Topic 1 · Foundation

1.2 Systems

Environmental Systems and Societies

Course Companion · Rutherford & Williams · Oxford 2024 · pages 16–31



Figure 2: All the air on Earth compressed into a sphere

Guiding question

How can the systems approach be used to model environmental issues at different levels of complexity and scale?

Understandings (1/4)

1. Systems are sets of interacting or interdependent components.
2. A systems approach is a holistic way of visualizing a complex set of interactions, and it can be applied to ecological or societal situations.
3. In system diagrams, storages are usually represented as rectangular boxes and flows as arrows, with the direction of each arrow indicating the direction of each flow.
4. Flows are processes that may be either transfers or transformations.
5. Systems can be open or closed.
6. The Earth is a single integrated system encompassing the biosphere, the hydrosphere, the cryosphere, the geosphere, the atmosphere and the anthroposphere.

Understandings (2/4)

7. The concept of a system can be applied at a range of scales.
8. Negative feedback loops occur when the output of a process inhibits or reverses the operation of the same process in such a way as to reduce change. They are stabilizing as they counteract deviation.
9. As an open system, an ecosystem will normally exist in a stable equilibrium, either in a steady-state equilibrium or in one developing over time (for example, succession), and will be maintained by stabilizing negative feedback loops.
10. Positive feedback loops occur when a disturbance leads to an amplification of that disturbance, destabilizing the system and driving it away from its equilibrium.

Understandings (3/4)

11. Positive feedback loops will tend to drive the system towards a tipping point.
12. Tipping points can exist within a system where a small alteration in one component can produce large overall changes, resulting in a shift in equilibrium.
13. A model is a simplified representation of reality; it can be used to understand how a system works and to predict how it will respond to change.
14. Simplification of a model involves approximation and, therefore, loss of accuracy.

Understandings (4/4)

15. Interactions between components in systems can generate emergent properties.
16. The resilience of a system, ecological or social, refers to its tendency to avoid tipping points and maintain stability.
17. Diversity and the size of storages within systems can contribute to their resilience and affect their speed of response to change (time lags).
18. Humans can affect the resilience of systems through reducing these storages and diversity.

What is a system?

Key term: A **system** is a set of inter-related parts working together to make a functioning whole.

There are a lot of key concepts involved in understanding **systems**, but it is important to understand them. After all, this course is called Environmental Systems and Societies.

You are made up of systems (e.g. digestive, nervous, skeletal and blood systems). You are also part of various systems (e.g. family, school, city, nation, the Earth) as well as your ecological, socio-economic, political and cultural systems.

Decisions about the environment are rarely based only on politics or science or economics. We may want to save the tigers, but we will be constrained by economic, societal and political systems which may alter our value systems.

The human place in the biosphere

The **biosphere** is all the parts of the Earth where life exists—all ecosystems. It includes living organisms, soil, water and air. Humans and all other organisms live within this thin layer, yet we know little about how it is regulated or self-regulates, or about the effects the human species is having on it.

The **anthroposphere** is the part of the Earth that is made or modified by humans—this includes cities, towns, roads, all our machines, mines, ports, energy networks, and land cultivated for crops and livestock. It reduces the biosphere because humans degrade land and damage habitats.

The other spheres are:

- air (**atmosphere**)
- rocks and soil (**geosphere**, which is composed of the **lithosphere** (rocks) and the **pedosphere** (soil))
- water (**hydrosphere**) and frozen water (**cryosphere**).

How much water and air does the Earth have?

Figures 1 and 2 show the comparative volumes of the Earth's water and air. Humans and all living things need both but there is not as much as you might think.

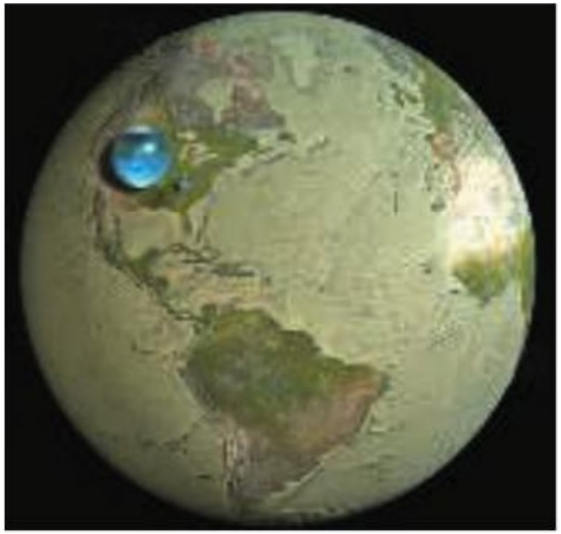


Figure 1 The Earth's water (hydrosphere) compressed into a series of spheres in comparison to the size of the Earth. The largest sphere represents all the water (in oceans, ice caps, lakes, rivers, groundwater, atmospheric water and living things). The medium-sized sphere is all the Earth's liquid freshwater. The smallest sphere is water in rivers and lakes.



Figure 2 All the air on Earth (atmosphere) compressed into a sphere. The atmosphere forms a thin layer around the Earth. Half the air is within 5 km of the surface and becomes less dense with increasing altitude.

TOK

To what extent do these images change the way you interpret the world?

Section

Systems diagrams

Storages, flows, inputs, outputs and boundaries

Systems diagrams

- **Inputs** and **outputs** to a system may be matter or energy.
- **Storages** (stores) may be living or non-living.
- **Flows** are movements of matter or energy.
- Sizes of storage boxes represent the relative sizes of the storages.

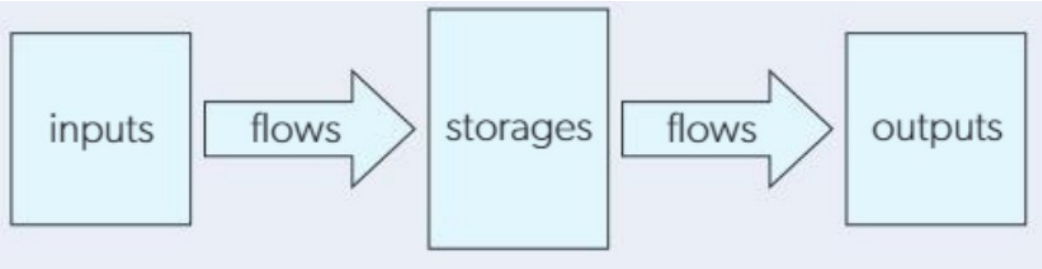


Figure 3 A general system diagram

Connections: This links to material covered in subtopics 2.4, 5.1 and 8.2.

Key to the general system diagram

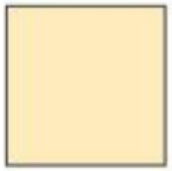
All systems have:	Represented by:
Storages or stores of matter or energy	a box or circle  
Flows into, through and out of the system	arrows  or 
Inputs	arrows in  or 
Outputs	arrows out  or 
Boundaries	lines
Processes which transfer or transform energy or matter from storage to storage	e.g. respiration, precipitation, diffusion

Figure 4 Key to the general system diagram

All systems have… / Represented by…

All systems have:	Represented by:
Storages or stores of matter or energy	a box or circle
Flows into, through and out of the system	arrows
Inputs	arrows in
Outputs	arrows out
Boundaries	lines
Processes which transfer or transform energy or matter from storage to storage	e.g. respiration, precipitation, diffusion

Activity 7

ATL skills used: thinking, communication

Using the model and key in Figures 3 and 4, draw your own systems diagram for the following systems:

- a candle
- a mobile phone
- a green plant
- a pond
- you
- your school.

Label the inputs, outputs, storages and flows.

