and cats who ate the fish received the highest doses of all. More than 2 000 people were officially recognized as victims. Almost every idea in this unit – point sources, bioaccumulation, biomagnification, toxicity – is in that one story.

Pollution sources are **point** or **nonpoint**:

- A **point source** 点源 is a single, identifiable source of a pollutant – a smokestack, a factory waste-discharge pipe, a sewage outfall. It is easy to locate, measure and regulate (for example with a discharge permit).
- A **nonpoint source** 非点源 is diffuse: the pollution comes from a wide area, so it is hard to identify and control – pesticide spraying, fertilizer runoff from many farms, urban runoff carrying oil and litter from streets, and car exhaust.



Point sources come from one outlet; nonpoint sources come from a wide area

Human Impacts on Ecosystems

Organisms have a **range of tolerance** for each pollutant, just as for temperature or salinity. Inside the optimum range they can maintain **homeostasis** (stable internal conditions). Outside it they experience physiological stress, limited growth, reduced reproduction and, in extreme cases, death. AP questions often ask how a specific

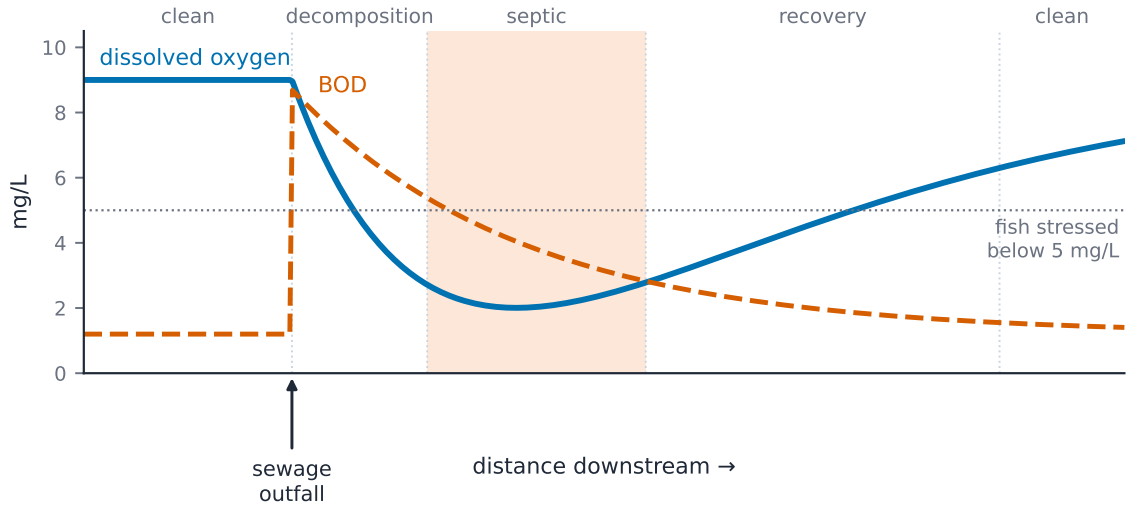
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pollutant pushes organisms out of their range:

- **Coral reefs** are damaged by rising ocean temperature (bleaching), **sediment runoff** that blocks the light their algae need, and destructive fishing practices such as dynamite and cyanide fishing.
- **Oil spills** kill marine organisms through the toxic hydrocarbons in oil. Floating oil coats the feathers of birds and the fur of marine mammals, so they lose insulation and buoyancy; some components sink and kill bottom-dwelling organisms. Oil washing onto beaches harms the **fishing and tourism** industries – the 2010 Deepwater Horizon spill closed large parts of the Gulf of Mexico to fishing.
- **Oceanic dead zones** are areas of low oxygen caused by nutrient pollution (see Eutrophication). The Gulf of Mexico dead zone, fed by fertilizer from the Mississippi basin, covers about 15 000 km^2 most summers.
- **Heavy metals** from mining, industry and burning fossil fuels (lead, mercury, arsenic, cadmium) can seep into **groundwater** and contaminate drinking water.
- **Litter** in water is unsightly, but it also causes intestinal blockage and choking in wildlife and introduces toxic substances (from plastics) into the food chain.
- **Sediment** from erosion makes water cloudy (high turbidity), reducing **light** for primary producers and making it hard for **visual predators** to find prey. When it settles, it smothers gravel beds where fish lay eggs.
- **Mercury**: after mercury enters water, certain microbes can convert inorganic mercury ions into **methylmercury**, which is far more toxic and easily absorbed by living things.

An **oxygen sag curve** plots dissolved oxygen against distance downstream from a source of organic pollution such as sewage or animal waste. Bacteria decomposing the waste use oxygen faster than air and plants can replace it, so dissolved oxygen "sags" to a minimum some distance downstream, then recovers as the waste is used up. **Biochemical oxygen demand (BOD)** – how much oxygen the microbes need – is highest at the outfall.

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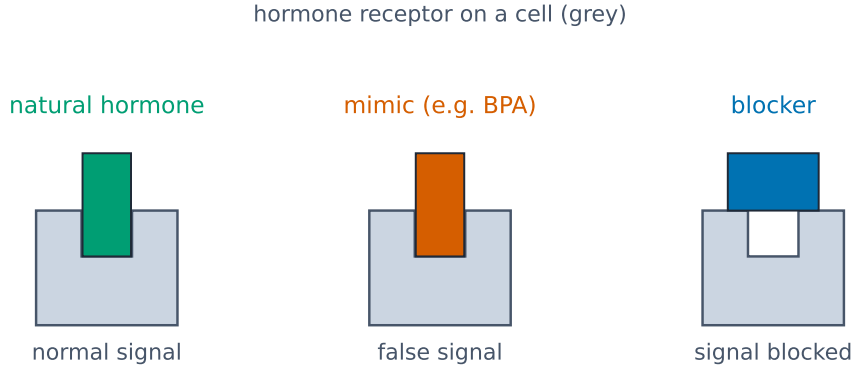


Below a sewage outfall, decomposing bacteria use up dissolved oxygen: it sags to a low point in the septic zone and then recovers downstream, while BOD peaks at the outfall

Endocrine Disruptors

Endocrine disruptors 内分泌干扰物 are chemicals that interfere with the **endocrine (hormone) system** of animals. Some mimic a natural hormone and send a false signal; others block the receptor so the real hormone cannot work. Examples include the pesticide atrazine, BPA and phthalates from plastics, PCBs, and the synthetic estrogen from birth-control pills that passes through sewage treatment into rivers.

Because hormones control growth, development and reproduction, even very low doses can cause **birth defects, developmental disorders and gender imbalances** in fish and other species. Male fish downstream of sewage outfalls have been found growing eggs, and frogs exposed to atrazine can develop both male and female organs.



Endocrine disruptors mimic or block hormones at their receptors

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Human Impacts on Wetlands and Mangroves

A **wetland** 湿地 is an area where water covers the soil, either part or all of the time – marshes, swamps, bogs, and coastal **mangroves** 红树林. Wetlands provide valuable ecosystem services:

- **water purification and filtration** – plants and sediments trap pollutants and excess nutrients;
- **flood protection** – wetlands soak up water like a sponge and release it slowly; mangroves absorb storm surges;
- **habitat** – nurseries for young fish and shellfish, and stopovers for migrating birds.

Threats to wetlands and mangroves include **commercial development** (draining for housing, farms and shrimp ponds), **dam construction** (which cuts off the water and sediment that feed downstream wetlands), **overfishing**, and **pollutants from agriculture and industrial waste**. The contiguous United States has lost more than half of its original wetlands. When they go, communities pay for flood defences and water treatment that the wetland once provided for free.



Mangrove roots: this tangle traps sediment, calms waves, and shelters young fish, all services lost when mangroves are cleared

Eutrophication

Eutrophication 富营养化 occurs when a body of water is enriched in nutrients, usually nitrogen and phosphorus. The anthropogenic causes are **agricultural runoff** (fertilizer and manure) and **wastewater release** (sewage, detergents). It proceeds in a chain that you should be able to write step by step:

1. Extra nitrogen and phosphorus enter the water.

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2. They remove the limit on plant growth, so algae grow rapidly – an **algal bloom** 藻华.
3. The bloom blocks sunlight, so plants on the bottom die.
4. The algae die, and **bacteria decompose them, using up dissolved oxygen**.
5. The water becomes **hypoxic** 缺氧 (low in dissolved oxygen), and fish and other aquatic animals die – a **dead zone**.

The opposite of a eutrophic lake is an **oligotrophic** lake: very low in nutrients, with a stable algae population, clear water and **high dissolved oxygen** – often deep, cold mountain lakes.



