1.3 Energy and equilibria

Significant ideas

The laws of thermodynamics govern the flow of energy in a system and the ability to do work.

Systems can exist in alternative stable states or as equilibria between which there are tipping points.

Destabilizing, positive feedback mechanisms drive systems towards these tipping points, whereas stabilizing, negative feedback mechanisms resist such changes.

Big questions

As you read this section, consider the following big questions:

- What strengths and weaknesses of the systems approach and the use of models have been revealed through this topic?
- How are the issues addressed in this topic of relevance to sustainability or sustainable development?

Knowledge and understanding

- The first law of thermodynamics is the principle of conservation of energy, which states that energy in an isolated system can be transformed but cannot be created or destroyed.
- The principle of conservation of energy can be modelled by the energy transformations along food chains and energy production systems.
- The second law of thermodynamics states that the entropy of a system increases over time. Entropy is a measure of the amount of disorder in a system. An increase in entropy arising from energy transformations reduces the energy available to do work.
- The second law of thermodynamics explains the inefficiency and decrease in available energy along a food chain and energy generation systems.
- As an open system, an ecosystem will normally exist in a stable equilibrium, either a steady-state or one developing over time (e.g. succession), and maintained by stabilizing negative feedback loops.
- Negative feedback loops (stabilizing) occur when the output of a process inhibits or reverses the operation of the same process in such a way to reduce change – it counteracts deviation.
- Positive feedback loops (destabilizing) will tend to amplify changes and drive the system towards a tipping point where a new equilibrium is adopted.
- The resilience of a system, ecological or social, refers to its tendency to avoid such tipping points, and maintain stability.
- Diversity and the size of storages within systems can contribute to their resilience and affect the speed of response to change (time lags).

- Humans can affect the resilience of systems through reducing these storages and diversity.
- The delays involved in feedback loops make it difficult to predict tipping points and add to the complexity of modelling systems.

Laws of thermodynamics and environmental systems

Energy exists in a variety of forms (light, heat, chemical, electrical, and kinetic). It can be changed from one form into another but cannot be created or destroyed. Any form of energy can be converted to any other form, but heat can be converted to other forms only when there is a temperature difference. The behaviour of energy in systems is defined by the laws of thermodynamics. There are two laws, which relate to how energy moves through systems.

First law of thermodynamics

The **first law of thermodynamics** states that energy can neither be created nor destroyed: it can only change form. This means that the total energy in any system, including the entire universe, is constant and all that can happen is change in the form the energy takes. This law is known as the law of conservation of energy. In ecosystems, energy enters the system in the form of sunlight, is converted into biomass via photosynthesis, passes along food chains as biomass, is consumed, and ultimately leaves the ecosystem in the form of heat. No new energy has been created – it has simply been transformed and passed from one form to another (Figure 1.13). Heat is released because of the inefficient transfer of energy (as in all other systems).

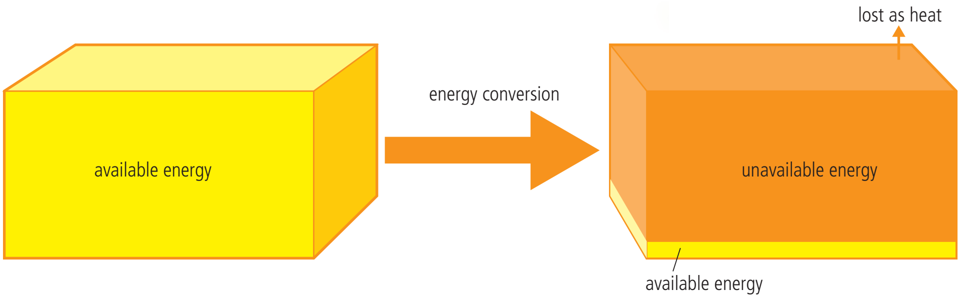

Figure 1.13 Energy cannot be created or destroyed: it can only be changed from one form into another. The total energy in any system is constant, only the form can change.

Available energy is used to do work such as growth, movement, and the assembly of complex molecules. Although the total amount of energy in a system does not change, the amount of available energy does (Figure 1.13).

The available energy in a system is reduced through inefficient energy conversions. The total amount of energy remains the same, but less is available for work. An increasing quantity of unusable energy is lost from the system as heat (which cannot be recycled into useable energy).