A deciduous forest as a system

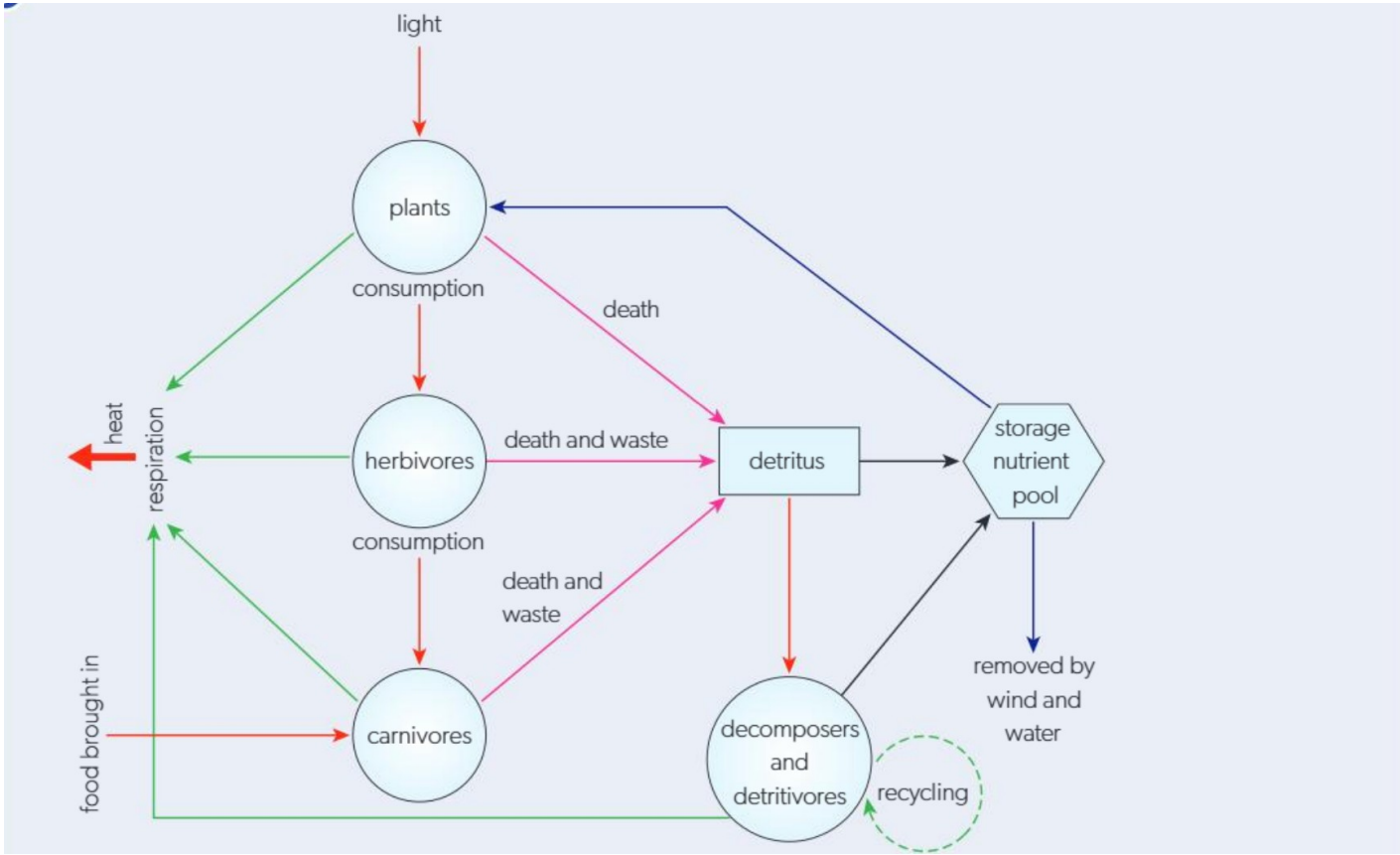


Figure 5 Energy and matter exchanges in a deciduous forest ecosystem (adapted from: Six Red Marbles and OUP)

Key words

Herbivores are animals that eat plants.

Carnivores are animals that eat other animals.

Decomposers and **detritivores** break down dead organic matter such as leaves (**detritus**) or dead animals.

Activity 8

ATL skills used: thinking, research

Study Figure 5, a systems diagram of a deciduous forest ecosystem.

1. List the storages.
2. List the flows.
3. Give three examples of plants that may be growing here.
4. Give two examples of herbivores.
5. Give two examples of carnivores.
6. Which input is brought in from outside the system?
7. How may it be brought in?
8. What flows out of the system?
9. What is the process by which it flows out?
10. What else leaves the system?

Transfers and transformations

Both matter (or material) and energy move or flow through ecosystems as **transfers** or **transformations**.

In **transfers**, the matter or energy moves from one place to another but does not change its state or chemical nature. Examples include:

- water moving from a river to the sea
- chemical energy in the form of sugars moving from a herbivore to a carnivore when a carnivore eats the herbivore
- energy in the form of heat moving in ocean currents.

Connections: This links to material covered in subtopics 2.3, 4.1 and 5.1.

Transformations

In **transformations**, the matter or energy changes state (such as liquid to gas; light to chemical energy). Examples include:

- **matter to matter** (soluble glucose converted to insoluble starch in plants)
- **energy to energy** (light converted to heat by radiating surfaces)
- **matter to energy** (burning wood)
- **energy to matter** (photosynthesis).

Both types of flow (transfers and transformations) require energy. Transfers are simpler—they require less energy and are more efficient than transformations.

Section

Open and closed systems

Open systems

Most systems are **open systems**. All ecosystems are open systems exchanging matter and energy with their environment.

Open system models can even be applied to the remotest oceanic island—energy and matter are exchanged with the atmosphere, surrounding oceans and even migratory birds.



Figure 6 A deciduous forest (deciduous trees shed their leaves each year)

Activity 9 (1/2)

ATL skills used: thinking, self-management

In the forest ecosystem, which of the following processes are transfers and which are transformations?

1. Plants fix (capture) energy from light entering the system and use it in photosynthesis to make sugars from carbon dioxide and water.
2. Soil bacteria fix nitrogen from the air into nitrates.
3. Herbivores that live within the forest may graze in adjacent ecosystems such as a grassland but when they return, they enrich the soil with faeces.



Figure 6 A deciduous forest

Activity 9 (2/2)

Transfer or transformation?

4. Forest fires expose the topsoil, which may be removed by wind and rain.
5. Mineral nutrients are leached (washed) out of the soil and transported in groundwater to streams and rivers.
6. Water is lost through evaporation and transpiration from plants.
7. Heat is exchanged with the surrounding environment across the boundaries of the forest.

Closed systems

A **closed system** exchanges energy but not matter with its environment.

System	Energy exchanged	Matter exchanged
Open	Yes	Yes
Closed	Yes	No

Table 1 The difference between open and closed systems

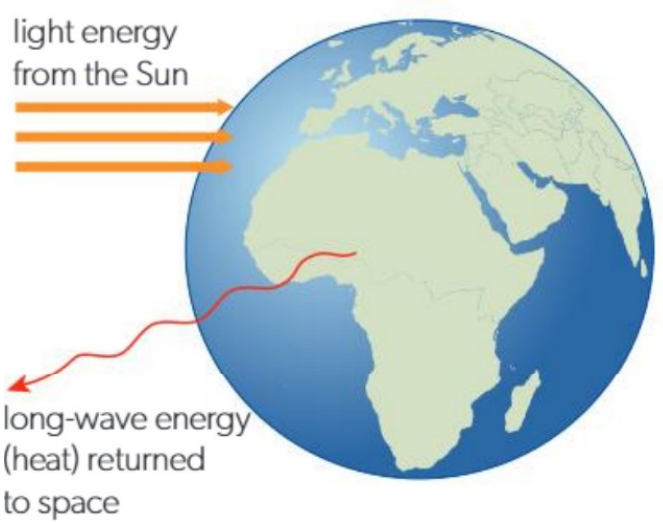


Figure 7 A closed system—the Earth

Closed systems are extremely rare in nature. No natural closed systems exist on Earth but the Earth itself can be thought of as an “almost” closed system.