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

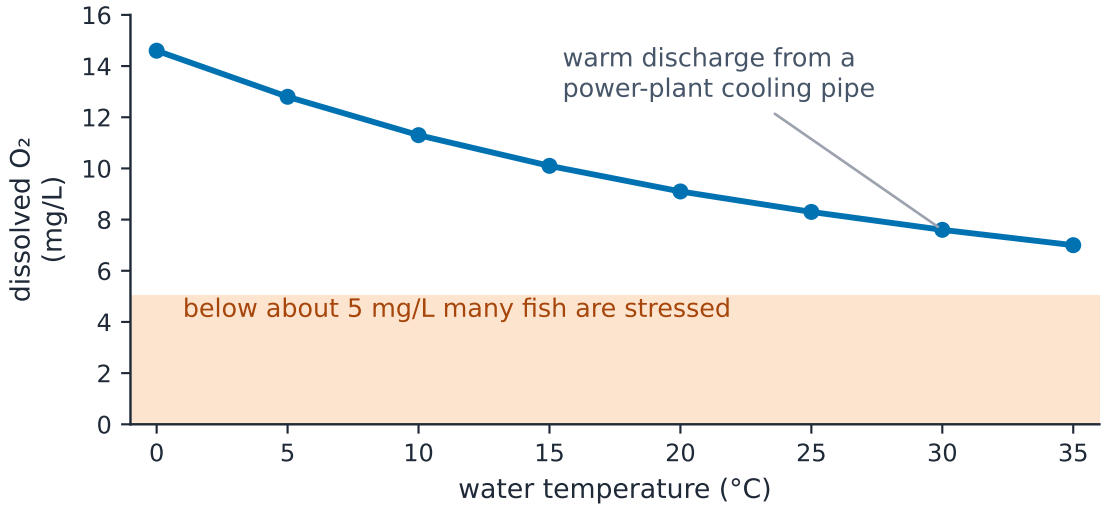
Solutions target the nutrient source: apply fertilizer only as needed, plant **buffer strips** of vegetation along streams, restore wetlands to catch runoff, use phosphate-free detergents, and add **tertiary sewage treatment** to remove nitrogen and phosphorus.

Thermal Pollution

Thermal pollution 热污染 occurs when heat released into water harms the organisms living there. The usual source is a power plant or factory that takes in cool river water to cool its machinery and returns it several degrees warmer.

Warm water **holds less dissolved oxygen** than cold water, while fish and other cold-blooded animals breathe faster in warm water and need *more* oxygen. Heat also speeds up decomposition (using more oxygen), and sudden changes in temperature (**thermal shock**) can kill organisms adapted to stable conditions. Solutions include cooling towers and cooling ponds that release the heat to the air before the water returns to the river.

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Warmer water holds less dissolved oxygen

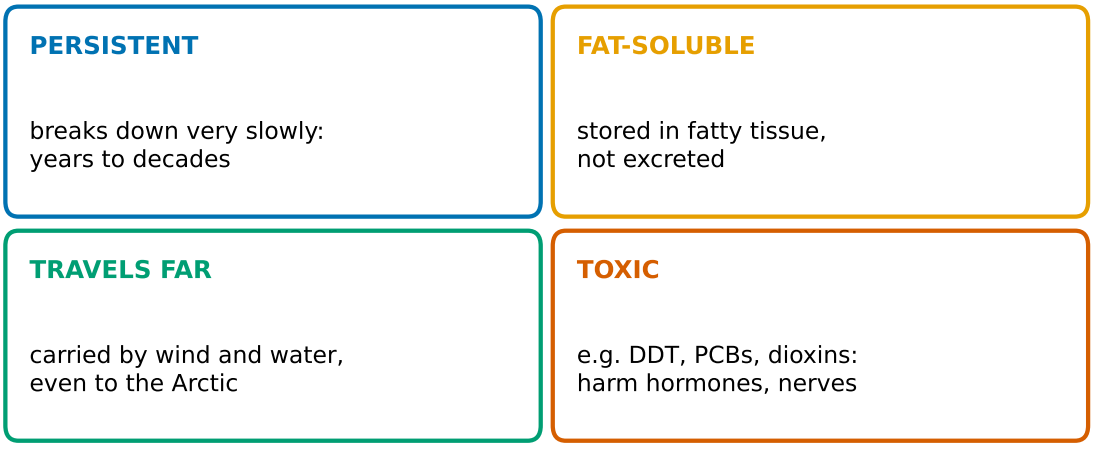
Persistent Organic Pollutants (POPs)

Persistent organic pollutants 持久性有机污染物 (POPs) are synthetic, carbon-based molecules – such as the pesticide **DDT** and the industrial chemicals **PCBs** – that do not easily break down in the environment. Three properties make them dangerous:

- **Persistent** – microbes and sunlight break them down very slowly, so they last for years or decades.
- **Fat-soluble** – they dissolve in fat rather than water, so they are stored in organisms' fatty tissues instead of being excreted.
- **Mobile** – they travel long distances on wind and water before being redeposited. POPs used in the tropics evaporate, drift toward the poles and condense in the cold, so Inuit people and polar bears in the Arctic carry some of the highest levels on Earth.

The 2001 **Stockholm Convention** bans or restricts the worst POPs worldwide.

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What makes a persistent organic pollutant

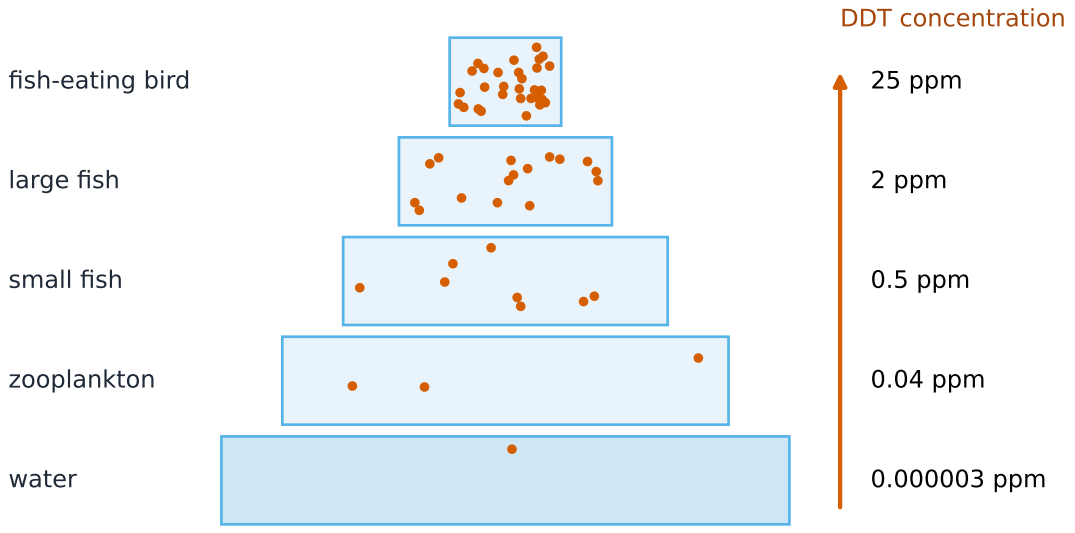
Bioaccumulation and Biomagnification

Bioaccumulation 生物累积 is the selective absorption and concentration of a substance by cells **within one organism** over its lifetime – most commonly fat-soluble compounds that the body cannot excrete. An older fish carries more mercury than a younger one of the same species.

Biomagnification 生物放大 is the increase in concentration per unit of body tissue at **successively higher trophic levels** of a food chain or web. Each predator eats many prey and keeps their stored toxin, so top predators end up with the highest levels – which is why large predatory fish such as tuna and swordfish carry the most mercury.

Effects of biomagnification on top carnivores include **eggshell thinning** (DDT made eagle, osprey and pelican eggs so thin they broke under the parents' weight, and bald eagles nearly vanished from the lower 48 US states until DDT was banned in 1972) and **developmental deformities**. Humans suffer harm to their **reproductive, nervous and circulatory systems**. The three classic substances that bioaccumulate are **DDT, mercury and PCBs**.

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Biomagnification: DDT concentration rises at each trophic level

Worked example (biomagnification). In the classic DDT study shown above, water held 0.000003 ppm of DDT and a fish-eating bird held 25 ppm. The bird's concentration is $\dfrac{25}{0.000003} \approx 8\,300\,000$ times that of the water. From small fish (0.5 ppm) to the bird alone, the concentration rose $\dfrac{25}{0.5} = 50$-fold. This is why a top predator can be poisoned even when the water itself looks clean.

