Unit 4

Ecology

This unit online, with its interactives:
science-playground.com/s/10a4

In July 2026, Nepal announced its latest count of wild tigers: **429**, up from 355 in 2022, in five national parks of the Tarai: Chitwan (145), Bardiya (112), Parsa (71), Banke (51) and Shuklaphanta (50). A tiger eats only meat. Yet every one of those tigers depends on grass, and on the sunlight that grass catches. Take away the tall grasslands of the Tarai, and the deer go first, then the tigers.

Why does a park with thousands of deer have only a hundred or so tigers? Why can't a food chain go on for ten or twenty steps? And what happens to the carbon, oxygen and nitrogen in a deer after the tiger has eaten it? This unit answers all three with three ideas: the **pyramids** that show the levels of an ecosystem, the one-way **flow of energy** up those levels, and the **cycles** that carry matter round and round.

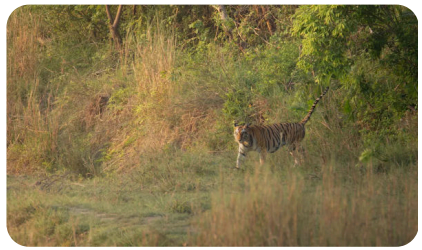


Figure 4.1 *A tiger in the tall grass of Dalla Community Forest, near Bardiya National Park. The grass feeds the deer, and the deer feed the tiger.*
Photo: Robirob4433, CC BY-SA 4.0

4.1 Biological pyramid

What a biological pyramid is

Count every living thing in a field of grass, sort them by **trophic level** (what level of the food chain they feed at), and draw each level as a bar: the producers at the bottom, the plant-eaters on top of them, the meat-eaters above. In most ecosystems each bar is narrower than the one below it, and the bars stack into a shape like a pyramid.

A **biological pyramid** (also called an **ecological pyramid**) is a diagram that shows the number of organisms, their biomass or their energy at each trophic level of a food

chain, drawn as bars one above the other, with the producers at the base and the top consumers at the apex.

The British ecologist **Charles Elton** first drew pyramids of numbers in 1927, in his book *Animal Ecology*. He had noticed, on Arctic islands and in English woods, that small animals are many and big ones few, and that the animals at the top of a food chain are always the rarest. Pyramids of numbers are still sometimes called **Eltonian pyramids** after him.

Every pyramid follows three rules:

- The **producers** are always at the base, the **primary consumers** (herbivores) on the next bar, then the **secondary** and **tertiary consumers** (carnivores and top carnivores).
- Each bar shows **one trophic level** of one ecosystem, all measured the same way, for the same area (a square meter, a hectare) or the same volume of water.
- **Decomposers** are not drawn as a bar: they feed on dead matter from every level.

There are three kinds of pyramid, by what is measured: **numbers**, **biomass** and **energy**.

Pyramid of numbers

A **pyramid of numbers** shows how many individual organisms there are at each trophic level of an ecosystem, in a given area, at a given time.

In a **grassland**, the producers are small grass plants in huge numbers. A few hundred thousand insects eat them, fewer spiders and insect-eating insects eat those, and a bird or two eat them. Each level has fewer individuals than the one below, so the pyramid is **upright**. A pond is the same: millions of tiny algae, thousands of water fleas, hundreds of small fish, a few large fish.

But a pyramid of numbers doesn’t always stand the right way up, because it counts a blade of grass and a sal tree as one each.

- In a **forest** in summer, a few big trees carry a hundred thousand or more caterpillars and other insects, which feed fewer birds. The base is narrow, the middle wide and the top narrow again: a **spindle-shaped** pyramid, inverted at the base.
- In a **parasite chain**, each feeder is smaller and more numerous than the one it lives on: one tree, a few dozen birds feeding on its fruit, thousands of lice on the birds. The pyramid of numbers is fully **inverted** (upside down).

The bars are on a ten-times scale (the key under them), so that 1 bird and 1,500,000 grass plants fit on one screen; the order of the widths, and so the shape, is the same as on an ordinary scale. The numbers for the grassland and the forest are real counts per tenth of a hectare in summer, collected by the American ecologist **Eugene Odum** (as given in OpenStax *Biology 2e*). The tree's numbers are made up, round numbers to show the shape.

Pyramid of biomass

Counting can't tell a tree from a blade of grass, but weighing can. **Biomass** is the total mass of living matter at a trophic level, usually as **dry mass** (with the water dried out) in grams per square meter, g/m^2.

A **pyramid of biomass** shows the total biomass of the organisms at each trophic level, in a given area, at a given time.

Weigh the forest instead of counting it, and the inverted pyramid of numbers turns **upright**: a few trees weigh many tonnes, far more than all the caterpillars on them. On land, pyramids of biomass are almost always upright. So are those of most rivers and lakes with large water plants: at Silver Springs, a clear river in Florida, the plants and algae weighed 809 g/m^2, the plant-eaters 37, the fish that ate them 11 and the top fish 1.5 (H. T. Odum, 1957).

In some seas and lakes, though, the pyramid of biomass is **inverted**. In the English Channel the tiny floating algae (**phytoplankton**) weighed about 4 g/m^2 and the tiny animals eating them (**zooplankton**) about 21 g/m^2. How can 4 g of food feed 21 g of animals? Because a pyramid of biomass is a **snapshot** at one moment. Phytoplankton live only a few days. They divide so fast, and are eaten so fast, that a small crop at any moment adds up to far more food over a year than the zooplankton weigh. Going Further compares this to a small tea stall: Pyramids of energy and mass.