Second law of thermodynamics

The transformation and transfer of energy is not 100 per cent efficient: in any energy conversion there is less usable energy at the end of the process than at the beginning (Figure 1.15). This means there is a dissipation of energy which is then not available for work. The **second law of thermodynamics** states that energy goes from a concentrated form (e.g. the Sun) into a dispersed form (ultimately heat): the availability of energy to do work therefore decreases and the system becomes increasingly disordered.

The first law of thermodynamics concerns the conservation of energy (i.e. energy can be neither created nor destroyed); whereas the second law explains that energy is lost from systems when work is done, bringing about disorder (entropy).

The first law of thermodynamics explains how some of the energy entering an ecosystem is lost as heat energy, because energy entering must equal energy remaining in the system plus energy leaving the system. The second law of thermodynamics explains how energy transformations in living systems can lead to loss of energy from the system. The order in living systems is only maintained by constant input of new energy from the Sun.

Entropy is a measure of the amount of disorder in a system. An increase in entropy arising from energy transformations reduces the energy available to do work.

TOK

The laws of thermodynamics are examples of scientific laws. In what ways do scientific laws differ from the laws of human science subjects, such as economics?

You need to be able to explain the implications of the laws of thermodynamics to ecological systems.

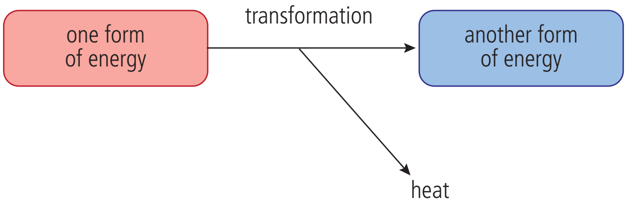

Figure 1.14 The second law of thermodynamics states that energy is converted into heat when energy is transformed from one form to another.

Energy is needed to create order (e.g. to hold complex molecules together). The second law states that the disorder in a system increases over time. Disorder in a system is called **entropy**. An increase in entropy arising from energy transformations reduces the energy available to do work. Therefore, as less energy becomes available, disorder (entropy) increases. In any isolated system, where there is no new input of energy, entropy tends to increase spontaneously. The universe can be seen as an isolated system in which entropy is steadily increasing so eventually, in billions of years' time, no available energy will be present.

The laws of thermodynamics and environmental systems

Natural systems can never actually be isolated because there must always be an input of energy for work (to replace energy that is dissipated). The maintenance of order in living systems requires a constant input of energy to replace available energy lost through inefficient transfers. Although matter can be recycled, energy cannot, and once available energy has been lost from a system in the form of heat energy it cannot be made available again.

One way energy enters an ecosystem is as sunlight energy. This sunlight energy is then changed into biomass by photosynthesis: this process captures sunlight energy and transforms it into chemical energy. Chemical energy in producers is passed along food chains as biomass, or transformed into heat during respiration. Available energy is used to do work such as growth, movement, and making complex molecules. As we know from the second law of thermodynamics, the transfer and transformation of energy is inefficient with all energy ultimately being lost into the environment as heat. This is why food chains tend to be short.

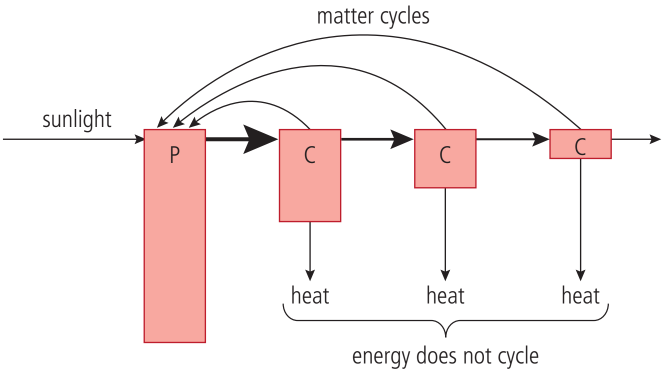

Figure 1.15 Energy flow through a food chain; P = producers, C = consumers. The boxes show energy available to do work at each feeding level. Energy decreases through the food chain as some is converted to heat. The '10 per cent rule' indicates that on average only around 10 per cent of the available energy is passed on to the next trophic level.