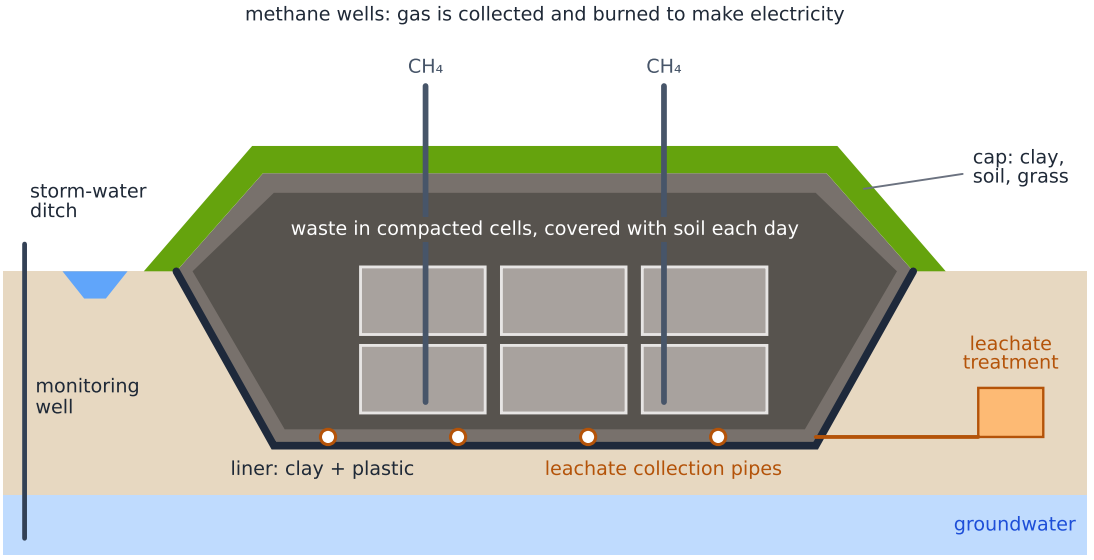
Solid Waste Disposal

Solid waste is any discarded material that is not a liquid or gas. It is generated in **domestic, industrial, business and agricultural** sectors; in the US, households produce about 2 kg per person per day.

Solid waste is most often disposed of in **landfills**, which can **contaminate groundwater** (through leachate, the polluted liquid that drains out of trash) and **release harmful gases** – mostly methane and carbon dioxide from decomposition. A **sanitary municipal landfill** 卫生填埋场 is designed to prevent this. It has:

- a **bottom liner** of plastic and compacted clay, so leachate cannot reach groundwater;
- a **leachate collection system** – pipes along the liner that carry leachate to treatment;
- a **storm-water collection system** – ditches that carry rain away before it soaks into the trash;
- a **cap** of clay and soil, planted with grass, once a section is full;
- a **methane collection system** – wells and pipes that collect landfill gas.

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A sanitary landfill: a clay and plastic liner, leachate pipes, compacted waste cells, a cap, methane wells and a groundwater monitoring well

Decomposition inside a landfill depends on the **composition of the trash** (food and yard waste rot; plastics and metals do not) and the **conditions microbes need** – moisture, oxygen and warmth. Because landfills are sealed, dry and low in oxygen, even newspapers can stay readable for decades.

Incineration 焚烧 burns waste at high temperatures. It **significantly reduces the volume** of waste (by about 90%) and can generate electricity, but it **releases air pollutants** (particulates, dioxins, heavy metals) and leaves toxic ash that must itself go to a landfill.

Some items are **not accepted** in sanitary landfills and may be **dumped illegally**. Piles of used **rubber tires**, for example, collect rainwater and become breeding grounds for **mosquitoes** that spread disease; they can also catch fire and burn for months.

E-waste 电子垃圾 is discarded electronic devices – televisions, phones, computers. Some countries dump waste in the **ocean**; together with plastic from rivers and ships, this has created large floating **garbage patches** 垃圾带, such as the Great Pacific Garbage Patch. Wildlife becomes **entangled** in nets and plastic, and **ingests** it – sea turtles mistake plastic bags for jellyfish, and seabirds feed bottle caps to their chicks.



A landfill: solid waste is buried here in lined cells. It takes up land and can leak, which is why reducing waste comes first

Microplastics. Plastic does not biodegrade; sunlight and waves break it into ever smaller pieces. Pieces under 5 mm, together with the tiny **microbeads** once added to face scrubs and toothpaste, are **microplastics**. Filter feeders and fish swallow them, mistaking them for food. Microplastics fill the stomach without giving energy, so animals feel full and starve, and they can block or damage the gut. Persistent organic pollutants stick to the plastic surface, so the plastic also carries toxins into the food chain, where they biomagnify. Many countries now ban microbeads in cosmetics.

> **Worked example (percent increase).** US municipal solid waste rose from 152 million tons in 1980 to 251 million tons in 2012.

1. Percent increase $= \dfrac{251 - 152}{152} \times 100 \approx 65\%$.
2. Always divide by the **old** (earlier) value.
3. Over the same years the population grew more slowly, so waste **per person** also rose.

Waste Reduction Methods

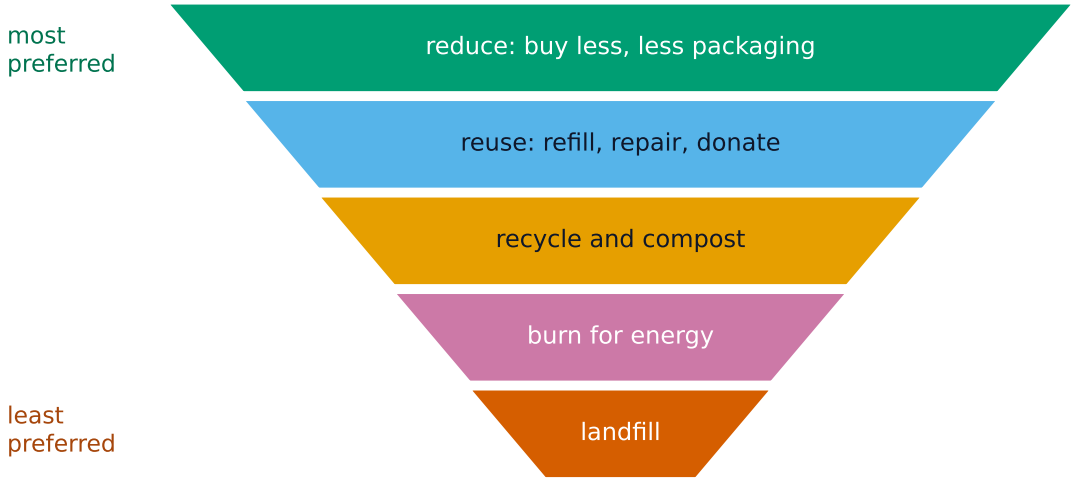
The waste hierarchy is **reduce, reuse, recycle** 减量、再利用、回收. Reducing consumption is best, because there is then no waste to manage at all.

- **Recycling** processes certain waste materials (paper, glass, aluminium, some plastics) and converts them into new products. It reduces the demand for mining new minerals – recycled aluminium needs about 95% less energy than new aluminium from ore – but the process itself is **energy-intensive and can be costly** (collecting, sorting and cleaning).

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- **Composting** 堆肥 lets organic matter such as food scraps, paper and yard waste decompose; the product can be used as a natural **fertilizer**. Drawbacks are **odour and rodents**.
- **E-waste** can be reduced by recycling and reuse (repairing and passing on devices). E-waste contains hazardous chemicals – heavy metals such as **lead and mercury** – that can leach from landfills into groundwater if not disposed of properly. It also contains valuable gold, copper and rare metals worth recovering.

Landfill mitigation ranges from **burning waste for energy** to **restoring habitat** on closed landfills and turning them into parks. The methane collected from decomposing organic waste can be **burned to turn turbines and generate electricity**; this reduces methane emissions and produces useful energy; it does not directly reduce the volume of solid waste.



The waste hierarchy: reduce first, landfill last

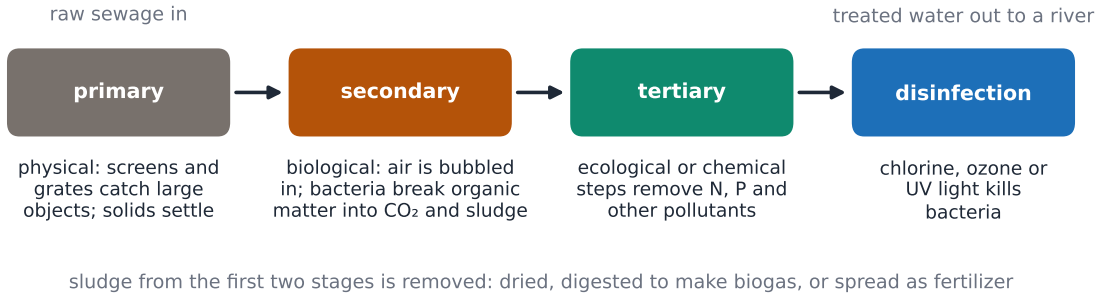
Sewage Treatment

Sewage treatment 污水处理 cleans wastewater in stages before it returns to a river or the sea:

1. **Primary treatment** (physical): screens and grates remove large objects (rags, sticks, plastic), then the water sits in a tank so solid waste settles to the bottom as sludge.
2. **Secondary treatment** (biological): bacteria break down organic matter, releasing carbon dioxide and producing more microbial biomass, which settles as sludge. The tank is **aerated** (air is bubbled through) to give the bacteria oxygen and speed up their work.