The Earth: an “almost” closed system

Light energy in large amounts enters the Earth’s system and some is eventually returned to space as long-wave radiation (heat) (see Figure 7).

Because a small amount of matter is exchanged between the Earth and space, it is not truly a closed system.

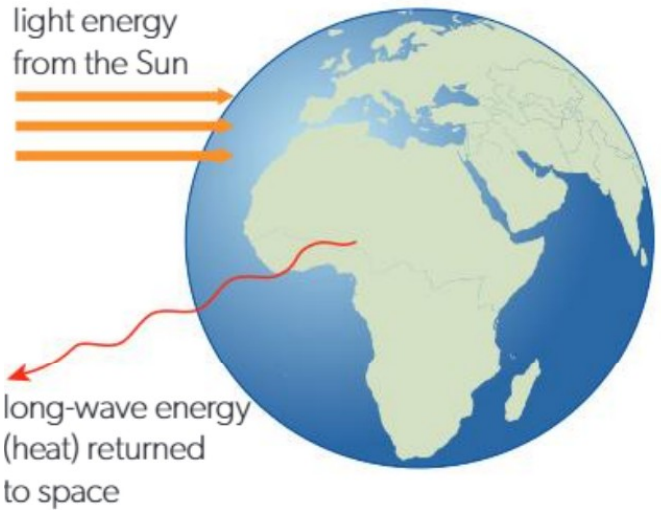


Figure 7 A closed system—the Earth

Think about it

What types of matter can you think of that enter the Earth’s atmosphere and what types leave it?

Artificial closed systems

Most examples of closed systems are artificial and are constructed for experimental purposes.

An aquarium or terrarium may be sealed so that only energy in the form of light and heat but not matter can be exchanged.

Bottle gardens or sealed terraria usually do not survive for long because the system becomes unbalanced (not in equilibrium). For example, there may not be enough oxygen or carbon dioxide for plants and animals, and the organisms die.

An example of a closed system that went wrong is **Biosphere 2** (see Case study 4). An example of a closed system that is in equilibrium is a **bottle garden** that is sealed for decades with only light entering.

Section

Equilibrium

Steady-state, stable and unstable equilibria

Equilibrium

Open systems tend to exist in a state of balance or **stable** equilibrium which avoids sudden changes. This does not mean that systems do not change, but that if change exists, it tends to exist between limits.

Key terms

A **stable** equilibrium is the condition of a system in which there is a tendency for it to return to the previous equilibrium following disturbance.

A **steady-state** equilibrium is the condition of an open system in which flows are still occurring, but inputs are constantly balanced with outputs.

Examples of a steady-state equilibrium (1)

- If a **water tank** fills at the same rate that it empties, there is no net change but the water flows in and out. It is in a steady state.
- In **economics**, a market may be stable but there are flows of capital in and out of the market.
- In **ecology**, a population of ants or any organism may stay the same size but individual organisms are born and die. If these birth and death rates are equal, there is no net change in population size.

Examples of a steady-state equilibrium (2)

- A **mature climax ecosystem**, like a forest, is in **steady-state** equilibrium with no long-term changes. It usually looks much the same for long periods of time, although all the trees and other organisms are growing, dying and being replaced by younger ones.
- There are flows in and out of the system—light inputs from the Sun; energy outputs as heat lost through respiration; matter inputs in rainwater and gases; matter outputs in salts lost in leaching and rain washing away the soil. Over years, the inputs and outputs balance.

Examples of a steady-state equilibrium (3)

- The maintenance of a constant **body temperature** is another example. We sweat to cool ourselves and shiver to warm up, but our core body temperature is about 37°C.

Maintenance of a steady-state equilibrium is achieved through **negative feedback** mechanisms (see Figure 8).

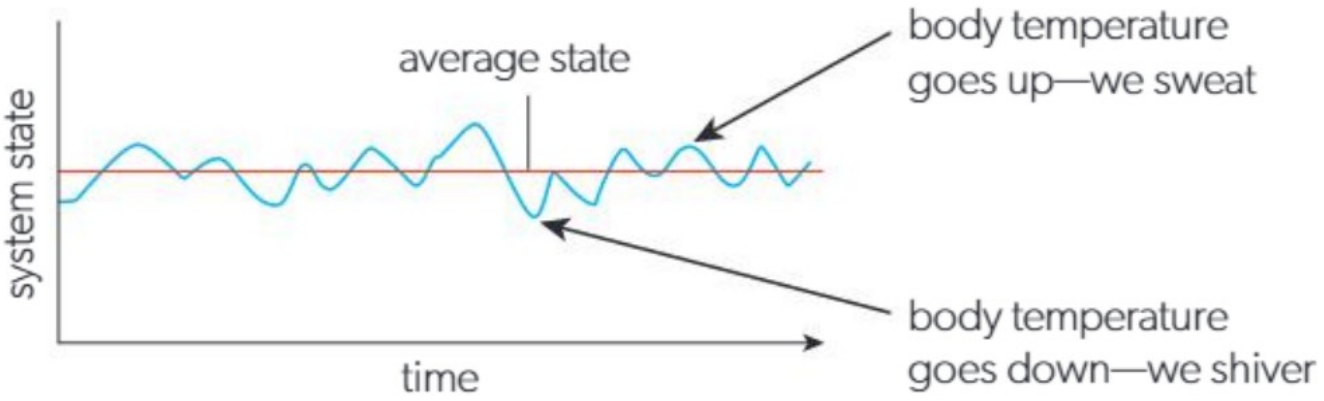


Figure 8 Steady-state equilibrium

Unstable and stable equilibria

Systems can be stable or unstable.

In a **stable equilibrium** the system tends to return to the same equilibrium after a disturbance.

In an **unstable equilibrium** the system returns to a new equilibrium after disturbance.

The differences are shown in Figure 9.

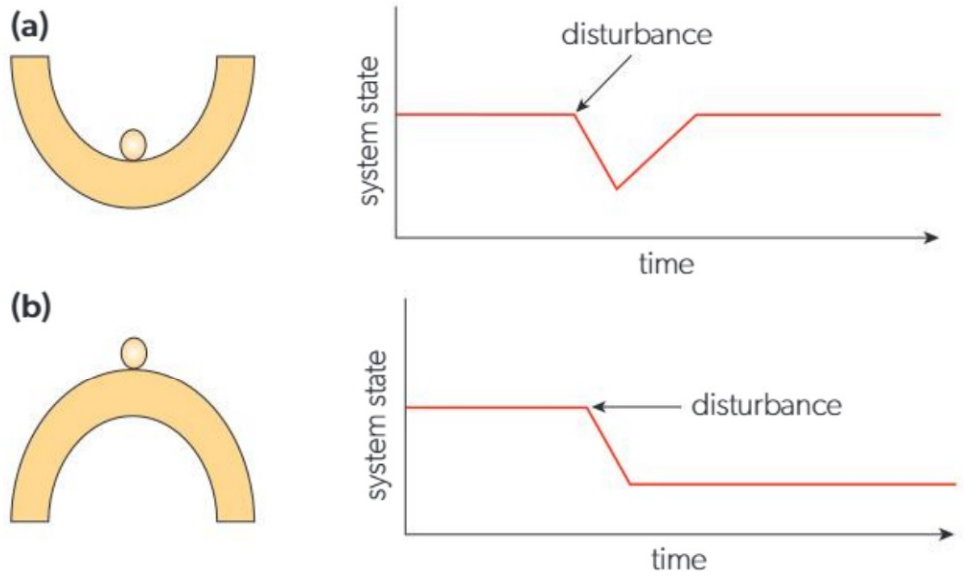


Figure 9 Diagrams of (a) stable and (b) unstable equilibria

Is the Earth's climate in an unstable equilibrium now?