Pyramid of energy

A snapshot can mislead, so ecologists also measure the flow. A **pyramid of energy** shows the amount of energy taken in by each trophic level, per unit area, **over a period of time**, usually in kilojoules per square meter per year (kJ/m^2 per year).

At Silver Springs the levels took in 87,100, 14,100, 1,600 and 88 kJ per square meter in a year (try **A river** under Energy in the widget). Each level takes in only part of the energy of the level below, and some of that is lost as heat at every step (4.2). So in every ecosystem, on land or in water, **a pyramid of energy is always upright**. It can never be inverted.

CAREFUL

Why energy can't be upside down

A bar on a pyramid of energy is the energy a level **took in** over a year, and all of it came from the level below. If the zooplankton took in more energy than the phytoplankton they eat, energy would be made from nothing. Numbers and biomass are counts at one moment, and a moment can catch a level small. Energy over a year can't.

The three pyramids compared

	Pyramid of numbers	Pyramid of biomass	Pyramid of energy
What it shows	individuals at each level	dry mass of living matter at each level	energy taken in by each level
Unit	number per area	g/m² (dry mass)	kJ/m² per year
Time	at one moment	at one moment	over a period (a year)
Shape	upright, spindle or inverted	upright, or inverted (some seas and lakes)	always upright
Inverted example	a tree with its insects; a parasite chain	phytoplankton and zooplankton	never
Weakness	counts a tree and a blade of grass alike	misses how fast a level grows and is eaten	hardest to measure

The pyramid of energy gives the truest picture of how an ecosystem works, because it shows the flow that everything else depends on. It is also the hardest to make: an ecologist has to measure how much each level eats, grows, breathes out and drops, through a whole year.

Check 1

A single mango tree carries about 2,000 caterpillars, which are eaten by 20 birds. The pyramid of numbers for this chain is:

a upright
b inverted at the base (spindle-shaped)
c always the same shape as the pyramid of energy
d impossible to draw

e. Describe the oxygen cycle with a labeled diagram.

f. Describe the carbon cycle with a labeled diagram.

g. Describe the nitrogen cycle with a labeled diagram. Name the bacteria involved in each step.

h. How do human activities change the carbon and nitrogen cycles?

5. Numerical problems

a. In a grassland, the producers take in 15,000 kJ/m² per year and the primary consumers 1,800 kJ/m² per year. Find the percentage of energy transferred. How much energy is lost from the producer level?

b. Basanta says a snake at level 4 of a food chain received 50 kJ, and the primary consumers below it received 20,000 kJ. Is this possible by the ten percent law? Show your working.

c. Lhamu counted the organisms in 1 m² of grassland: 600 grass shoots, 40 grasshoppers, 6 spiders and 1 lizard. (i) Draw the pyramid of numbers using 1 cm for every 50 organisms (draw any level shorter than half a centimeter as half a centimeter). (ii) If the grass stores 9,000 kJ, find the energy at each level by the ten percent law.

d. How many trophic levels can a chain support if the producers store 100,000 kJ and a population needs at least 5 kJ at its level to survive? Use the ten percent law.

Found a mistake? Please tell us.

b. The pyramid of numbers in a parasite food chain (tree → birds → lice) is:

- **a** upright
- **b** spindle-shaped
- **c** inverted
- **d** the same as the pyramid of biomass

c. In a food chain the producers store 8,000 kJ. How much energy reaches the secondary consumers?

- **a** 800 kJ
- **b** 80 kJ
- **c** 8 kJ
- **d** 0.8 kJ

d. The oxygen given off in photosynthesis comes from:

- **a** carbon dioxide
- **b** water
- **c** glucose
- **d** chlorophyll

e. The change of ammonium into nitrite and nitrate in the soil is called:

- **a** nitrogen fixation
- **b** ammonification
- **c** nitrification
- **d** denitrification

f. Which of these is a sedimentary cycle?

- **a** the nitrogen cycle
- **b** the oxygen cycle
- **c** the carbon cycle
- **d** the phosphorus cycle

2. Give reasons

a. A pyramid of energy can never be inverted.

b. Food chains usually have no more than four or five trophic levels.

c. Energy flows one way in an ecosystem, but matter goes round.

d. Nitrogen is plentiful in the air, yet plants can suffer from nitrogen shortage.

3. Differentiate between

i. Pyramid of biomass and pyramid of energy

ii. Nitrogen fixation and nitrification

iii. Nitrification and denitrification

4. Answer the following questions

a. Draw an upright and an inverted pyramid of numbers, each with an example.

b. Why is the pyramid of biomass of some seas inverted? Explain how the producers can support a greater mass of consumers.

c. State the ten percent law. Explain, with a labeled diagram, how energy is transferred through the trophic levels of an ecosystem.

d. What is a biogeochemical cycle? Why are such cycles important?

Check 2

Which pyramid can be inverted for a sea, and why?

- **a** the pyramid of energy, because sea animals are larger than the algae
- **b** the pyramid of biomass, because the phytoplankton are replaced every few days and are small at any one moment
- **c** the pyramid of energy, because the sea's producers are tiny
- **d** none: pyramids are always upright in water

4.2 Energy transfer through different trophic levels in an ecosystem

Energy comes in as sunlight

Almost every ecosystem runs on sunlight. Green plants, algae and some bacteria catch light energy in **photosynthesis** and store it as chemical energy in food. Only a small share of the light falling on them is caught: usually **1–2%**, often less. The rest is reflected, passes through, or warms the leaves and the ground.

The energy the producers store is the food for every other level. A producer uses part of it itself, in its own **respiration**, to stay alive. Only what is left, built into new leaves, stems, roots and seeds, is there for the plant-eaters.