3. **Tertiary treatment**: ecological or chemical processes remove pollutants left after the first two stages – especially nitrogen and phosphorus, which would otherwise cause eutrophication. Constructed wetlands are one ecological method.
4. **Disinfection**: before discharge, the water is exposed to **chlorine, ozone or UV light** to kill bacteria and other pathogens.

The sludge is dried and buried, digested by bacteria to make **biogas**, or treated and spread on fields as fertilizer (if it is free of heavy metals).



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

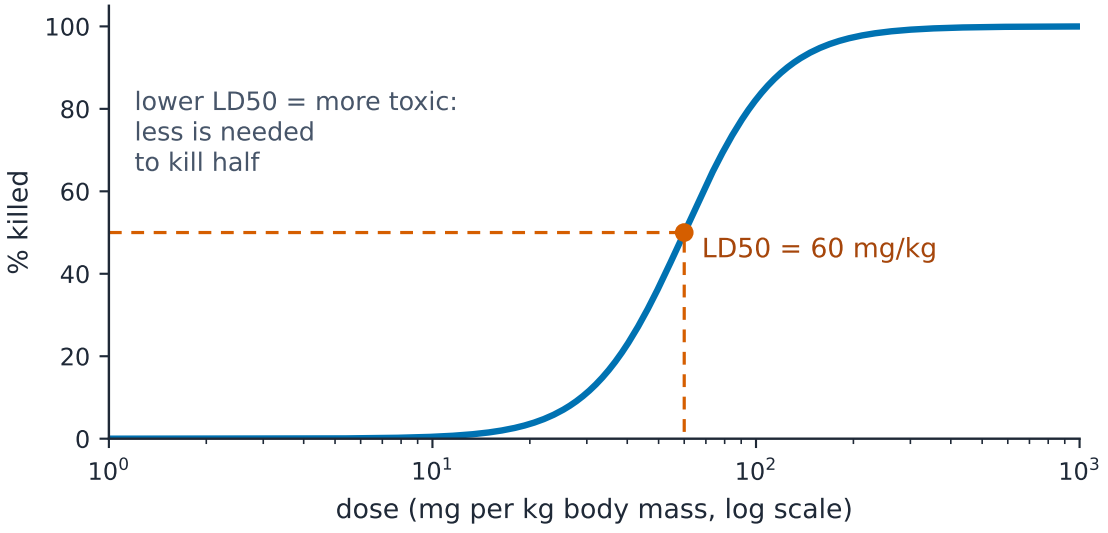
Lethal Dose 50% (LD50)

The **LD50** 半数致死量 (lethal dose 50%) is the dose of a chemical that is lethal to **50%** of a population of a particular species in a test. It is usually given in milligrams of chemical per kilogram of body mass (mg/kg), so it can be scaled to animals of different sizes. A **lower** LD50 means a **more toxic** substance – less of it is needed to kill half the population.

LD50 values are measured on lab animals such as rats, and humans may respond differently. Health-based exposure limits use appropriate toxicity studies and uncertainty factors; they are not obtained by simply dividing an LD50.

> **Worked example (LD50).** Chemical A has an LD50 of 5 mg per kg of body weight; chemical B, 500 mg/kg. Because A's value is 100 times smaller, A is about 100× **more toxic**. For a 70 kg test animal of the species studied, the corresponding LD50 dose of A is 5 mg/kg × 70 kg = 350 mg – a tiny amount, whereas B would take 500 × 70 = 35 000 mg (35 g).

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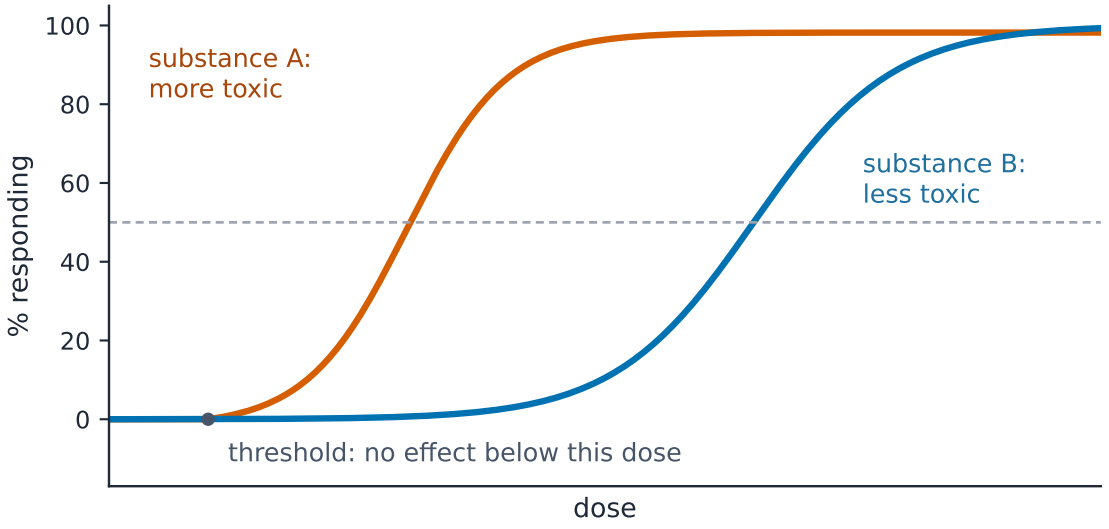
LD50 is the dose that kills half of a test population

Dose Response Curve

A **dose–response curve** 剂量反应曲线 shows the effect on an organism, or the mortality rate in a population, at each dose of a particular toxin or drug. Reading one:

- The x-axis is the **dose** (often on a log scale); the y-axis is the percentage of the population responding or dying.
- Generally, a higher dose causes a greater effect.
- The dose at which 50% respond is read straight from the curve: the LD50 for deaths, or the **ED50** for a non-lethal effect.
- Some chemicals have a **threshold** 阈值 – a dose below which there is no measurable effect. For others, such as many carcinogens, any exposure may carry some risk.
- A curve further to the **left** belongs to a **more toxic** substance.

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Dose-response curves: a threshold, and a more toxic substance acts at lower doses

Pollution and Human Health

It can be **difficult to establish cause and effect** between a pollutant and a human health problem, because people are exposed to many chemicals and pollutants at once, over many years, and also differ in diet, smoking, genes and age. Scientists rely on large studies comparing exposed and unexposed groups, and on animal experiments. **Dose, duration and individual sensitivity** all affect the outcome; children, the elderly and pregnant women are most sensitive. Poor communities are often the most exposed and the least protected.

Examples the exam names:

- **Dysentery** 痢疾 – caused by untreated sewage in streams and rivers.
- **Mesothelioma** – a cancer of the lining of the lungs caused mainly by breathing in **asbestos** fibres, once used in building insulation. It can appear 20–50 years after exposure.
- **Tropospheric (ground-level) ozone** – irritates the airways and reduces lung function, worsening asthma and other respiratory problems.

Pathogens and Infectious Diseases

Pathogens 病原体 (bacteria, viruses, parasites) **adapt** to take advantage of new opportunities to infect and spread through human populations – new hosts, crowded cities, air travel and changing climates. Specific pathogens can occur in many environments **regardless of how clean they look**: clear water can still carry cholera bacteria.