The nature of equilibria

Open systems tend to have a state of balance among the components of a system – they are in a state of **equilibrium**. This means that although there may be slight fluctuations in the system, there are no sudden changes and the fluctuations tend to be between closely defined limits. Equilibrium allows systems to return to an original state following disturbance. Two different types of equilibrium are discussed below.

Steady-state equilibrium

A **steady-state equilibrium** is the common property of most open systems in nature. Despite constant inputs and outputs of energy and matter, the overall stability of the system remains. In steady-state equilibrium there are no changes over the longer term, but there may be oscillations in the very short term. Fluctuations in the system are around a fixed level and deviation above or below results in a return towards this average state (Figure 1.16).

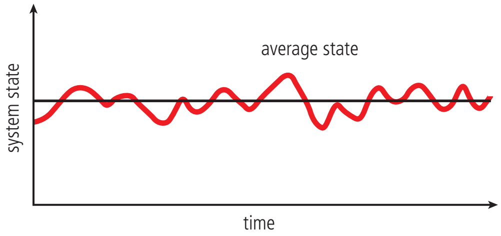

Figure 1.16 The conditions of an open system fluctuate around an average state in steady-state equilibrium.

There is a tendency in natural systems for the equilibrium to return after disturbance, but some systems (e.g. succession) may undergo long-term changes to their equilibrium until reaching a steady-state equilibrium with the climax community (Chapter 2, pages 118–119).

A steady-state equilibrium is the condition of an open system in which there are no changes over the longer term, but in which there may be oscillations in the very short term.

The stability of steady-state equilibrium means that the system can return to the steady state following disturbance. For example, the death of a canopy tree in the rainforest leaves a gap in the canopy, which eventually closes again through the process of succession (page 32 and Chapter 2, pages 114–115). Homeostatic mechanisms in animals maintain body conditions at a steady state – a move away from the steady state results in a return to the equilibrium (for example, temperature control in humans – see page 31). (You may come across the term ‘dynamic equilibrium’ to describe this phenomenon, but it is not used in this course.)

Static equilibrium

In **static equilibrium**, there are no inputs or outputs of matter or energy and no change in the system over time (Figure 1.17).

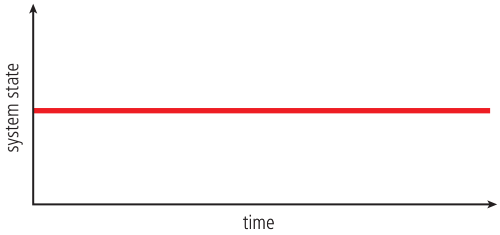

Figure 1.17 Static equilibrium

Inanimate objects such as a chair or table are in static equilibrium. No natural systems are in static equilibrium because all have inputs and outputs of energy and matter.

Most open systems have steady-state equilibrium, where any change to a stable system results in a return to the original equilibrium after the disturbance. Negative feedback (page 31) mechanisms return the system to the original state. This is because there are inputs and outputs of energy and matter to the system that allow this to happen. Static equilibrium is when there is no input or output from the system, and no change occurs; this does not apply to any natural system.

Stable and unstable equilibrium

If a system returns to the original equilibrium after a disturbance, it is a **stable equilibrium** (Figure 1.18a and b). A system that does not return to the same equilibrium but forms a new equilibrium is an **unstable equilibrium** (Figure 1.19a and b). Positive feedback mechanisms (see below) can lead to a system moving away from its original equilibrium.

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.

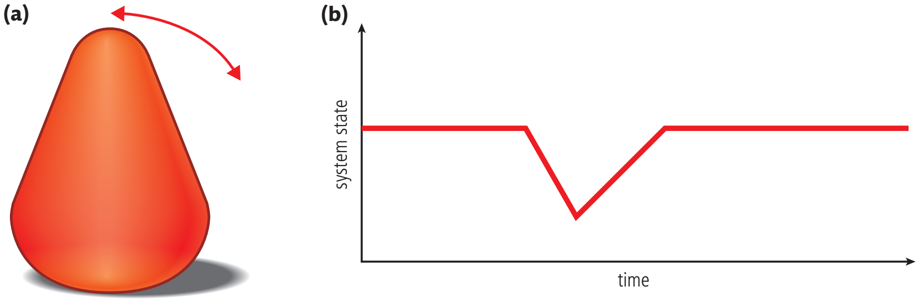

Figure 1.18 (a) Disturbance to the system results in it returning to its original equilibrium. (b) Immediately following disturbance, conditions may be very different in the system, but eventually return to the original equilibrium.