What happens to the energy at each level

Follow 100 kJ of food eaten by a grasshopper in a paddy field. It doesn't become 100 kJ of grasshopper:

1. **Not all is digested.** Part of the food passes out in the droppings, still holding energy.
2. **Most of the rest is used up in respiration.** The grasshopper burns food to move, fly, keep its cells working and make new ones. That energy ends up as **heat**, which warms the air and is never used by a living thing again.
3. **Only a little becomes new body.** That is the only energy a frog can get by eating the grasshopper.

And a frog doesn't eat every grasshopper: some die and are eaten by decomposers instead, and some escape. So at every step only a small share of a level's energy reaches the next level. The rest leaves as heat, from the level itself or from the decomposers that feed on its dead bodies and droppings.

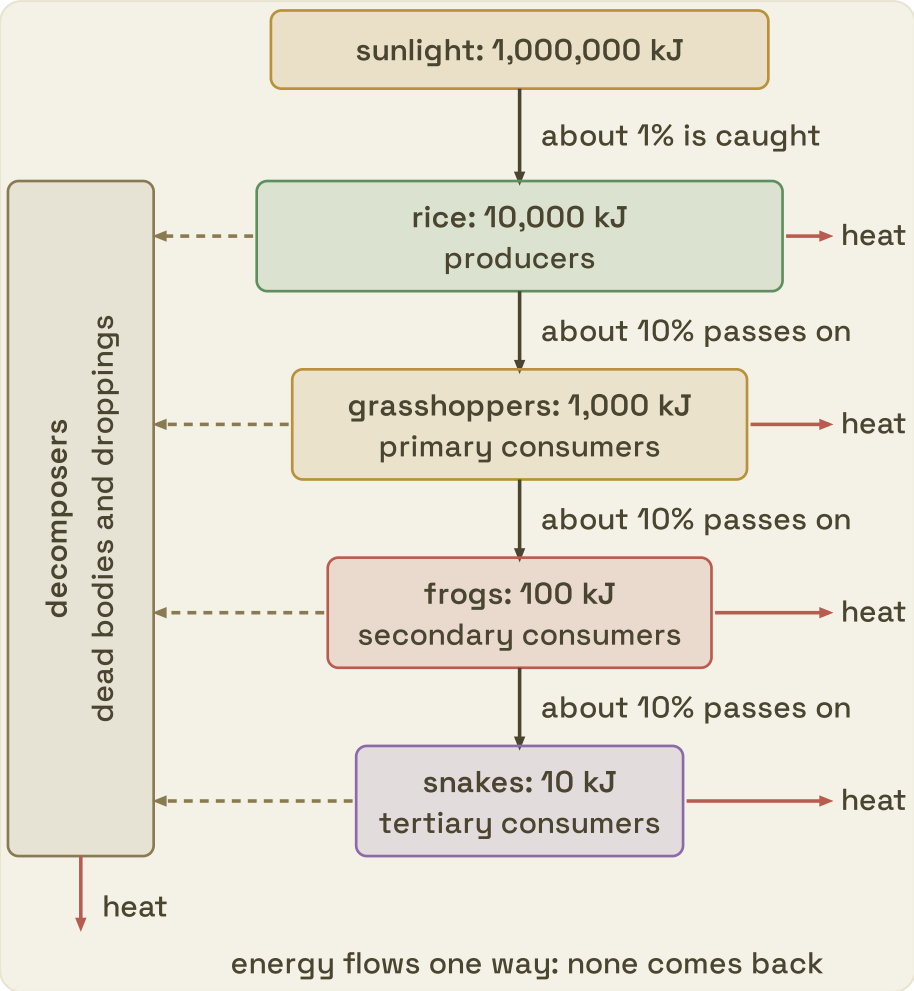


Figure 4.2 *Energy through the trophic levels of a paddy field, with the round numbers of the ten percent law. At every level most of the energy leaves as heat (right), and dead bodies and droppings go to the decomposers (left), who give it off as heat too. Not to scale.*

How the energy is shared inside one animal, the caterpillar's energy budget, is worked out in Going Further: Where the energy goes.

The ten percent law

In 1942 the American ecologist **Raymond Lindeman** published the first study of a whole lake (Cedar Bog Lake, in Minnesota, USA) as a flow of energy from level to level. From it came a rule of thumb, later called the **ten percent law**:

DID YOU KNOW?

Nepal buys all its fertilizer

Nepal doesn't make chemical fertilizer: it buys all of it from abroad, and in most years not enough of it arrives when farmers need it. In March 2026 the Ministry of Agriculture put the country's need at about **800,000 tonnes** a year, against about **500,000 tonnes** imported (Kathmandu Post, 12 March 2026). Growing lentils, beans or soybean between crops, and *Azolla* in paddy fields, puts some nitrogen into the soil for free.

CAREFUL

Fixation and nitrification are different

Students often mix them up. **Fixation** starts from nitrogen **gas** (N_2) in the air and turns it into ammonia or nitrate. **Nitrification** starts from **ammonium** already in the soil and turns it into nitrite and nitrate. Both end in useful nitrogen; only fixation brings new nitrogen in from the air.