Case study 4: Biosphere 2

Biosphere 2 was a prototype space city, a human attempt to create a habitable closed system on Earth.

Built in Arizona at the end of the 1980s, Biosphere 2 was a greenhouse covering three hectares and intended to explore the use of closed biospheres in space colonization.



Figure 10 Biosphere 2

Biosphere 2: two “missions”

Two major “missions” were conducted but both ran into problems.

The biosphere never managed to produce enough food to sustain the participants adequately and, at times, oxygen levels became dangerously low and needed augmenting.

The inhabitants opened the windows and doors thus making it an open system.

Biosphere 2: what happened inside

Inside Biosphere 2 were various ecosystems: a rainforest, coral reef, mangroves, savanna, desert, an agricultural area and living quarters. Electricity was generated from natural gas and the whole building was sealed off from the outside world.

For two years, eight people lived in Biosphere 2 in a first trial. But oxygen levels dropped from **21% to 14%** and of the **25 small animal species** put in, **19 became extinct**, while ants, cockroaches and katydids thrived.

Bananas grew well but there was not enough food to keep the eight people from being hungry. Oxygen levels gradually fell, and it is thought that soil microbes respired much of this. Carbon dioxide levels fluctuated widely.

Biosphere 2: the second trial and the result

A second trial started in 1994 but closed after a month when two of the team vandalized the project by opening up windows and doors to the outside.

Cooling the massive greenhouses was an issue, using three units of energy from air conditioners to cool the air for the input of every one unit of solar energy.

So, there were social, biological and technological problems with the project as the team split into factions and questions were asked as to whether this was a scientific, business or artistic venture.

The result was to show how difficult it is to make a sustainable closed system when the complexities of the component ecosystems are not fully understood. Search for Jane Poynter’s TED talk on Biosphere 2 online and watch it.

Biosphere 2: questions

1. Why do you think this project was called Biosphere 2?
2. Biosphere 2 has been described as a “closed system”. What does this mean?
3. Was it truly a closed system?
4. What type of equilibrium was reached in Biosphere 2?
5. Discuss what was learned from the Biosphere 2 experiments.
6. What does this suggest about humans’ ability to restore ecosystems once they have been destroyed?



Figure 10 Biosphere 2

Section

Feedback loops

Negative and positive feedback

Feedback loops

Systems are continually affected by information from outside and inside the system. Here are two simple examples.

1. If you start to feel cold, you can either put on more clothes or turn the heating up. The sense of cold is the information, putting on clothes or turning up the heating is the reaction.
2. If you feel hungry, you have a choice of reactions as a result of processing this information: eat food or do not eat and feel more hungry.

Key term

A **feedback loop** is when information starts a reaction that may input more information which may start another reaction.

Connections: This links to material covered in subtopics 2.1, 2.5, 3.3, 4.4, 5.2, 6.2 and 7.3.

Negative feedback

Key term

Negative feedback loops occur when the output of a process inhibits or reverses the operation of the same process in such a way as to reduce change. They stabilize the system and counteract deviation.

Examples of negative feedback

1. Your body temperature starts to rise above 37°C because you are walking in the tropical sun and the air temperature is 45°C. The sensors in your skin detect that your surface temperature is rising so you start to sweat and go red as blood flow in the capillaries under your skin increases. Your body attempts to lose heat.

Examples of negative feedback: a thermostat

2. A **thermostat** in a central heating system is a device that can sense the temperature. It switches a heating system on when the temperature decreases to a predetermined level, and off when it rises to another warmer temperature. So a room, a body or a factory can be maintained within narrow limits of temperature.

Examples of negative feedback: clouds

3. Global temperature rises causing ice caps to melt. More water in the atmosphere means more clouds. More solar radiation is reflected by the clouds so global temperatures fall.

(This is shown in Figure 11, but compare with Figure 13, which interprets the situation differently.)

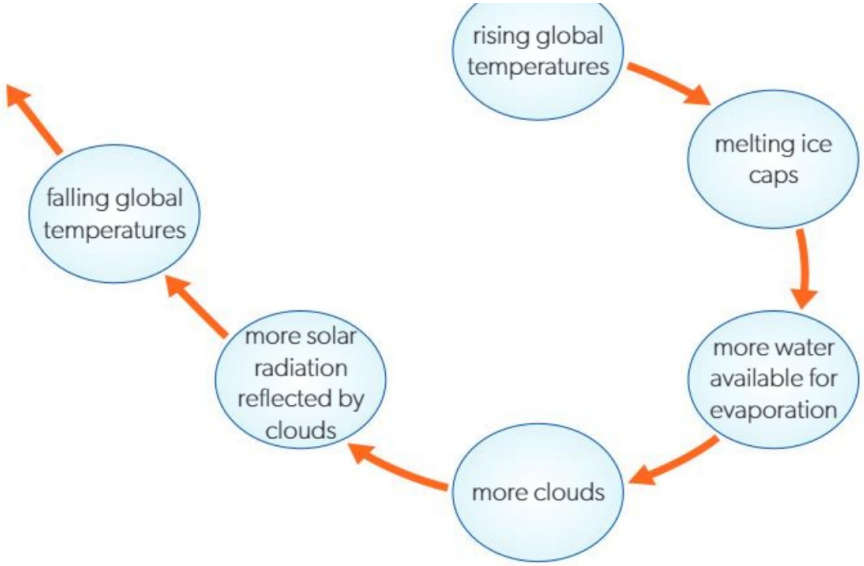


Figure 11 Negative feedback dampening change

Negative feedback: predator–prey interactions

4. **Predator–prey interactions.** The Lotka–Volterra model (proposed in 1925 and 1926) is also known as the predator–prey model and shows the effect of changing numbers of prey on predator numbers.

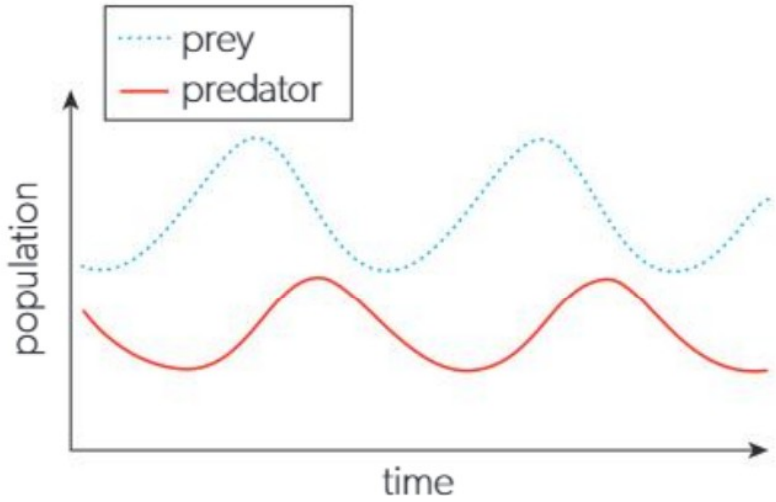


Figure 12 Cycles of predator and prey in the Lotka–Volterra model

Predator–prey: how the cycle works

When prey populations (e.g. mice) increase, there is more food for the predator (e.g. owls). The predators eat more and breed more, resulting in more predators which eat more prey so the prey numbers decrease. If there are fewer prey, there is less food, and the predator numbers decrease.

The change in number of predators lags behind the change in prey numbers (Figure 12).

The snowshoe hare and Canadian lynx is a well-documented example of this (see Data-based questions).

Negative feedback: “the balance of nature”

5. Some organisms have internal feedback systems, physiological changes occurring that prevent breeding when population densities are high, promoting breeding when they are low. It is negative feedback loops such as these that maintain “the balance of nature”.

In short

Negative feedback → reduces change → keeps the system **stable** (steady-state equilibrium).

Positive feedback

Key terms

Positive feedback loops occur when a disturbance leads to an amplification of that disturbance which destabilizes the system and drives it away from its equilibrium towards a tipping point.