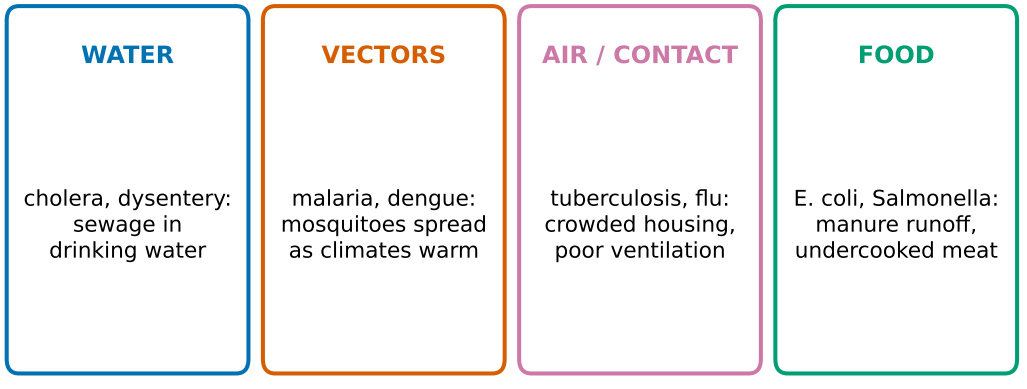
The exam names specific diseases and expects you to know **how each one is trans-**

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mitted, because the transmission route decides the defence:

Disease	Type	How it spreads
Cholera 霍乱	bacterial	drinking water contaminated with sewage
Dysentery	bacterial or parasitic	swallowing food or water contaminated with infected faeces
Plague 鼠疫	bacterial	bite of an infected organism (e.g. fleas) or contact with infected fluids or tissues
Tuberculosis (TB) 结核病	bacterial	inhaling airborne bacteria released by a person with infectious TB; usually attacks the lungs
Malaria 疟疾	parasitic	bite of an infected **mosquito** 蚊子 (mostly sub-Saharan Africa)
West Nile / Zika 西尼罗/寨卡	viral	bite of an infected mosquito (Zika also via sexual contact)
SARS / MERS	viral	SARS, a form of pneumonia: inhaling or touching infected fluids; MERS passes from animals (camels) to humans

Two big-picture ideas carry marks. **Poverty** deepens the problem – low-income areas often lack sanitary waste disposal and clean water, giving water-borne diseases a haven. And **climate change spreads disease**: as warm equatorial climate zones expand toward the poles, mosquitoes and other **vectors** 传播媒介 – and the diseases they carry – move into subtropical and temperate regions where these diseases were not known before. Clean water, sanitation, and vector control (draining standing water, bed nets) remain the main defences.



How pathogens spread and the environmental conditions that help them

Practice

Answer each before reading the answers below.

1. Describe the chain of events by which fertilizer runoff causes a fish kill.
2. DDT is 0.000003 ppm in lake water, 2 ppm in fish and 25 ppm in fish-eating birds. Name the process and explain why the concentration rises.
3. Substance A has an LD50 of 5 mg/kg and substance B of 500 mg/kg. Which is more toxic? Calculate the corresponding LD50 dose of A for a 70 kg test animal of the species studied.
4. Classify each as point or non-point source pollution: a factory pipe; runoff from farms; a leaking oil tanker.
5. Explain why thermal pollution from a power plant can kill fish.
6. Describe primary and secondary sewage treatment.

Answers

1. Nitrogen and phosphorus cause an algal bloom; the algae die; decomposers break them down and use up the dissolved oxygen; the water becomes hypoxic, and fish die.
2. Biomagnification: DDT is fat-soluble and persistent, so it stays in tissues, and each predator eats many prey, concentrating it at each trophic level.
3. A (a smaller dose kills half the population). $5 \times 70 = 350$ mg.
4. Point: the factory pipe, the oil tanker. Non-point: farm runoff.
5. Warmer water holds less dissolved oxygen and raises fish metabolism, so fish suffocate; the sudden change can also cause thermal shock.
6. Primary: solids settle out physically. Secondary: bacteria break down organic matter with aeration.

Exam tips

- Give a specific example of a **point source** (one pipe or smokestack) and a **nonpoint source** (farm or urban runoff), and say why nonpoint is harder to regulate.
- Trace **eutrophication** step by step: nutrient runoff → algal bloom → algae die → bacteria decompose them and use up oxygen → hypoxia → fish die. Contrast with **oligotrophic** water.
- On an **oxygen sag curve**, dissolved oxygen falls below a sewage outfall, reaches a minimum downstream, and recovers.
- Thermal pollution: warm water holds **less dissolved oxygen**.
- POPs are **persistent, fat-soluble and travel far**. **Bioaccumulation** builds up in one organism; **biomagnification** increases up the food chain, so top predators are hit hardest (eggshell thinning). Bacteria turn mercury into **methylmercury**.

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- Name the parts of a **sanitary landfill**: liner, leachate collection, storm-water collection, cap, methane collection.
- Incineration cuts volume but releases air pollutants; recycling saves minerals but is energy-intensive; composting smells and draws rodents.
- Describe the stages of **sewage treatment**: primary (physical), secondary (biological, aerated), tertiary (ecological or chemical), then disinfection.
- Read an **LD50**: a **lower** value means **more** toxic; multiply by body mass for the corresponding test-species LD50 dose, not a predicted lethal dose for a human.
- Match each disease to its **route of transmission**, and link vectors spreading poleward to climate change.

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Global Change

AP Environmental Science

Stratospheric Ozone Depletion

In 1985 three British scientists at a research station in Antarctica published a surprising result: every southern spring, the ozone above them dropped by about a third. Satellite readings had not raised the alarm: values that low were first treated as instrument errors. Within two years, the world had signed a treaty to stop making the chemicals responsible. This unit covers the global changes people cause, and the ones like this that we have learned to reverse.

The **ozone layer** 臭氧层 is a band of ozone (O_3) about 15–35 km up, in the stratosphere. It absorbs most of the Sun's harmful **ultraviolet** 紫外线 (UV) radiation, especially UV-B. Life on land only became possible after this layer formed, and it still protects every living thing on the surface.

CFCs 氯氟烃 (chlorofluorocarbons, once used in fridges, air conditioners, aerosol sprays and foam) are very stable, so they last long enough to drift up into the stratosphere. There, UV light breaks them apart and frees **chlorine atoms**. One chlorine atom acts as a catalyst – it is not used up – so it can destroy tens of thousands of ozone molecules:

$$\mathrm{Cl} + \mathrm{O_3} \rightarrow \mathrm{ClO} + \mathrm{O_2}$$

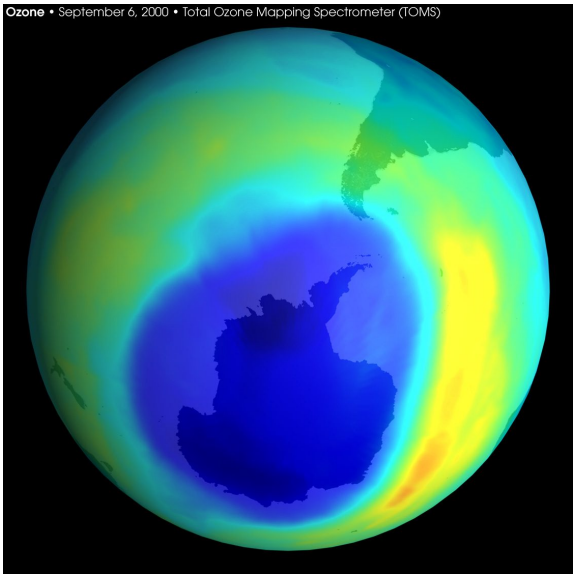
$$\mathrm{ClO} + \mathrm{O} \rightarrow \mathrm{Cl} + \mathrm{O_2}$$

The chlorine atom comes out of the second step free to start again.

A **natural factor** makes the damage worst over Antarctica. In the dark polar winter, extremely cold air forms ice-crystal clouds high in the stratosphere. Reactions on the cloud particles convert chlorine reservoirs into forms such as chlorine gas. When the Sun returns in spring (September–October), sunlight splits these molecules, releasing active chlorine that rapidly destroys ozone – the "**ozone hole**".

Less ozone means more UV reaches the surface. In humans, UV causes **skin cancer**, **cataracts** (clouding of the eye lens) and sunburn, and weakens the immune system. It also damages crops and kills the phytoplankton at the base of ocean food webs.

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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*

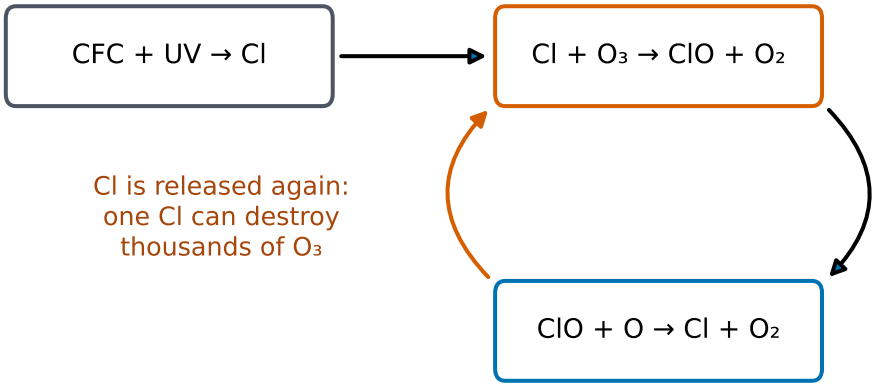
Reducing Ozone Depletion

The **Montreal Protocol** 蒙特利尔议定书 (1987) phased out CFCs worldwide and is a rare environmental success – every country in the world signed it, CFC levels in the air are falling, and the ozone layer is expected to recover to 1980 levels by about 2066 over Antarctica.