Check 6

A farmer in Dang grows lentils after the rice harvest and finds the next rice crop needs less urea. The main reason is:

a lentils take nitrogen out of the soil
b *Rhizobium* in the lentils' root nodules fixes nitrogen from the air, and some is left in the soil
c lentils turn nitrate into nitrogen gas
d lentil roots give off oxygen

Check 7

Which bacteria turn nitrite into nitrate?

a *Rhizobium*
b *Nitrosomonas*
c *Nitrobacter*
d *Pseudomonas*

Exercise

1. Choose the correct option

a. Which pyramid is always upright?

a pyramid of numbers
b pyramid of biomass
c pyramid of energy
d all three

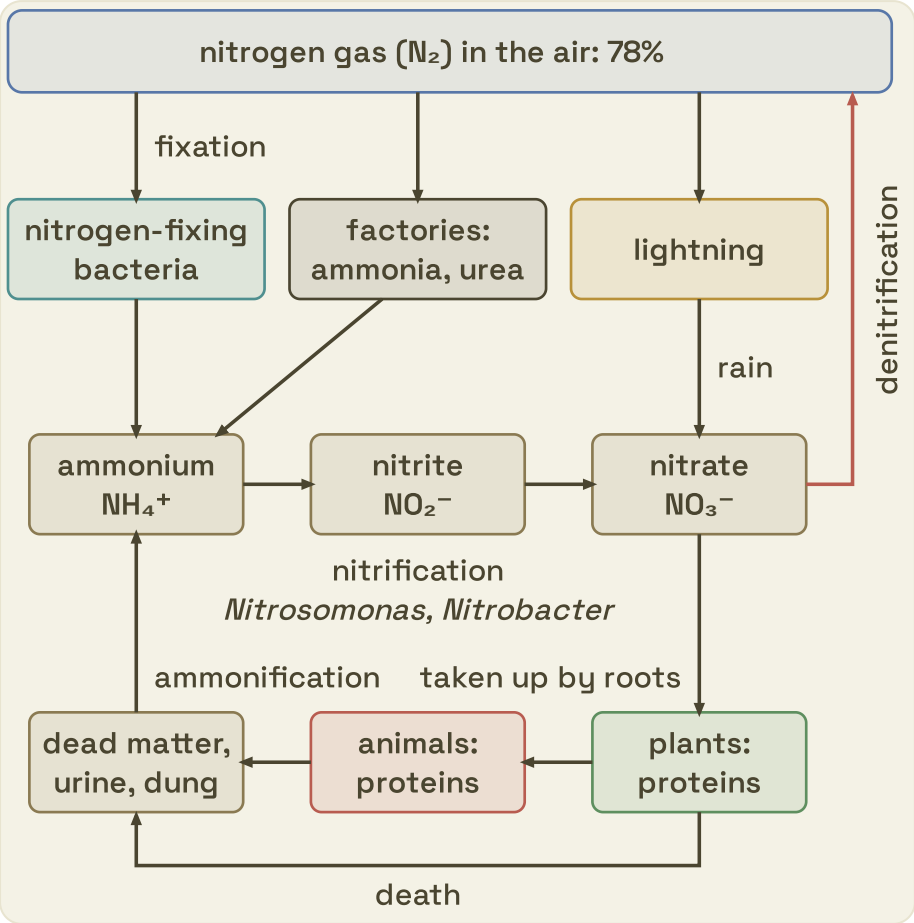


Figure 4.8 *The nitrogen cycle. Nitrogen gas is fixed by bacteria, factories and lightning; ammonium is turned into nitrite and nitrate (nitrification); roots take up nitrate and build proteins, which pass to animals; decomposers turn dead matter, urine and dung back into ammonium (ammonification); and denitrifying bacteria return nitrate to the air as nitrogen gas (denitrification).*

Ten percent law: at each step of a food chain, only about 10% of the energy of one trophic level is passed on and stored in the next; about 90% is lost, mostly as heat.

So if the producers store 10,000 kJ, the primary consumers get about 1,000 kJ, the secondary about 100 kJ and the tertiary about 10 kJ. Written as a formula, the energy at trophic level n (the producers are level 1) is

$$E_n = E_1 \times (0.1)^{n-1}$$

where E_1 is the energy stored by the producers. Going the other way, to put 1 kJ into a top consumer at level 4 the producers must store $10^3 = 1{,}000$ kJ.

Lindeman's own story, and how his paper was almost rejected, is in Pyramids of energy and mass.

CAREFUL

Ten percent is a rule of thumb

Real transfer efficiencies are anything from about 5% to 20%, depending on the animals: at Silver Springs they were about 16%, 11% and 5.5% for the three steps. Warm-blooded birds and mammals burn much more food just keeping warm, so they pass on less than insects or fish do. **In the exam, use 10% unless the question gives another figure.**

WORKED EXAMPLE

Example 1: Energy up a chain

In a paddy field, the rice stores 25,000 kJ of energy in a season. Using the ten percent law, how much energy reaches the snakes in the chain rice → grasshopper → frog → snake?

Answer

The snake is at trophic level 4, so

$$E_4 = E_1 \times (0.1)^3 = 25{,}000 \times 0.001 = 25 \text{ kJ}$$

Step by step: rice 25,000 kJ → grasshoppers 2,500 kJ → frogs 250 kJ → snakes **25 kJ**.

WORKED EXAMPLE

Example 2: Working back down the chain

An eagle at the fourth trophic level of a grassland food chain stores 12 kJ of energy. How much energy must the grass have stored, by the ten percent law?

Answer

Each step down, the energy is ten times as much: grass is three steps below the eagle.

$$E_1 = \frac{E_4}{(0.1)^3} = 12 \times 1{,}000 = 12{,}000 \text{ kJ}$$

12,000 kJ in the grass for 12 kJ in the eagle.

WORKED EXAMPLE

Example 3: Finding the efficiency

In a forest, the primary consumers take in 4,800 kJ/m² in a year and the secondary consumers take in 360 kJ/m². What percentage of energy is transferred between the two levels? Is it more or less than the ten percent law says?