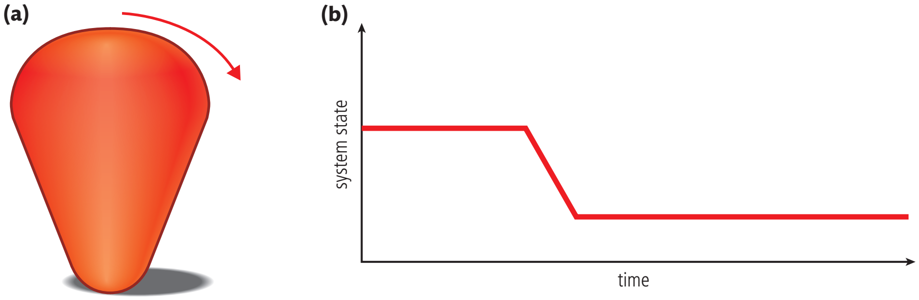

Figure 1.19 (a) Disturbance results in a new equilibrium very different from the first (in this case the object lying horizontally rather than standing vertically). (b) Scientists believe that the Earth's climate may reach a new equilibrium following the effects of global warming, with conditions on the planet dramatically altered.

Positive and negative feedback

Homeostatic systems in animals require **feedback** mechanisms to return them to their original steady state. This is also true of all other systems. Such mechanisms allow systems to self-regulate (Figure 1.20). Feedback loops can be positive or negative.

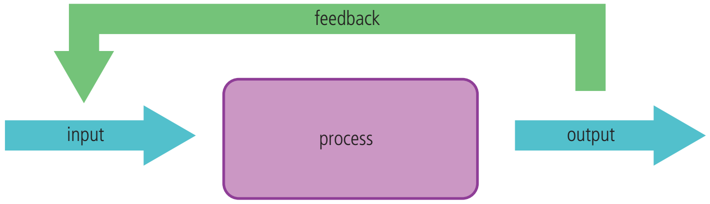

Figure 1.20 Changes to the processes in a system lead to changes in the level of output. This feeds back to affect the level of input.

Positive feedback

Positive feedback occurs when a change in the state of a system leads to additional and increased change. Thus, an increase in the size of one or more of the system's outputs feeds back into the system and results in self-sustained change that alters the state of a system away from its original equilibrium towards instability (Figure 1.21). For example, increased temperature through global warming melts more of the ice in the polar ice caps and glaciers, leading to a decrease in the Earth's **albedo** (reflection from the Earth's surface) – the Earth absorbs more of the Sun's energy which makes the temperature increase even more, melting more ice (Chapter 7, pages 377–378). Exponential population growth is also an example of positive feedback.

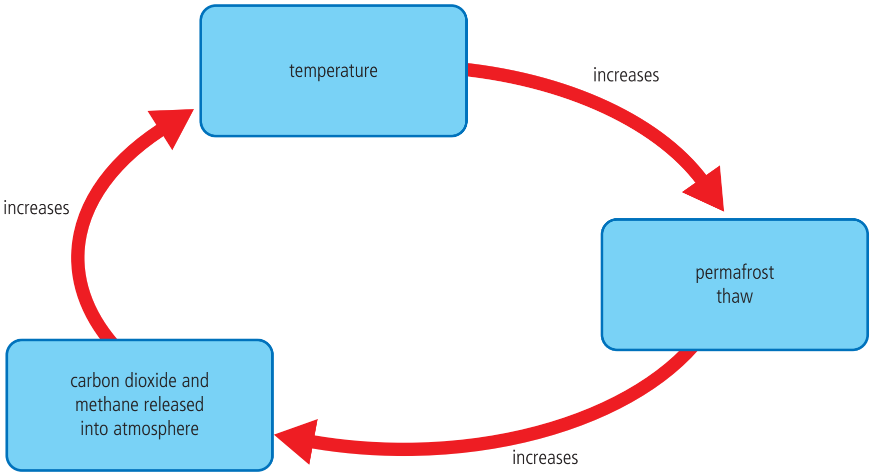

Figure 1.21 A positive feedback mechanism enhancing climate change. Such mechanisms are often linked to tipping points, when the system becomes unstable and forms a new equilibrium.