Ozone depletion is reduced by **replacing ozone-depleting chemicals with substitutes**:

- **HCFCs** – contain chlorine but break down sooner than CFCs; a temporary step, now also being phased out.
- **HFCs** (hydrofluorocarbons) – contain no chlorine, so they do **not** harm ozone. *But* many HFCs are strong greenhouse gases, with GWPs in the thousands. The 2016 **Kigali Amendment** to the Montreal Protocol now phases down HFCs too.
- Natural refrigerants (ammonia, propane, CO_2) and pump sprays instead of aerosols.

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

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

Common mistake. Ozone depletion and climate change are **different problems**. The ozone hole lets in more UV; it does not cause global warming. CFCs and HFCs are *also* greenhouse gases, and ozone changes affect stratospheric temperatures and atmospheric circulation.

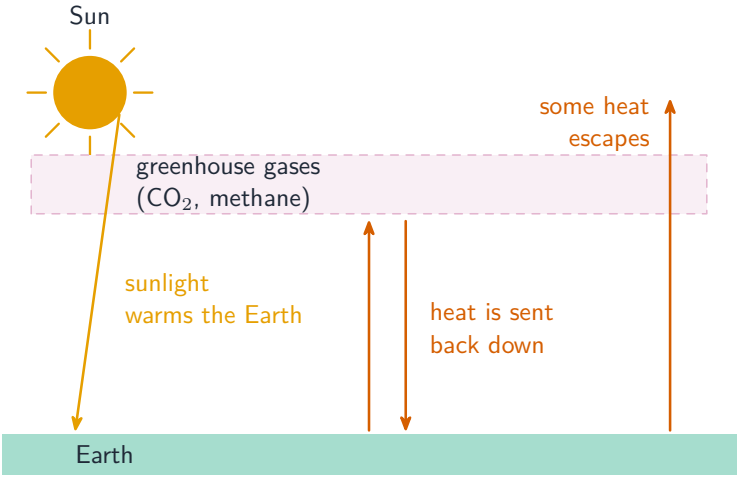
The Greenhouse Effect

The **greenhouse effect** 温室效应 keeps Earth warm. Sunlight (mostly visible light) passes through the atmosphere and warms the surface. The warm surface gives off **infrared** (heat) radiation. **Greenhouse gases** 温室气体 absorb much of this infrared and send part of it back down. Without this natural effect, Earth's average surface temperature would be about −18 °C instead of about 15 °C – too cold for most life.

The principal greenhouse gases are **carbon dioxide, methane, water vapour, nitrous oxide and CFCs**. Water vapour is actually the most abundant greenhouse gas, but it does not drive climate change: it has a **short residence time** (about 9 days before it rains out), so warming increases its amount, amplifying the original warming as a positive feedback.

The problem is the **enhanced** greenhouse effect – humans adding extra long-lived gases that trap more heat, so the surface warms further.

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greenhouse gases trap some of the Earth's heat,
so less escapes to space and the Earth warms up

Greenhouse gases absorb the heat the Earth gives off and send some back

Increases in the Greenhouse Gases

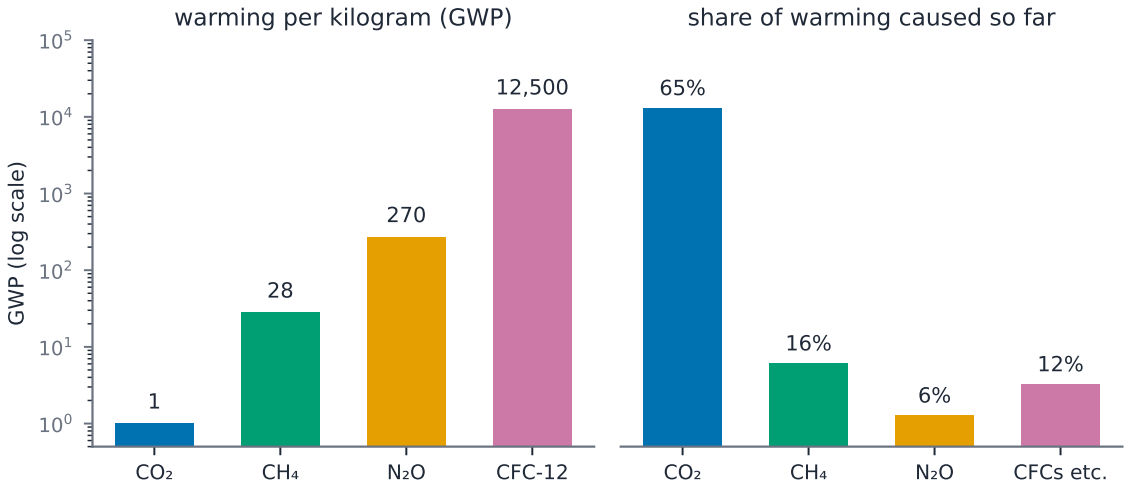
Human activities raise each greenhouse gas:

Gas	Main human sources
CO_2	burning fossil fuels (power plants, vehicles), cement making, deforestation
Methane 甲烷 (CH_4)	cattle and other livestock, landfills, rice paddies, leaks from natural gas wells and pipes, thawing permafrost
Nitrous oxide (N_2O)	nitrogen fertilizers on farms, animal manure, burning fuels
CFCs and HFCs	refrigerants, air conditioners, old aerosols and foams

To compare gases fairly, we use **global warming potential (GWP)** 全球变暖潜能值 – how much heat one kilogram of a gas traps over a set time (usually 100 years), relative to CO_2. **CO_2 is the reference, with GWP = 1**, so every other gas is measured against it. Ranked by GWP: **CFCs** are highest, then **nitrous oxide**, then **methane** – all have a greater warming effect per kilogram than CO_2.

But GWP alone does not decide impact: CO_2 still causes the most warming overall because it is released in vastly greater **quantity** and stays in the air for centuries. The exam expects both ideas – a high GWP *and* how much is emitted.

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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

Worked example (CO_2 equivalent). A landfill releases 500 tonnes of methane a year. Methane's GWP is about 28. Its warming effect equals $500 \times 28 = 14\,000$ tonnes of CO_2 (14 000 t CO_2-equivalent). If the landfill captures the methane and burns it to make electricity, it releases about 1 375 t of CO_2 instead (each tonne of methane burns to 2.75 t of CO_2) – a cut of about 90% in warming effect, *and* useful energy.

Rising greenhouse gases threaten human health and the environment. Expect to explain:

- **Rising sea levels**, from melting ice sheets *and* the expansion of warming ocean water, which floods coasts and pushes salt water into farmland and aquifers.
- **Disease vectors** – carriers such as mosquitoes and ticks – spreading from the tropics toward the poles and to higher altitudes, bringing malaria, dengue and Lyme disease to new places.
- More frequent **heat waves**, droughts and heavy rainfall events.

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Coal mining and combustion: burning fossil fuels is the main driver of rising atmospheric CO2

Global Climate Change

Global climate change 气候变化 is the long-term shift in climate from the enhanced greenhouse effect: rising average temperatures, melting ice, rising **sea levels** 海平面, more extreme weather, and shifting rainfall.

Climate has always changed. Air bubbles trapped in **ice cores** from Antarctica record the atmosphere for the past 800 000 years. They show ice ages and warm periods rising and falling together with CO_2 – but CO_2 never went above about 300 ppm. Today it is over 420 ppm, and it has risen in about 150 years rather than thousands.

> **Worked example.** Atmospheric CO_2 rose from about 280 ppm before industrialisation to about 420 ppm today. The percent increase is $\frac{420-280}{280} \times 100\% = \frac{140}{280} \times 100\% = 50\%$. This roughly 50% rise in the main long-lived greenhouse gas is the core driver of the enhanced greenhouse effect and modern warming.

Effects on Earth's systems.