Answer

$$\text{efficiency} = \frac{\text{energy at the higher level}}{\text{energy at the lower level}} \times 100\% = \frac{360}{4{,}800} \times 100\% = 7.5\%$$

7.5%, a little less than the 10% of the law. (Real efficiencies vary.)

WORKED EXAMPLE

Example 4: From the sunlight

Sunlight brings 2,000,000 kJ to a pond in a day, and the algae store 1% of it. How much of it can reach the small fish that eat water fleas, which eat the algae?

Answer

Algae: 1% of 2,000,000 = 20,000 kJ (level 1). Water fleas (level 2): 2,000 kJ. Small fish (level 3):

$$E_3 = 20{,}000 \times (0.1)^2 = 200 \text{ kJ}$$

200 kJ, one ten-thousandth of the sunlight.

4. Nitrification

Nitrification is the change of ammonium into nitrite and then into nitrate by **nitrifying bacteria**, in two steps, each done by a different kind of bacterium using oxygen:

- ***Nitrosomonas*** turns ammonium into **nitrite** (NO_2^-).
- ***Nitrobacter*** turns nitrite into **nitrate** (NO_3^-).

Both steps need oxygen, so they happen in well-aired soil. The bacteria get their energy from these reactions, and plants get nitrate, the form most of them take up best.

5. Denitrification

In waterlogged, airless soil (a flooded paddy field, a swamp, the mud of a pond), **denitrifying bacteria** such as ***Pseudomonas*** use nitrate in place of oxygen for their respiration and give off **nitrogen gas** (and a little nitrous oxide, N_2O) to the air. **Denitrification** is the change of nitrate in the soil back into nitrogen gas by denitrifying bacteria. It closes the cycle, and it is one way a waterlogged field loses its fertilizer.

Some nitrate also washes out of the soil in rainwater into streams, lakes and wells (**leaching**). Too much nitrate in a pond or lake feeds a thick growth of algae, which use up the water's oxygen when they die and rot, and fish die.

sure, giving **ammonia**:

$$N_2 + 3H_2 \rightleftharpoons 2NH_3$$

The ammonia is made into fertilizers such as **urea**, $CO(NH_2)_2$. The German chemist **Fritz Haber** won the 1918 Nobel Prize in Chemistry for it (his story).

2. Assimilation

Assimilation is the uptake of nitrate and ammonium by plant roots and their use in making amino acids, proteins, DNA and chlorophyll. Animals get their nitrogen by eating plants, or animals that ate plants: they can't use nitrate themselves (Where the nitrogen comes from).

3. Ammonification

When plants and animals die, and when animals pass urine and dung, their nitrogen is still locked in proteins and urea. **Decomposers** (bacteria such as *Bacillus*, and fungi) break these down and give off **ammonia**, which forms ammonium ions in the soil. **Ammonification** is the change of the nitrogen in dead matter, urine and dung into ammonia or ammonium by decomposers. A heap of cow dung smells of ammonia for this reason.

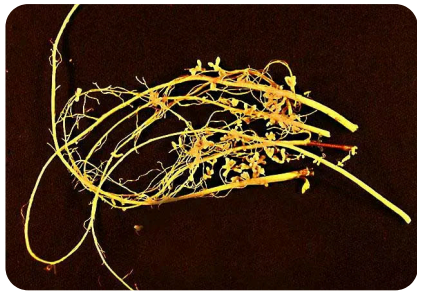


Figure 4.6 *Root nodules on a soybean plant. Each lump is full of Rhizobium bacteria fixing nitrogen from the air for the plant.*
Photo: Wikimedia Commons, Public domain

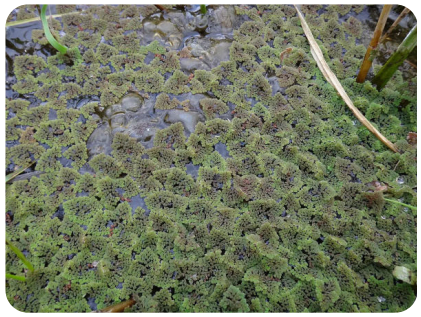


Figure 4.7 *Azolla covering the water of a rice field. The fern holds nitrogen-fixing Anabaena inside its leaves; when it dies and rots, its nitrogen feeds the rice.*
Photo: Retdar, CC BY-SA 4.0

DID YOU KNOW?

Half the world's fixed nitrogen is now made by people

A study of the world's nitrogen in 2013 (Fowler and others) estimated that about **413 million tonnes** of nitrogen are fixed each year on land and in the sea, and that about **half** of it is now fixed by human activity: fertilizer factories, the beans, soybeans and other legumes farmers grow, and the engines and fires that make nitrogen oxides. Without fertilizer from the Haber process, the world could not grow enough food for the people it has now.

What the one-way flow means

Energy flows one way. It comes in as light, passes up the levels as food, and leaves as heat. No living thing can turn heat back into food, so energy is never recycled: every ecosystem needs a steady supply of sunlight. (Matter is different: it goes round, as 4.3 shows.)

Three things follow from the ten percent law.

- **Food chains are short.** After four or five steps so little energy is left that it can't support another level of animals. Most food chains have three to five trophic levels.
- **Top carnivores are few.** In the chain grass → chital → tiger, the tiger is at the third trophic level, and tens of thousands of kilograms of grass a year stand behind every tiger. That is why Nepal's parks hold thousands of deer but only a few hundred tigers, and why a tiger needs a large area. Going Further 6–8 works out how many deer a tiger needs: Energy flows one way.
- **Eating lower in the chain feeds more people.** A field of maize eaten as maize feeds several times as many people as the same maize fed to chickens that people then eat.