A **tipping point** is the minimum change in a system that destabilizes it and shifts the regime to a new equilibrium or stable state.

Albedo is a measure of how much a surface reflects. The more reflective, the higher the albedo, measured from 0 to 1 or as a percentage.

Examples of positive feedback

1. You are lost on a high snowy mountain. When your body senses that it is cooling below 37°C, various mechanisms such as shivering attempt to raise your core body temperature again. But if these are insufficient to restore normal body temperature, your metabolic processes start to slow down, because the enzymes that control them do not work so well at lower temperatures. As a result, you become lethargic and sleepy and move around less and less, so your body cools even further. Unless you are rescued at this point, your body will reach a new equilibrium: you will die of hypothermia.

Examples of positive feedback

2. In some low-income countries (LICs), poverty causes illness and contributes to poor standards of education. In the absence of knowledge of family planning methods and hygiene, this contributes to population growth and illnesses, adding further to the causes of poverty. This is sometimes referred to as “a vicious circle of poverty”.

Examples of positive feedback

3. Global temperature rises causing ice caps to melt. Dark soil is exposed so more solar radiation is absorbed. This reduces the **albedo** (reflecting ability of a surface) of the Earth so global temperature rises.

Compare Figure 13 with Figure 11 and you can see that the same change can result in positive or negative feedback. This is one reason why predicting climate change is so difficult.

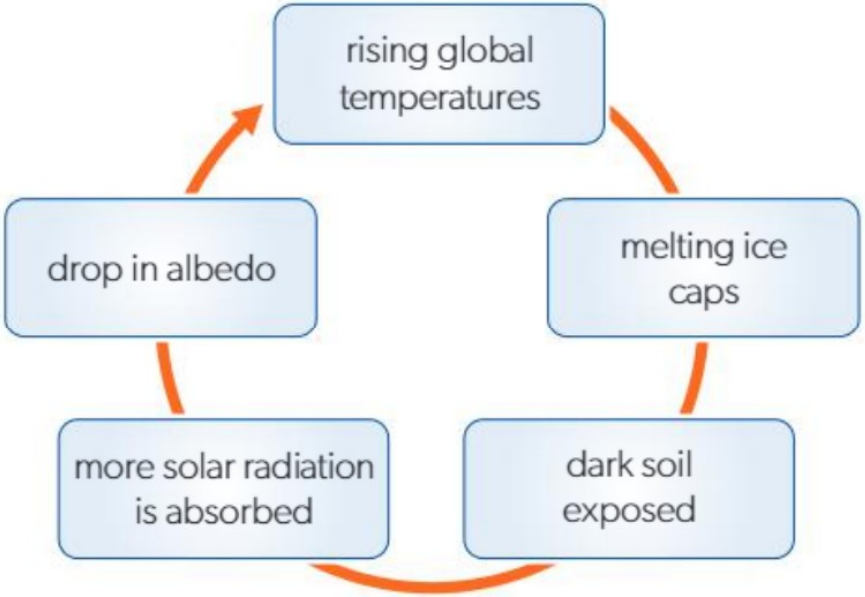


Figure 13 Positive feedback in global warming

Same change, different feedback

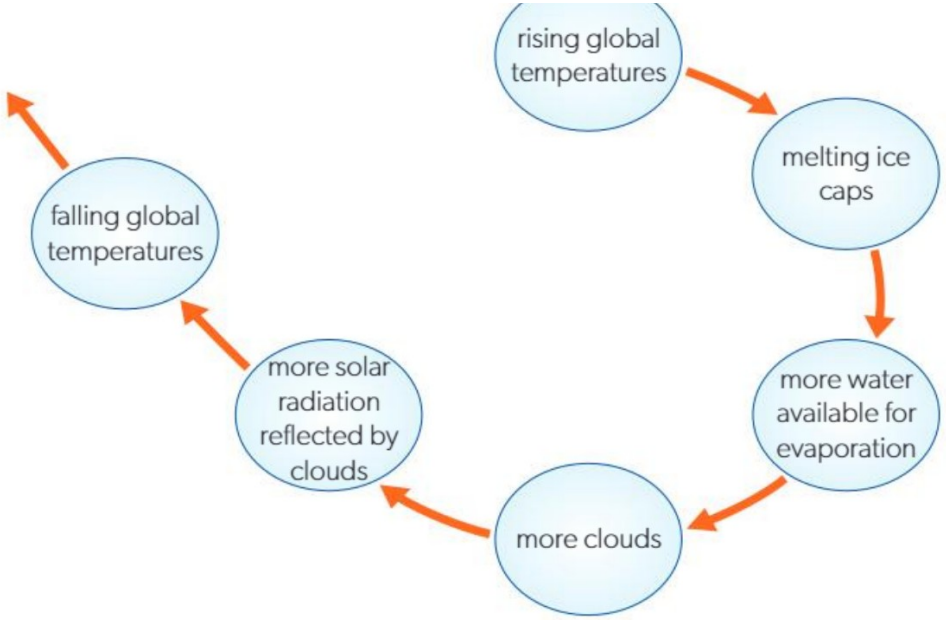


Figure 11 Negative feedback dampening change

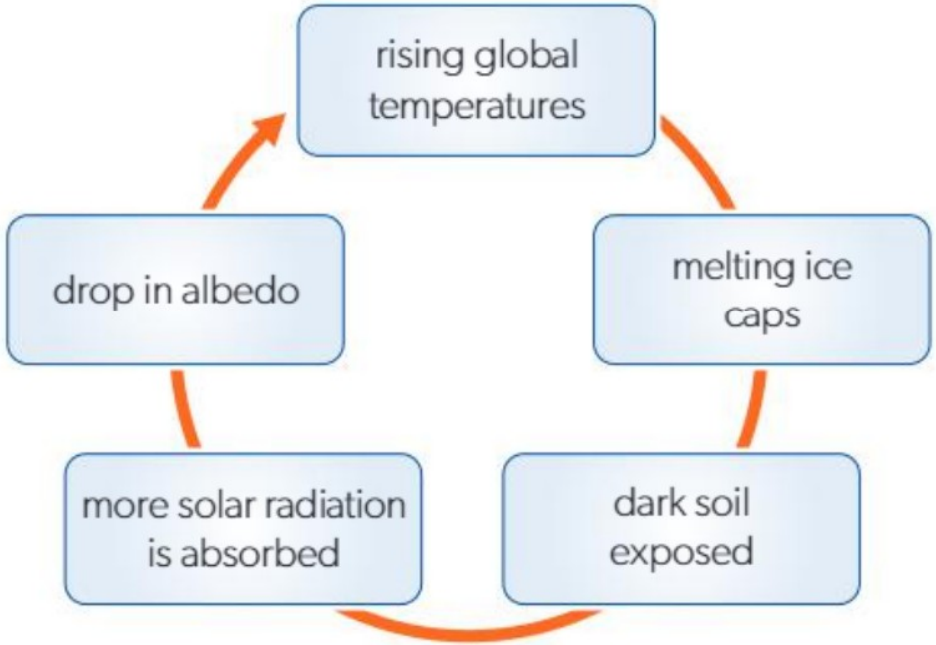


Figure 13 Positive feedback in global warming

Feedback in natural and human systems

Both natural and human systems are regulated by feedback mechanisms.

Generally, we wish to preserve the environment in its present state, so **negative feedback is usually helpful** and **positive feedback is usually undesirable**.

However, there are situations where change is needed and positive feedback is advantageous. For example, if students enjoy their Environmental Systems and Societies lessons, they want to learn more so they attend classes regularly and complete assignments. Consequently, they move to a new equilibrium of being better educated about the environment.

We shall come back to feedback loops in various sections of this book, particularly in those relating to climate change and sustainable development.