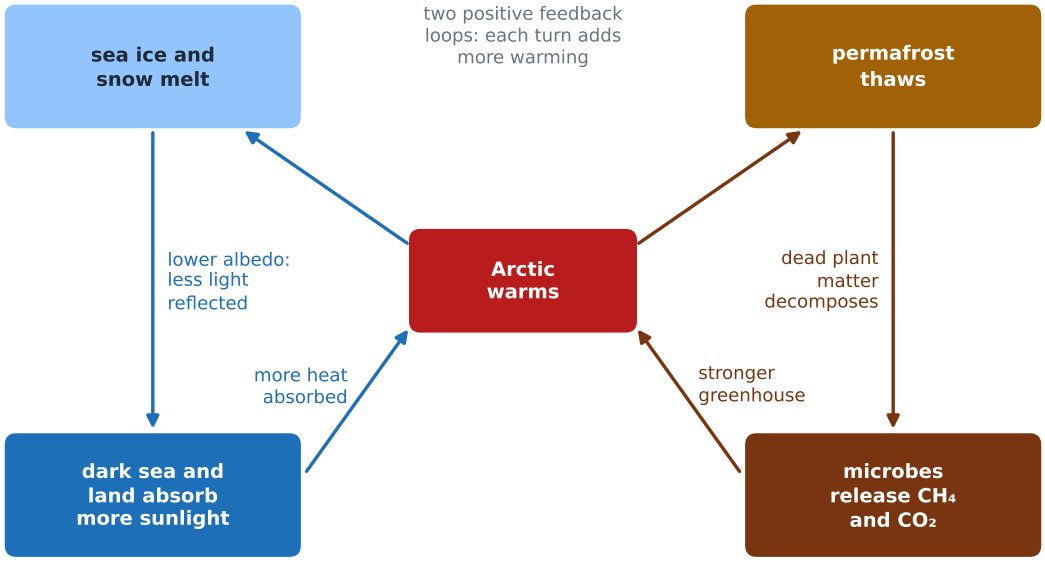
- On land: rising temperatures, melting **permafrost** 永久冻土 and sea ice, rising sea levels and the **displacement of coastal populations** (people forced to move, such as from low Pacific islands and Bangladesh's delta).
- In the sea: rising sea level floods continental shelves, creating new shallow habitat for some species. But communities near the lower edge of the **photic zone** (the sunlit layer) may end up below it, so their algae and seagrass can no longer photosynthesize.

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- In the air: winds carry heat from the equator toward the poles. Warming changes **Hadley cells** and the **jet stream**, shifting where deserts and rain belts lie and making weather patterns "stick" for longer.
- In the ocean: currents such as the **ocean conveyor belt** (thermohaline circulation) carry heat around the world. Fresh meltwater from Greenland can slow it, with big effects on coastal climates such as western Europe.
- In soil: more heat and changed rainfall dry out some soils and flood others, reducing fertility and increasing **erosion**.

Why the Arctic warms so fast. Ice and snow reflect most sunlight back to space – they have a high **albedo** 反照率. The Arctic is warming roughly two to four times faster than the global average because of **positive feedback loops** 正反馈:

1. **Ice–albedo loop:** warming melts sea ice and snow → the darker ocean and land beneath absorb more sunlight → more warming → more melting.
2. **Permafrost loop:** warming thaws the frozen tundra soil → microbes decompose the dead plant matter stored in it → methane and CO_2 are released → a stronger greenhouse effect → more warming.



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

Species that depend on ice lose habitat and food. Polar bears hunt seals from sea ice; walruses rest on it between dives; Arctic cod and the krill that many Antarctic animals eat live under it.

Protecting coasts from rising seas. Sea level rises for two reasons: water expands as it warms (thermal expansion), and melting ice on land, such as the Greenland and

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Antarctic ice sheets, adds water to the ocean. (Melting **sea ice** does not raise sea level much, because it was already floating.) Local ways to protect coastal communities:

- building **sea walls** and levees, or raising buildings and roads;
- restoring **wetlands, mangroves and dunes**, which absorb storm surges;
- **managed retreat**: moving homes and roads away from the most exposed coast, and banning new building there.

Rising seas also cost coastal towns money: flooded property, beach erosion that drives away tourists, and salt water getting into wells.



A glacier 冰川 breaking apart into the sea. Warming melts land ice, which adds water to the ocean and raises sea level

Ocean Warming

The oceans have absorbed more than 90% of the extra heat trapped by greenhouse gases. **Ocean warming** is caused by the rise in greenhouse gases, and it affects marine species in several ways:

- **Habitat loss** – species move toward the poles or into deeper water to stay cool; those that cannot move lose their range.
- **Metabolic changes** – cold-blooded animals use energy faster in warm water, while warm water holds **less dissolved oxygen**. Fish need more oxygen just when less is available.
- **Reproductive changes** – spawning and migration timing shifts; in sea turtles, warmer sand produces more females.
- **Thermal expansion** – warm water takes up more space, which accounts for about a third of sea-level rise so far.

Coral bleaching 珊瑚白化 happens when water stays even 1–2 °C above the normal

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summer maximum for a few weeks. The corals expel the algae (zooxanthellae) living in their tissues. These algae give corals their colour *and* most of their food, so the coral turns white and starts to starve. If the water cools in time, some corals take algae back in and recover; if the heat lasts, they die.



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

Ocean Acidification

The ocean absorbs about a quarter of the CO_2 we release. Dissolved CO_2 reacts with water to form carbonic acid, which releases hydrogen ions – **ocean acidification** 海洋酸化, a fall in the ocean's pH:

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$$

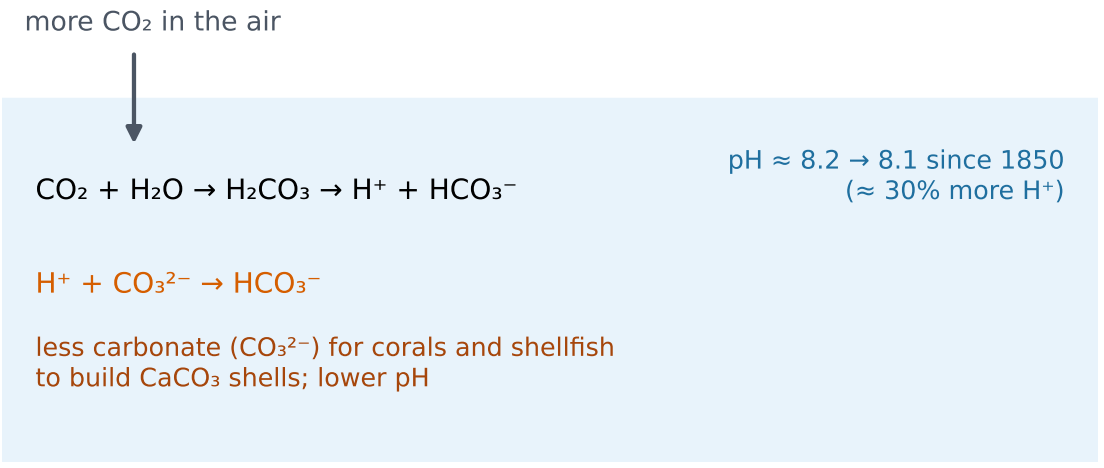
The extra H^+ ions then combine with carbonate ions that shell-builders need:

$$H^+ + CO_3^{2-} \rightarrow HCO_3^-$$

With less carbonate available, corals, oysters, clams, sea snails and some plankton find it harder to build **calcium carbonate** 碳酸钙 ($CaCO_3$) shells and skeletons, and in more acidic water existing shells can start to dissolve. Because plankton and shellfish sit near the base of marine food webs, the damage spreads upward to fish, seabirds and people who depend on fisheries.

The human activities behind ocean acidification are the same ones that raise atmospheric CO_2: **burning fossil fuels, vehicle emissions and deforestation**.

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Dissolved CO_2 produces H^+, leaving less carbonate for shells

Worked example (pH). Average ocean surface pH has fallen from about 8.2 to about 8.1 since the 1800s. The pH scale is logarithmic: each drop of 1 unit means 10 times more H^+. A drop of 0.1 means $10^{0.1} \approx 1.26$ times as much H^+ – about **26% more acidic**, even though the number changed only a little. (With the more exact values, 8.18 to 8.07, scientists quote about 30%.)

Invasive Species

An **invasive species** 入侵物种 is a non-native species that lives, and often thrives, outside its normal range and **threatens native species**. Not every introduced species is invasive – many crops and garden plants cause no harm, and some introduced species are beneficial. Invasive species are often **generalists** and **r-selected** (they mature fast and have many offspring), so with no natural predators or diseases in their new home, they outcompete natives for resources.

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Species	How it arrived	Harm
Zebra mussels	in ships' ballast water into the Great Lakes	cover native mussels, clog water-intake pipes, filter out plankton that native fish need
Asian carp	brought to fish farms in the southern US to eat algae; escaped in floods	eat huge amounts of plankton, outcompete native fish, spread up the Mississippi
Kudzu	planted in the US to control erosion	grows up to 30 cm a day and smothers trees
Burmese pythons	released or escaped pets in Florida	have eaten most of the small mammals in parts of the Everglades
Brown tree snake	stowaway on cargo planes to Guam	wiped out most of the island's native forest birds

Invasive species can be controlled through human interventions:

- **Prevention** (cheapest): inspecting cargo and luggage, laws requiring ships to exchange or treat ballast water, banning the sale of risky pets and plants, cleaning boats between lakes.
- **Early detection** and rapid removal before a population spreads.
- **Physical removal**: trapping, hunting, pulling or cutting plants, electric barriers in rivers (used against Asian carp near Chicago).
- **Biological control**: introducing a natural predator or disease from the invader's home range – which must be tested carefully, since the new species could become invasive itself (cane toads in Australia).
- **Chemical control**: herbicides and pesticides, which can also harm non-target species.