DID YOU KNOW?

Where do people sit on the food chain?

In 2013, a team of French scientists worked out the average trophic level of the people of every country from what they eat. A plant-eater is at level 2 and a pure meat-eater above 3. The world's average person came out at **2.21** in 2009, up from 2.15 in 1961: about as high as an anchovy. People in countries that eat mostly rice, wheat, lentils and vegetables, as most of Nepal does, sit lower than the world's average.

Check 3

In the chain grass → grasshopper → frog → snake → hawk, the grass stores 50,000 kJ. By the ten percent law, how much energy reaches the hawk?

a 500 kJ
b 50 kJ
c 5 kJ
d 0.5 kJ

Check 4

Most of the energy that is not passed from one trophic level to the next:

a. is stored in the soil for the next season
b. goes back to the producers
c. is lost as heat, from respiration of the organisms and of the decomposers
d. is changed into matter

4.3 Biogeochemical cycle

Matter goes round

Energy passes through an ecosystem once. Matter doesn't. The carbon, oxygen, nitrogen, hydrogen, phosphorus and other elements in a living thing were in the air, water, soil or rocks before, and they go back there when it breathes out, sheds leaves, drops dung or dies. Then other living things take them up again. The same atoms have been going round for billions of years.

A **biogeochemical cycle** is the circulation of an element (or a compound such as water) between the living parts of an ecosystem (*bio*) and its non-living parts, air, water, soil and rocks (*geo*), by chemical and physical processes (*chemical*).

Each cycle has a **reservoir** (a large store where the element stays for a long time, such as nitrogen gas in the air or carbon in limestone rock) and an **exchange pool** (where it is taken up and given back quickly, such as the soil, the living things and the air near them).

The cycles are often sorted into two kinds:

- **Gaseous cycles**, whose main reservoir is the air (or the sea): the oxygen, carbon and nitrogen cycles. They are fast and balance out quickly.
- **Sedimentary cycles**, whose main reservoir is the rocks and soil: the phosphorus and sulphur cycles. They are slow; an atom can stay locked in a rock for millions of years.

Decomposers keep every cycle turning: they break dead matter and dung down into simple substances that plants can take up again. How they do it, step by step, is in Grade 9 Optional Science: The steps of decomposition.

Oxygen cycle

Oxygen makes up about 21% of the air by volume, and it is in water, in carbon dioxide, in every food and body, and in most rocks (sand is silicon dioxide). The **oxygen cycle** is the movement of oxygen between the air, water, living things and rocks.

Nitrogen cycle

Nitrogen is in every protein and in DNA. And the air is 78% nitrogen gas. Yet a wheat plant can starve for nitrogen in a field bathed in it, and so can you. Almost no living thing can use nitrogen gas: its two atoms are held by a **triple bond** (N≡N), one of the strongest bonds in chemistry. Plants take their nitrogen from the soil instead, as **nitrate** (NO_3^-) and **ammonium** (NH_4^+) ions, and animals get theirs by eating plants. The **nitrogen cycle** is the movement of nitrogen between the air, the soil, water and living things, which turns the useless gas into compounds that living things can use, and back again.

It has five steps.

1. Nitrogen fixation

Nitrogen fixation is the change of nitrogen gas from the air into compounds of nitrogen (ammonia, ammonium or nitrate) that plants can use. It happens in three ways.

Biological fixation. Some bacteria and cyanobacteria can break the triple bond, using an enzyme called **nitrogenase**, and turn nitrogen gas into ammonia:

- ***Rhizobium*** lives in the **root nodules** of legumes (beans, peas, lentils, gram, soybean, clover). The plant gives the bacteria sugar and a home; the bacteria give the plant fixed nitrogen. This is **symbiosis**, which you met in Grade 9 Science.
- **Free-living bacteria** in the soil, such as ***Azotobacter*** (which needs oxygen) and ***Clostridium*** (which lives without it), fix nitrogen on their own.
- **Cyanobacteria** (blue-green algae) such as ***Nostoc*** and ***Anabaena*** fix nitrogen in water and in wet paddy fields. *Anabaena* lives inside the leaves of a tiny floating fern, ***Azolla***, which farmers in Asia have grown in rice fields for centuries as a natural fertilizer.

Atmospheric fixation (lightning). The great heat of a lightning flash makes nitrogen and oxygen of the air join. The oxides dissolve in rain as nitric acid and reach the soil as nitrates:

$$N_2 + O_2 \xrightarrow{\text{lightning}} 2NO \qquad 2NO + O_2 \rightarrow 2NO_2$$

$$4NO_2 + 2H_2O + O_2 \rightarrow 4HNO_3$$

Lightning fixes only a small share of the world's nitrogen; bacteria and factories fix far more.