Data-based questions: predator–prey interactions

The Hudson Bay Trading Company in Northern Canada kept very careful records of pelts (skins) brought in and sold by hunters over almost a century (Figure 15).

This is a classic set of data and shows this relationship because the hare is the only prey of the lynx and the lynx is the only predator of the hare. Usually, things are more complicated.



Figure 14 Canadian lynx chasing snowshoe hare

Data-based questions: assumptions

It is assumed that the numbers of animals trapped was small compared to the total populations and that the numbers trapped were roughly proportional to total population numbers.

Also, that the prey always has enough food so does not starve.

Given that, the cycles are remarkably constant, with the lynx populations always smaller than and lagging behind the hare ones.

Snowshoe hare and Canadian lynx, 1845–1940

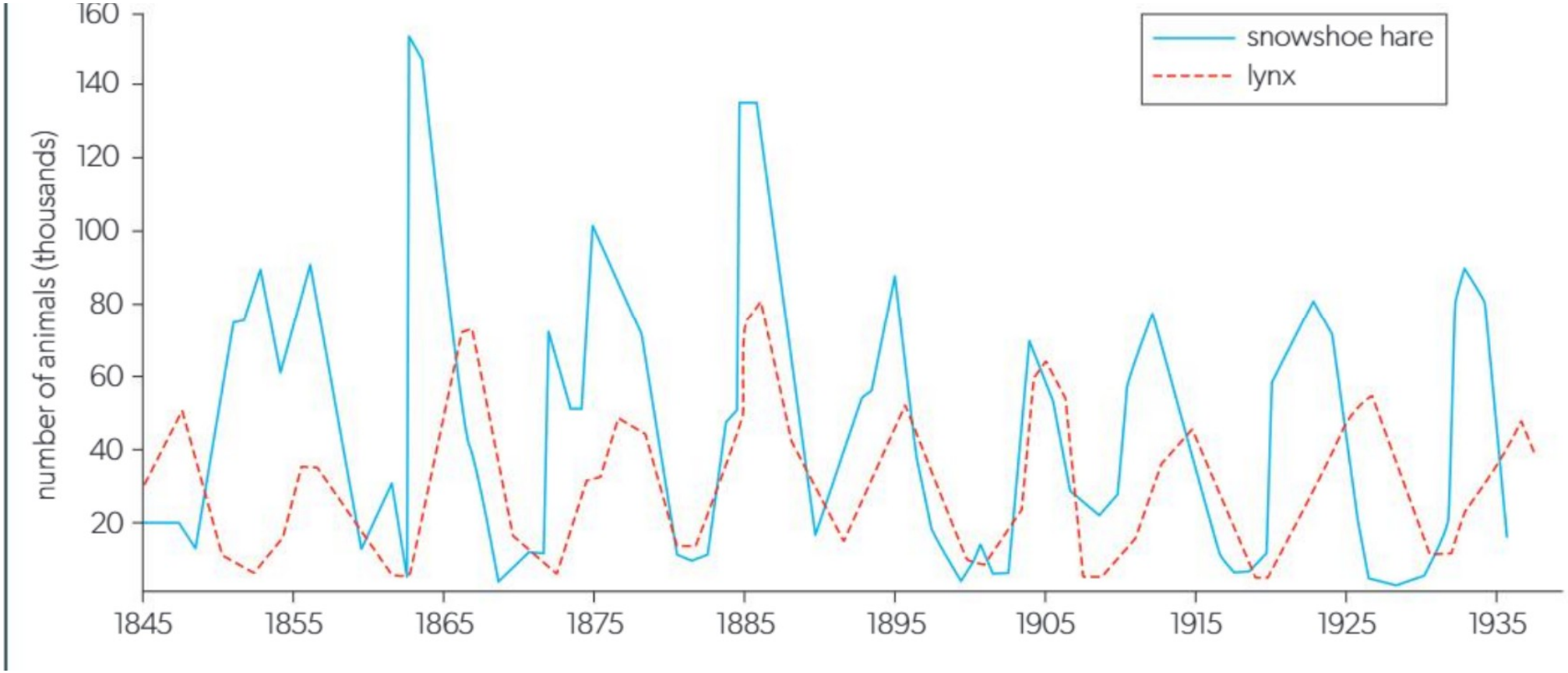


Figure 15 Snowshoe hare and Canadian lynx population numbers from 1845 to 1940 (blue line: snowshoe hare; red dashed line: lynx; y-axis: number of animals in thousands)

Data-based questions

Predator–prey interactions and negative feedback

1. On average, what was the cycle length of the lynx population?
2. On average, what was the cycle length of the hare population?
3. Why do lynx numbers lag behind hare numbers?
4. Why are lynx numbers smaller than hare numbers?
5. Things are never as straightforward in ecology as we expect, though. In regions where lynx died out, hare populations continued to fluctuate. Why do you think this was?

Activity 10: Examples of feedback

ATL skills used: thinking, research

Below are seven examples of positive and negative feedback mechanisms that might operate in the physical environment. No one can be sure which of these effects is likely to be most influential, and consequently we cannot know if the Earth will manage to regulate its temperature despite human interference with many natural processes.

- Label each of the seven examples as either positive or negative feedback.
- From the same seven examples select one example of positive feedback and one of negative feedback. Draw diagrams to show how the feedback in your selections affects the system. Include feedback loops on your diagrams.

Activity 10: examples 1–2

1. As carbon dioxide levels in the atmosphere rise:

- the temperature of the Earth rises
- as the Earth warms, the rate of photosynthesis in plants increases so more carbon dioxide is removed from the atmosphere by plants, reducing the greenhouse effect and reducing global temperatures.

2. As the Earth warms:

- ice cover melts, exposing soil or water
- albedo decreases (albedo is the fraction of light that is reflected by a body or surface)
- more energy is absorbed by the Earth's surface
- global temperature rises
- more ice melts.

Activity 10: examples 3–4

3. As the Earth warms:

- upper layers of permafrost melt, producing waterlogged soil above frozen ground
- methane gas is released in an anoxic environment
- the greenhouse effect is enhanced
- the Earth warms more, melting more permafrost.

4. As the Earth warms:

- increased evaporation of water produces more clouds
- clouds increase albedo, reflecting more light away from the Earth
- temperature falls
- rates of evaporation fall.

Activity 10: examples 5–6

5. As the Earth warms:

- organic matter in soil is decomposed faster so more carbon dioxide is released
- enhanced greenhouse effect occurs
- the Earth warms further
- rates of decomposition increase.

6. As the Earth warms:

- evaporation increases
- snowfall at high latitudes increases
- ice caps enlarge
- more energy is reflected by increased albedo of ice cover
- the Earth cools
- rates of evaporation fall.

Activity 10: example 7

7. As the Earth warms:

- polar ice caps melt releasing large numbers of icebergs into oceans
- warm ocean currents such as the Gulf stream are disrupted by additional freshwater input into oceans
- reduced transfer of energy to the poles reduces temperature at high latitudes
- ice sheets reform and icebergs retreat
- warm currents are re-established.

Your task

- Label each example as positive or negative feedback.
- Draw a feedback loop diagram for one of each.

Section

The Gaia hypothesis

A model of the Earth

The Gaia hypothesis—a model of the Earth

In the 1970s, **James Lovelock** and **Lynn Margulis** put forward the Gaia hypothesis.

They argued that the Earth and its biological systems act as a single entity which has self-regulating negative feedback loops to keep conditions on Earth within a range favourable to life.

The name “Gaia” was used because it is the name of an Ancient Greek Earth goddess.



Figure 16 An image of Gaia—Ancient Greek Earth goddess

TOK

Does this image change the way we interpret the hypothesis?

Gaia: the argument is based on these facts

- The temperature at the Earth's surface is constant even though the Sun is giving out 30% more energy than when the Earth was formed.
- The composition of the atmosphere is constant with 79% nitrogen, 21% oxygen and 0.03% carbon dioxide. Oxygen is a reactive gas and should be reacting, but it does not.
- The oceans' salinity is constant at about 3.4% but rivers washing salts into the seas should increase this.
- Despite volcanic eruptions and meteor impacts the Earth remains habitable.