Case study

Humans, resources, and space

Human population is growing at an ever-increasing rate – more people on the planet produce more children (positive feedback) and the rate will continue to increase as long as there are sufficient resources available to support the population. Human population is growing exponentially, which means that growth rate is proportional to its present size.

Some 2000 years ago, the Earth's population was about 300 million people. In 2015, it was 7.3 billion. It took the human population thousands of years to reach 1 billion, which it did in 1804. However, it took only 123 years to double to 2 billion in 1927. The population doubled again to 4 billion in 1974 (after only 47 years), and if it continues at the current rate it will reach 8 billion in 2028. Doubling from the 2015 figure of 7.3 billion to 14.6 billion will have a much greater impact than any previous doubling because of the increased gap between the potential food supply (arithmetic growth) and population size (geometric growth).

Negative feedback

Negative feedback can be defined as feedback that counteracts any change away from equilibrium, contributing to stability. Negative feedback is a method of control that regulates itself. An ecosystem, for example, normally exists in a stable equilibrium, either a steady-state equilibrium or one developing over time (e.g. succession, page 114), because it is maintained by stabilizing negative feedback loops. Steady-state equilibrium in the human body is also maintained by negative feedback. For example, in temperature control, an increase in the temperature of the body results in increased sweat release and vasodilation, thus increasing evaporation of sweat from the skin, cooling the body and returning it to its original equilibrium. On a larger scale, increased release of carbon dioxide through the burning of fossil fuels leads to enhanced plant growth through increased photosynthesis. This reduces atmospheric levels of carbon dioxide. Negative feedback mechanisms are stabilizing forces within systems. They counteract deviation. Consider Figure 1.22: if high winds blow down a tree in the rainforest, a gap is left in the canopy and more light is let in to the forest floor. This encourages new growth: rates of growth are rapid as light levels are high, so new saplings compete to take the place of the old tree in the canopy and equilibrium is restored. In this way, negative feedback and succession (page 114) have closed the gap.

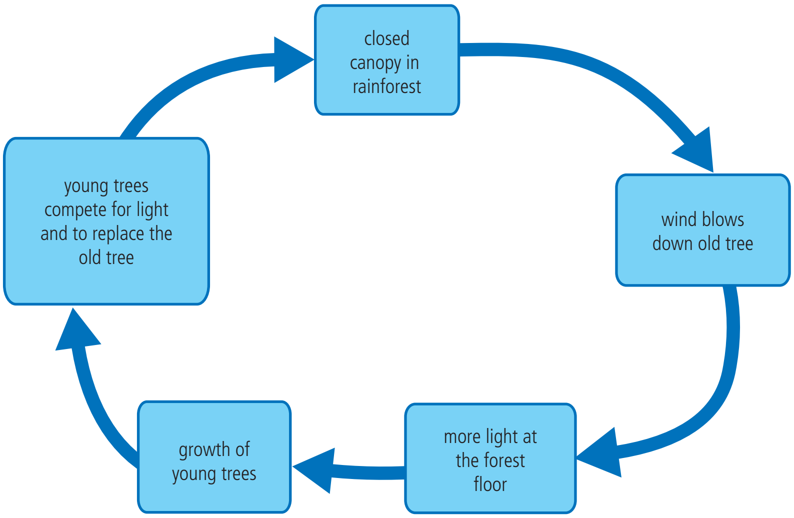

Figure 1.22 Negative feedback can lead to steady-state equilibrium in a rainforest. Gaps in the forest canopy are closed when young trees compete for light and replace the old tree.

Predator–prey relationships are another example of negative feedback (page 66).

Feedback refers to the return of part of the output from a system as input, so as to affect succeeding outputs. There are two type of feedback.

- **Negative feedback tends to reduce, neutralize, or counteract any deviation from an equilibrium, and promotes stability.**
- **Positive feedback amplifies or increases change; it leads to exponential deviation away from an equilibrium.**

A system may contain both negative and positive feedback loops resulting in different effects within the system (Figure 1.23).