Industrial fixation. In the **Haber process**, nitrogen from the air and hydrogen are made to react over an iron catalyst at about 450 °C and about 200 times the air's pres-

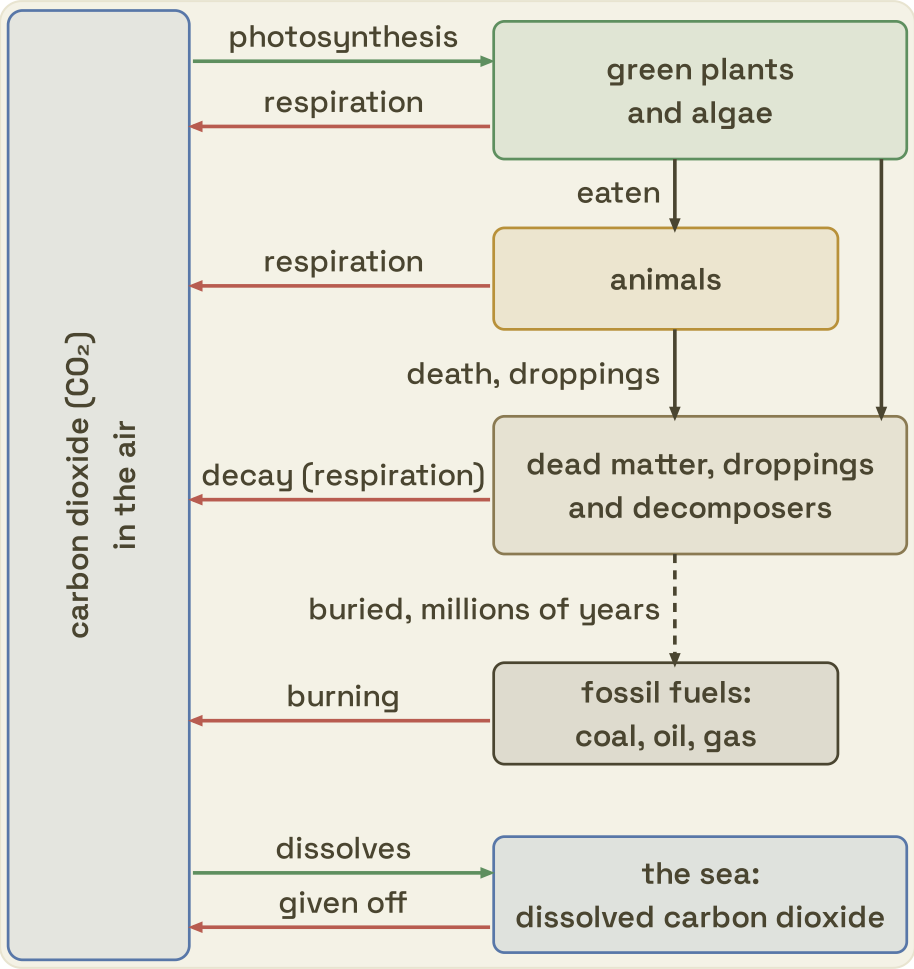


Figure 4.5 *The carbon cycle. Photosynthesis and dissolving in the sea take carbon dioxide from the air (green arrows); respiration, decay, burning and the sea give it back (red arrows). Carbon passes down the right from plants to animals to dead matter, and some dead matter, buried for millions of years, became fossil fuels.*

Check 5

In the carbon cycle, which process takes carbon out of the air?

a respiration
b combustion of fossil fuels
c photosynthesis
d decomposition

Oxygen is given to the air almost entirely by **photosynthesis**, in land plants and in the algae and cyanobacteria of the sea and fresh water:

$$6CO_2 + 6H_2O \xrightarrow[\text{chlorophyll}]{\text{sunlight}} C_6H_{12}O_6 + 6O_2$$

The oxygen given off comes from the **water**, which the plant splits using light energy, not from the carbon dioxide. (Written in full, 12 molecules of water are split and 6 are made again, $6CO_2 + 12H_2O \rightarrow C_6H_{12}O_6 + 6O_2 + 6H_2O$, so every atom of the oxygen gas can come from water.) (American scientists showed this in 1941 by giving algae water made with a rare, heavier kind of oxygen atom: the heavy oxygen came out as the gas.)

Oxygen is taken from the air by:

- **Respiration** of plants, animals and microbes, which uses oxygen to break down food and gives back carbon dioxide and water: $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O +$ energy.
- **Decay** of dead matter by aerobic decomposers, which is respiration too.
- **Burning** (combustion) of wood, cow-dung cakes, coal, petrol and LPG, for example $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$.
- **Rusting** of iron, $4Fe + 3O_2 \rightarrow 2Fe_2O_3$ (with water, as hydrated iron oxide), and the **weathering** of rocks, which slowly lock oxygen into minerals.

Water, too, carries oxygen round. Fish and other water animals breathe oxygen dissolved in water. Respiration and burning make water, and photosynthesis splits it again.

High in the air, 15 to 35 km up, the Sun's ultraviolet light splits some oxygen molecules into single atoms, which join other oxygen molecules to make **ozone**, O_3; ozone is split back by ultraviolet light. This ozone layer takes in most of the Sun's harmful ultraviolet before it reaches the ground.

$$O_2 \xrightarrow{UV} 2O \qquad O + O_2 \rightarrow O_3$$

Photosynthesis and respiration are two halves of one loop: each uses what the other makes. On the whole Earth they balance so closely that the air's oxygen has stayed near 21% for millions of years. About half of all the world's photosynthesis happens in the sea, in phytoplankton too small to see (Pyramids of energy and mass).