DaisyWorld

After much criticism, James Lovelock and Andrew Watson developed a **DaisyWorld** as a mathematical simulation to show that feedback mechanisms can evolve from the activities of self-interested organisms—black and white daisies in this case.

Activity 11

ATL skills used: research

Search on the web for a DaisyWorld or DaisyBall computer simulation and have a go at the game.

The Revenge of Gaia

In Lovelock's book **The Revenge of Gaia**, he makes a strong case for the Earth being an "older lady" now, more than halfway through her existence as a planet and so not being able to bounce back from changes as well as she used to.

He suggests that we may be entering a phase of positive feedback when the previously stable equilibrium will become unstable—passing a tipping point—and we will shift to a new, hotter, equilibrium state.

Controversially, he suggests that the human population would survive but with a 90% reduction in numbers.

Section

Tipping points

Tipping points

Small changes occur in systems and may not make a huge difference. But when these changes tip the equilibrium over a threshold, known as a **tipping point** (Figure 17), the system may transform into a very different one. Then positive feedback loops drive the system to a new steady state.

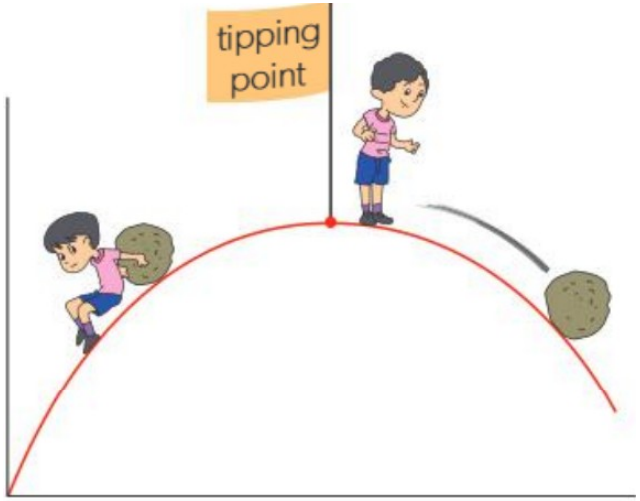


Figure 17 Illustrating a tipping point

Key term

An ecological **tipping point** is reached when an ecosystem experiences a shift to a new state in which there are significant changes to its biodiversity and the services it provides.

Characteristics of tipping points

- They involve positive feedback which makes the change self-perpetuating (for example, deforestation reduces regional rainfall, which increases fire-risk, which causes forest dieback).
- There is a threshold beyond which a fast shift of ecological states occurs.
- The threshold point cannot be precisely predicted.
- The changes are long-lasting.
- The changes are hard to reverse.
- There is a significant time lag between the pressures driving the change and the appearance of impacts, creating great difficulties in ecological management.

Examples of tipping points

1. **Lake eutrophication**—if nutrients are added to a lake ecosystem, it may not change much until enough nutrients are added to shift the lake to a new state—then plants grow excessively, light is blocked by decomposing plant material, oxygen levels fall, and animals die. The lake is described as eutrophic. It takes a great effort to restore such a lake to its previous state.

Examples of tipping points

2. **Extinction of a keystone species**—if a keystone species is lost from an ecosystem, the system may be transformed to a new state which cannot be reversed.
3. **Coral reef death**—if ocean acidity levels rise enough, reef coral dies and cannot regenerate.

Key term

Keystone species are species which have a large influence on an ecosystem relative to their population size. They are the "glue" of their ecosystem and their loss alters the ecosystem greatly. They may be animals, plants or microorganisms. Without them, the ecosystem may not exist or may exist in a very different form. Examples include elephants, sea stars, sea otters and grey wolves.

Is there a global tipping point?

Tipping points are well-known in local or regional ecosystems but there is debate about whether or not we are reaching a global tipping point. Some people say that climate change caused by human activities will force the Earth to a new, much warmer state—as much as 8°C warmer than today. But evidence is that we see warming in one region and cooling in others, wetter in some and drier in others. The global system is extremely complex and every ecosystem responds differently.

TOK

Does the use of the metaphor “tipping point” influence our perspective on this knowledge?

Tipping points and decision-makers

If there are global tipping points, there are major implications for decision-makers. Some may think that below this point not much would change but once it is reached, all is lost as society could not respond fast enough. That could lead to inaction or despair: a point of view summed up as: “What’s the point? There is nothing we can do now.”

The precautionary approach

The best approach may be the precautionary one. This means that although we do not know what will happen, we can take steps to modify what we do and so minimize risk. Such risk management is the responsible route to take.

Section

Complexity, stability and resilience

Complexity and stability

Most ecosystems are very complex. There are many feedback links, flows and storages. It is likely that a high level of complexity makes for a more stable system that can withstand stress and change better than a simple one. This may be because another pathway can take over if one is removed.

Imagine a road system where one road is blocked by a broken-down truck; vehicles can find an alternative route on other roads. If a community has a number of predators and one is wiped out by disease, the other predators will increase in number because there is more prey for them to eat. So prey numbers will not increase in these circumstances.

Simple systems are less stable

- **Tundra** ecosystems are fairly simple and populations in them may fluctuate widely (e.g. lemming population numbers).
- **Monocultures** (farming systems in which there is only one major crop) are vulnerable to the sudden spread of a pest or disease through a large area with devastating effect.
- The spread of **potato blight through Ireland in 1845–48** provides an example. Potato was the major crop grown over large areas of the island, and the cultural, biological, economic and political consequences were severe.

Resilience of systems

The **resilience** of a system measures how it responds to a disturbance.

Resilience is the ability of a system to return to its initial state after a disturbance.

If it has low resilience, it will enter a new state (see Figure 18).

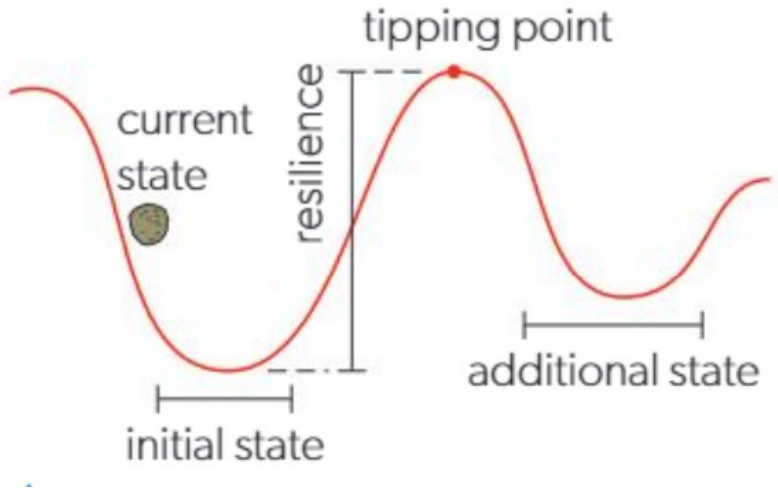


Figure 18 The more resilient a system, the more disturbance it can deal with

Resilience: a ball in a bowl

Resilience can be modelled as a **ball in a bowl**. If the ball is pushed upwards, it returns to the bottom of the bowl—its initial state. But if it is pushed enough, it will leave the bowl and settle elsewhere—in an additional state.

The higher the walls of the bowl, the more resilience the system has because the more energy you need to push it out of the bowl. See Figure 17 as well.