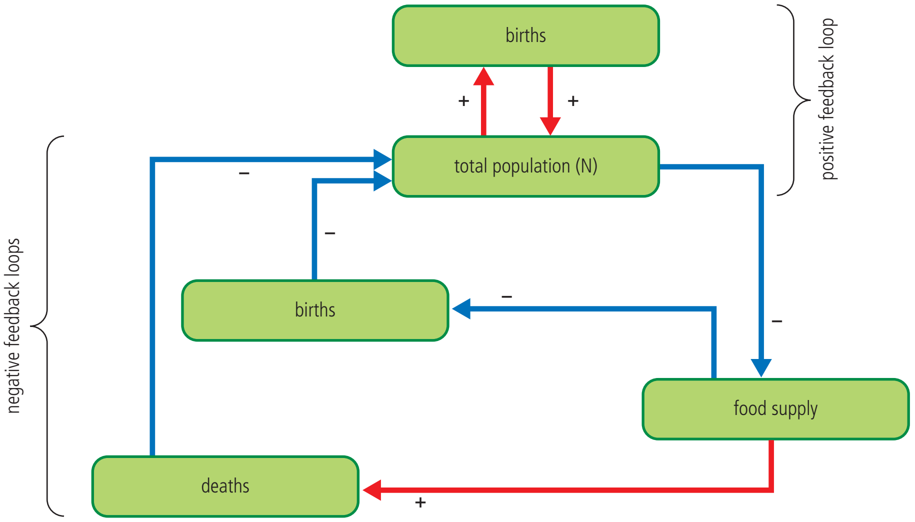

Figure 1.23 Population control in animal populations contains both negative and positive feedback loops.

Tipping points

A **tipping point** is a critical threshold when even a small change can have dramatic effects and cause a disproportionately large response in the overall system. Positive feedback loops are destabilizing and tend to amplify changes and drive the system towards a tipping point where a new equilibrium is adopted (Figure 1.24; Figure 1.19, page 30). Most projected tipping points are linked to climate change (Chapter 7), and represent points beyond which irreversible change or damage occurs. Increases in CO_2 levels above a certain value (450 ppm) would lead to increased global mean temperature, causing melting of the ice sheets and permafrost (Chapter 7). Reaching such a tipping would, for example, cause long-term damage to societies, the melting of Himalayan mountain glaciers, and a lack of fresh water in many Asian societies.

Positive feedback loops (destabilizing) will tend to amplify changes and drive the system towards a tipping point where a new equilibrium is adopted.

A tipping point is the minimum amount of change within a system that will destabilize it, causing it to reach a new equilibrium or stable state.

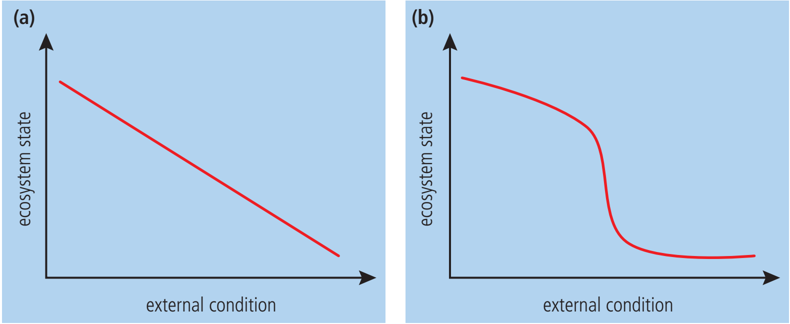

Figure 1.24 How different types of ecosystem may respond to changing external conditions

If external conditions in the environment, such as nutrient input or temperature, change gradually, then ecosystem state may respond gradually (Figure 1.24a), in which case there are no tipping points involved. In other cases, there may be little response below a certain threshold, but fast changes in the system can occur once the threshold is reached (Figure 1.24b), even though a small change in environmental conditions has occurred – in such cases, a tipping point has been reached.

Case study

Krill harvesting in the southern ocean

Krill is a small shrimp-like crustacean that is a food source for seals, whales, penguins, and other seabirds. Krill is harvested to produce food for farmed fish and nutritional supplements for people. Research into the effects of Antarctic krill in the seas near South Georgia have indicated the level of fishing that is sustainable, beyond which a tipping point would be reached leading to rapid change in the southern ocean ecosystem. Krill form the base of the food chain, and so significant reduction in their population density severely affects other animals (e.g. gentoo and macaroni penguins, and Antarctic fur seal). The study showed that animals that feed on the krill begin to suffer when the krill population declined below a critical level of 20 g m^{-2}, which is approximately one-third of the maximum measured amount of krill available (Figure 1.25). This critical level is also shown in seabird species around the world, from the Arctic to the Antarctic, and from the Pacific to the Atlantic.