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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

Endangered Species

An **endangered species** 濒危物种 is at risk of extinction. A species is more likely to become endangered if it:

- is **extensively hunted** or poached (for meat, ivory, horn, fur, or the pet trade);
- has a **limited diet** (the giant panda and bamboo) or **specific and limited habitat** requirements (a specialist);
- is **outcompeted by invasive species**;
- has a **low reproductive rate** and large body size (K-selected – elephants, whales, rhinos).

Not every species is equally at risk when the same change hits its ecosystem. Species that can **adapt** to the change, or **move** to a new environment, are less likely to go extinct. Any factor that changes the behaviour and **fitness** (survival and reproduction) of organisms is a **selective pressure** 选择压力. Competition between species for territory, food, mates and habitat is also a selective pressure, and when resources shrink it can push the weaker competitor toward extinction.

Strategies to protect animal populations:

- **Criminalizing poaching** and enforcing the law (anti-poaching patrols, bans on ivory sales).
- **Protecting habitats** (national parks, marine reserves, wildlife refuges).
- **Legislation**: the US **Endangered Species Act** (1973) lists threatened and endangered species and protects their critical habitat; **CITES** is an international treaty that controls trade in endangered species and their products.

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- Captive breeding and reintroduction (California condors, black-footed ferrets).
- **Reducing accidental deaths**: North Atlantic right whales die mainly from ship strikes and tangling in fishing gear, so ships are made to slow down in whale areas, shipping lanes are moved, and fishing ropes are designed to break.

Worked example (percent loss). Africa had about 1.3 million elephants in 1970 and about 0.6 million in 2000.

1. Percent change $= \dfrac{0.6 - 1.3}{1.3} \times 100 \approx -54\%$.
2. So about **54%** of the elephants were lost in 30 years.

Why amphibians are declining. Amphibians are falling fast worldwide, not only from deforestation. Their thin, permeable skin absorbs pollutants such as pesticides; the fungal disease **chytridiomycosis**, spread by the international trade in frogs, has wiped out many species; and climate change dries the ponds they breed in. Because they live both in water and on land, they are exposed to problems in both.

Example – piping plovers. These small shorebirds nest on open sandy beaches. They were nearly hunted to extinction for hat feathers around 1900, recovered after a law protected them, and are now threatened again by beach development, vehicles and people on nesting beaches, and predators drawn by human food waste. Fencing nest sites and closing parts of beaches during nesting season has helped some populations grow.



A coral reef: habitat loss, warming and acidification put whole reef communities at risk of extinction

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Human Impacts on Biodiversity

Together, human pressures are driving a rapid loss of biodiversity – extinction rates are now hundreds of times the natural background rate, and some scientists call it a sixth mass extinction. The main causes are summarized as **HIPPCO**:

- **H**abitat destruction
- **I**nvasive species
- **P**opulation growth (human)
- **P**ollution
- **C**limate change
- **O**verexploitation (overhunting, overfishing, overharvesting)

A specific and heavily-tested driver is **habitat fragmentation** 栖息地破碎化: large continuous habitats are broken into smaller, isolated patches by **roads and pipelines, clearing for agriculture or development, and logging**. Fragmentation is worse than simple area loss, because the small patches cut populations off from each other, reduce genetic diversity, and expose more **edge** to predators, invasive species, wind and drying. The scale that causes harm **varies from species to species**: a road that a beetle cannot cross may mean nothing to a hawk, while a forest patch large enough for a squirrel population is far too small for a bear or a jaguar.

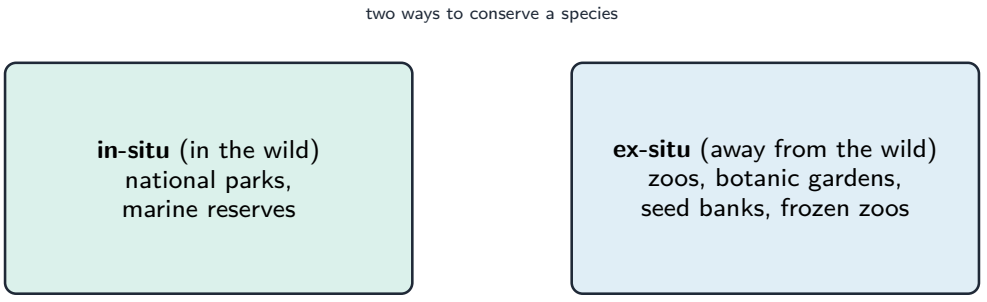
Climate change causes habitat loss through changes in temperature, precipitation and sea-level rise – for example, mountain species pushed uphill until no higher ground is left, and coastal marshes drowned by rising seas.

Domestication reduces biodiversity too. Honeybee colonies and livestock are bred for a few useful traits, so they have low genetic diversity, and one disease or pest can spread through them quickly. Managed honeybees can also outcompete wild native bees for flowers.

Ways humans can reduce biodiversity loss:

- **Creating protected areas** – national parks, wildlife refuges and marine reserves.
- **Habitat corridors** – strips of habitat, or bridges and tunnels for wildlife, that link fragments so animals can move and breed.
- **Sustainable land use** – selective logging instead of clear-cutting, agroforestry, and building housing in compact areas rather than spreading it out.
- **Restoring lost habitats** – replanting forests, restoring wetlands, removing old dams.

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In-situ and ex-situ conservation protect species

Worked example (FRQ style). *Populations of large animals such as African elephants and snow leopards are declining. Identify one human activity responsible and propose one solution.* **Activity:** habitat fragmentation from farming and road building cuts the large territories these animals need into small patches, so they cannot find enough food or mates. **Solution:** create protected areas linked by **habitat corridors**, so animals can move between patches safely; this keeps populations large enough to breed and keeps genetic variety flowing. (Poaching with an anti-poaching law is another valid pair.)

Practice

Answer each before reading the answers below.

1. Explain how CFCs destroy stratospheric ozone, and name the agreement that phased them out.
2. Methane has a global warming potential of about 28. What does that mean?
3. Write the reaction that acidifies the ocean, and explain how it affects corals and shellfish.
4. Atmospheric CO_2 rose from 280 ppm before industrialization to about 420 ppm. Calculate the percent increase.
5. Give two causes of sea-level rise.
6. Name two traits that make a species likely to become invasive.

Answers

1. UV light breaks CFCs, releasing chlorine atoms; each Cl atom catalytically breaks down thousands of ozone molecules. The Montreal Protocol (1987).
2. Over 100 years, 1 kg of methane traps about 28 times as much heat as 1 kg of CO_2.
3. $CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^-$. The extra H^+ reduces carbonate ions, so corals and shellfish struggle to build calcium carbonate shells and skeletons.

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4. $\frac{420 - 280}{280} \times 100 = 50\%$.
5. Thermal expansion of warming seawater, and melting of land ice (glaciers and ice sheets).
6. Any two: generalist; r-selected (fast reproduction); tolerant of many conditions; no predators in the new habitat.

Exam tips

- Keep **ozone depletion** (CFCs → chlorine → less ozone → more UV → skin cancer, cataracts) and **climate change** (greenhouse gases trap more heat) as **two different problems**.
- Name a natural factor in the ozone hole: **reactions on polar stratospheric cloud particles, followed by sunlight releasing active chlorine in spring**.
- HFCs do not harm ozone but **are** strong greenhouse gases.
- GWP: CFCs > nitrous oxide > methane > CO_2 (= 1). CO_2 causes the most warming because of its **quantity**. Water vapour mainly amplifies warming as a feedback; its atmospheric residence time is short.
- Explain a polar **positive feedback loop** step by step (ice melts → lower albedo → more absorption → more warming).
- **Ocean acidification**: CO_2 + water → carbonic acid → H^+ → less carbonate → weaker shells. Its causes are fossil fuels, vehicles and deforestation.
- Invasive species are often **generalist, r-selected** species with no natural predators; give a control method and its drawback.
- Summarise threats to biodiversity with **HIPPCO** (Habitat destruction, Invasive species, Population growth, Pollution, Climate change, Overexploitation).
- Solutions to biodiversity loss: protected areas, **habitat corridors**, sustainable land use, habitat restoration.

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