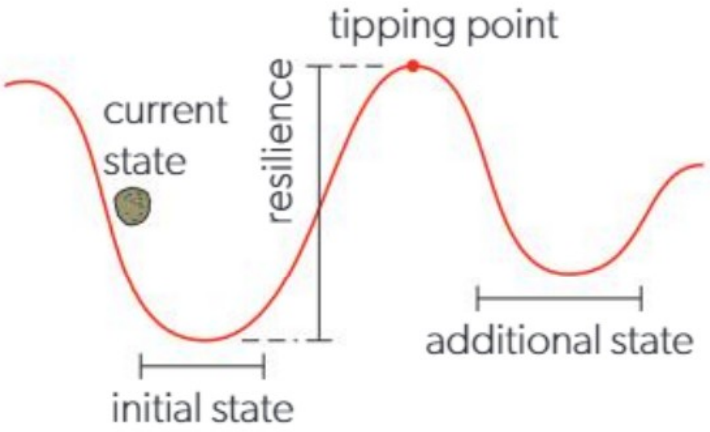


Figure 18

Resilience: eucalypt forests

Resilience is generally considered a good thing, whether in a society, individual or ecosystem, as it maintains stability of the system.

In eucalypt forests of Australia, fire is seen as a major hazard. But eucalypts have evolved to survive forest fires. Their oil is highly flammable and the trees produce a lot of litter which also burns easily.



Figure 19 Fire in a eucalypt forest in Australia

Resilience: eucalypt forests

But the trees regenerate quickly after a fire because they have buds within their trunks and plants that would have competed with them are destroyed. The eucalypts are resilient.

But when the indigenous eucalypts are replaced by tree species that cannot withstand fire, it can be devastating.



Figure 19

Is resilience always good?

In managed systems, such as agriculture, we want stability so we can predict that the amount of food grown is about the same each year. If this does not happen, there can be disastrous consequences (for example, the 1840s Irish potato famine, and the 2022 East Africa drought and famine).

But resilience is not always good

For example, a pathogenic bacterium causing a fatal disease could be very resilient to antibiotics. This would mean that it would kill many people. In this case, resilience of the bacterium to antibiotics is not good for us.

Factors affecting ecosystem resilience (1)

- The more **diverse and complex** an ecosystem, the more resilient it tends to be as there are more interactions between different species.
- The greater the **species biodiversity** of the ecosystem, the greater the likelihood that there is a species that can replace another if it dies out and so maintain the equilibrium.
- The greater the **genetic diversity** within a species, the greater the resilience. A monoculture of wheat or rice can be wiped out by a disease if none of the plants have resistance which is more likely in a diverse gene pool.
- Species that can **shift their geographical ranges** are more resilient.

Factors affecting ecosystem resilience (2)

- The **larger** the ecosystem, the more resilience as animals can find each other more easily and there is less edge-effect. For example, a lake is more resilient than a puddle.
- The **climate** affects resilience—in the Arctic, regeneration of plants is very slow as the low temperatures slow down photosynthesis and so growth. In the tropical rainforests, growth rates are fast as light, temperature and water are not limiting.
- A species that **reproduces at a faster rate** can recover more quickly. Those with a fast reproductive rate can recolonize the ecosystem faster.

Factors affecting ecosystem resilience (3): humans

- Humans can **remove or mitigate the threat** to the system (e.g. remove pollutants, reduce invasive species) and this will result in faster recovery.
- Humans can **decrease resilience** by:
  - reducing biodiversity, e.g. monoculture crops in the North American prairies
  - reducing size, e.g. making roads through ecosystems and splitting them into smaller areas
  - reducing genetic diversity, in cloning e.g. bananas (see subtopic 3.1).

Section

Emergent properties and models

Emergent properties

An **emergent property** is a property of a system but not of the individual parts of the system.

Examples of emergent properties

1. **Your face:** your eyes, ears, nose and mouth are all sensory organs but only together do they make your face what it is.
2. **Salt:** chlorine is a toxic gas and sodium is a very reactive metal. Bonded together, they make the compound sodium chloride (salt).

Examples of emergent properties

3. **Honey bees:** a honey bee colony shows division of labour in which the queen lays eggs, workers collect pollen and nectar and care for the eggs, and drones mate with the queen. Individually a bee is not a functioning colony, collectively bees are.
4. Predator–prey oscillations (see Figure 12).
5. Trophic cascades (see subtopic 2.5).

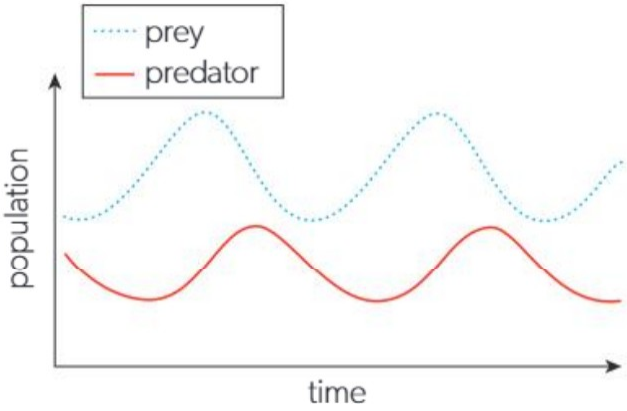


Figure 12 Predator–prey cycles

Models of systems

A **model** is a simplified version of the real thing. Humans use models to help us understand how a system works and to predict what happens if something changes. Systems work in predictable ways, following rules. But as humans, we do not always know what these rules are. A model can take many forms. It could be:

- a **physical model** (e.g. a wind tunnel or river, a globe or model of the solar system, an aquarium or a terrarium)
- a **software model** (e.g. of climate change or evolution such as DaisyWorld)
- **mathematical equations**
- **data flow diagrams**.

Connections: This links to material covered in subtopic 1.1.

Strengths of models

Models have limitations as well as strengths. They may omit some of the complexities of the real system (through lack of knowledge or for simplicity), but they enable us to predict the effects of change to the inputs of the system.

The strengths of models are that they:

- are easier to work with than complex reality
- can be used to predict the effect of a change of input
- can be applied to other similar situations
- can help us see patterns
- can be used to visualize really small things (atoms) and really large things (the solar system).

Weaknesses of models

The weaknesses of models are:

- accuracy is lost because the model is simplified
- if our assumptions are wrong, the model will be wrong
- predictions may be inaccurate.

Check your understanding: summary (1)

In this subtopic, you have covered:

- systems being: living or non-living (e.g. biological, social, economic); open (exchanging energy and matter) or closed (exchanging energy only); at any scale—small or large (a cell is a system; so are you, a bicycle, a car, a home, a pond, an ocean, a smart phone, a farm, the Earth)
- systems as sets of interacting or interdependent components which are organized to make a functioning whole
- systems having storages and flows between storages
- flows providing the inputs and outputs of energy and matter to a system and sometimes inputs are stored in storage or stock

Check your understanding: summary (2)

- material and energy undergo transfers and transformations in flowing from one storage to the next
- feedback loops may be negative (reduce change and stabilize the equilibrium) or positive (increase change and destabilize equilibrium leading to a tipping point)
- models have their limitations but can be useful in helping us to understand systems
- emergent properties are those properties of a system which are not held by its individual components
- resilience of a system is its ability to resist change or adapt to disturbance; it is reduced in lower diversity or smaller systems, and by humans who fragment ecosystems or reduce their biodiversity.

Check your understanding: questions

1. Define a system.
2. Draw an open theoretical system diagram showing storages, flows, inputs and outputs.
3. List four ecosystems in increasing order of size.
4. Explain how (a) negative and (b) positive feedback loops affect a system in terms of the equilibrium reached.
5. Describe an example of a tipping point.
6. Explain what a model is and what its advantages and disadvantages are.
7. Explain an emergent property using a named example.
8. Describe resilience of a system and explain how scale and complexity affect it.

Taking it further

- Build a bottle ecosystem, or other lab-based ecosystem (i.e. a mesocosm, terrarium, or aquarium) and use it to construct a systems diagram.
- Use your skills of system analysis to help solve a whole-school problem.
- Educate your peers about the importance of tipping points.



Figure 6 A deciduous forest