Carbon cycle

Carbon is the element every food and every living thing is built on (Unit 9 of this book is all about its compounds). The **carbon cycle** is the movement of carbon be-

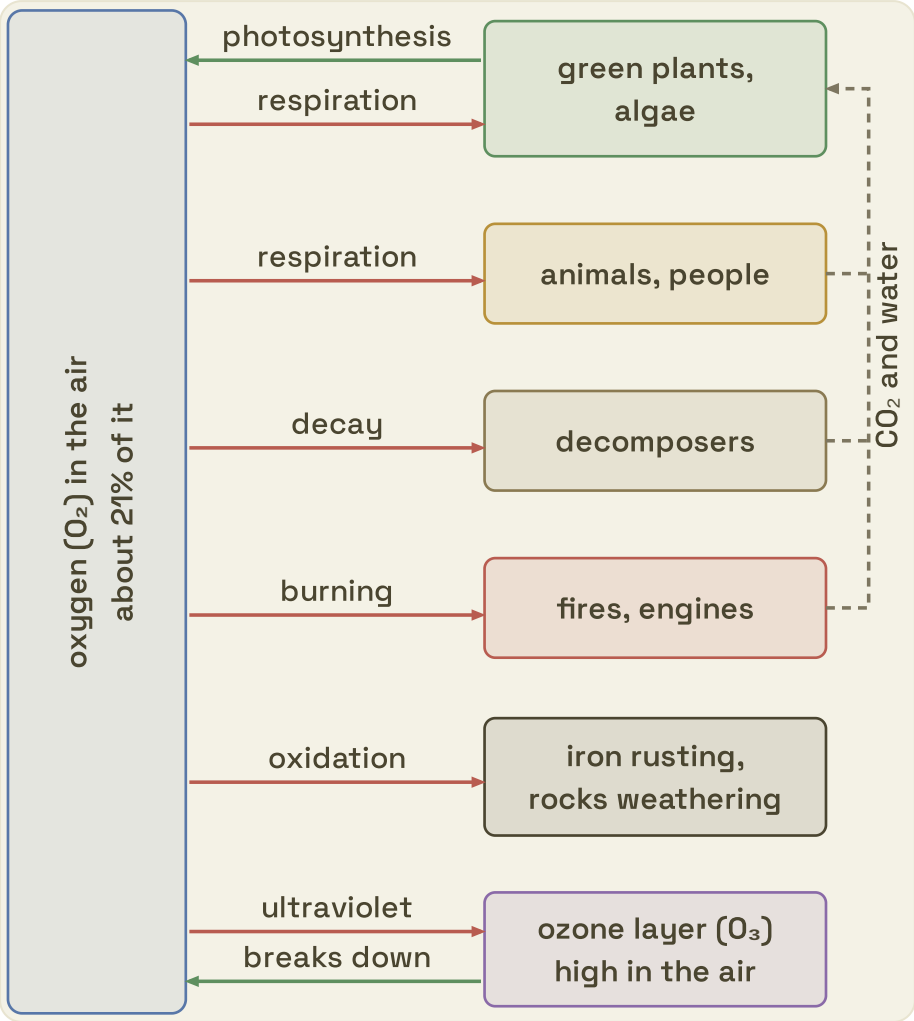


Figure 4.3 *The oxygen cycle. Photosynthesis gives oxygen to the air (green arrows); respiration, decay, burning, rusting and weathering take it from the air (red arrows). The carbon dioxide and water they make go back to the plants (dashed), and high in the air some oxygen becomes ozone and back again.*

tween the air, living things, the sea, the soil and the rocks.

In the air, carbon is in **carbon dioxide**, only about 0.04% of it. The steps of the cycle:

1. **Photosynthesis** takes carbon dioxide from the air (and from water) and builds it into sugar, then into every compound of the plant.
2. **Feeding** passes the carbon on: herbivores eat plants, carnivores eat herbivores.
3. **Respiration** by plants, animals and decomposers breaks down food and gives the carbon back to the air as carbon dioxide.
4. **Decomposition** of dead bodies, fallen leaves and dung by bacteria and fungi gives back the carbon that was not eaten.
5. **Fossil fuels.** Some dead matter, buried in mud and rock before it could decay, was turned over millions of years into **coal, oil and natural gas**. Their carbon stays locked away until they are dug up and burned.

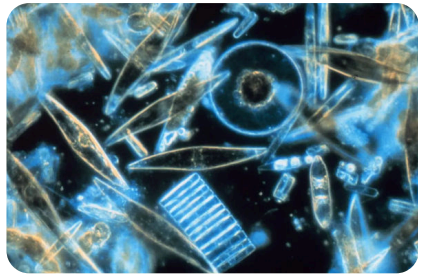


Figure 4.4 *Diatoms, one kind of phytoplankton, through a microscope. These single-celled algae, each smaller than the full stop at the end of this sentence, do a large share of the photosynthesis in the sea and in lakes.*
Photo: Prof. Gordon T. Taylor, Stony Brook University, Public domain

A STORY FROM SCIENCE

The day the air filled with oxygen

For the first half of Earth's history there was almost no oxygen in the air. Then, about **2.4 billion years ago**, oxygen made by cyanobacteria, the first living things to split water in photosynthesis, began to build up in the air. Geologists call it the **Great Oxidation Event**. The evidence is in the rocks: grains of pyrite ("fool's gold"), which oxygen soon rusts away, survive in river sands older than that, and only younger sandstones and old soils are stained red with rust. Every breath you take depends on what those bacteria started.

6. **Burning** (combustion) of wood, coal, petrol, diesel and gas gives the carbon back to the air as carbon dioxide.
7. **The sea** takes carbon dioxide in, where it dissolves, and gives it off again. Sea animals build shells of calcium carbonate; their shells pile up on the sea floor and become **limestone**, which holds the largest store of carbon on Earth.

For thousands of years before about 1800, photosynthesis and the sea took in about as much carbon dioxide as respiration, decay and fires gave out, and the air held about 280 parts per million (ppm). Burning fossil fuels puts back, in a few centuries, carbon that took millions of years to bury, and cutting forests removes some of the photosynthesis. At Mauna Loa in Hawaii, where it has been measured since 1958, the carbon dioxide in the air averaged **427 ppm in 2025** (NOAA). It traps more of the Earth's heat: The greenhouse effect, in Grade 10 Science.