Antarctic krill (*Euphausia superba*). Krill live in huge swarms which can be kilometres across and reach densities of 10 000 individuals per cubic metre. Each individual is at most 6 cm long. They feed on algae. Krill are a major food species for a wide array of oceanic creatures, ranging from small fish, such as sardines and herring, to blue whales.

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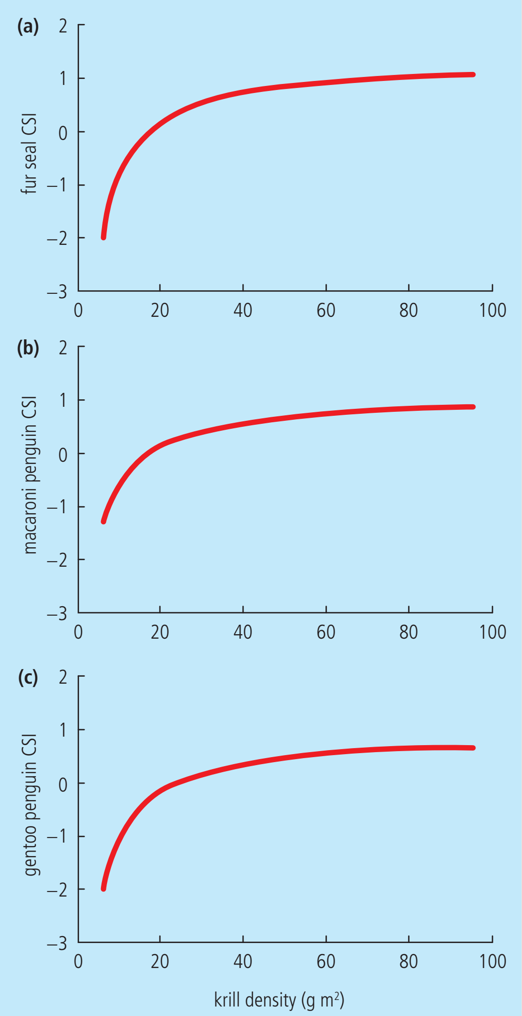

Figure 1.25 Graphs showing the effect of changes in krill density on upper trophic level predators (fur seals, macaroni penguins, and gentoo penguins). The combined standardized index (CSI) uses a range of variables to assess the health of predator populations (e.g. population size, breeding performance, offspring growth rate, foraging behaviour and diet). Data show that a tipping point is reached at 20 g m^{-2} of krill.

To learn more about conservation of the Antarctic ocean ecosystem, go to www.pearsonhotlinks.co.uk, enter the book title or ISBN, and click on weblink 1.2.

Systems at threat from tipping points include:

- Antarctic sea ecosystems (case study)
- Arctic sea-ice
- Greenland ice sheet
- West Antarctic ice sheet
- El Niño Southern Oscillation (ENSO)
- West African monsoon
- Amazon rainforest
- boreal forest.
- thermohaline circulation (THC) (Chapter 7).

Some of these are discussed below.

El Niño Southern Oscillation

El Niño Southern Oscillation (ENSO) refers to fluctuation in sea surface temperatures across the Pacific Ocean, with oscillations occurring every 3 to 7 years. Warming and cooling of the tropical eastern Pacific Ocean (i.e. off the west coast of South America) are known as El Niño and La Niña, respectively. Because ocean circulation has a global extent (Chapter 4, pages 221–222), ENSO can have large-scale effects on the global climate system, and cause extreme weather such as droughts and floods. El Niño events, for example, can lead to warm and very wet weather in the months April to October with flooding along the western coast of South America (in countries such as

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Peru and Ecuador). At the same time, drought occurs in Australia, Malaysia, Indonesia, and the Philippines; warmer than normal winters occur in northern USA and Canada, with greater rainfall in south-west USA, and droughts in Africa and India. Developing countries bordering the Pacific Ocean (on both its eastern and western extremes) are particularly affected by ENSO events.

West African monsoon

The heavy rains that occur in West Africa are affected by sea surface temperature. A change in global mean temperature of 3–5 °C could lead to a collapse of the West African monsoon. With reduced rainfall in western Africa, more moisture would reach areas such as the Sahara, which could lead to increased rainfall and a ‘greening’ as more vegetation grows.

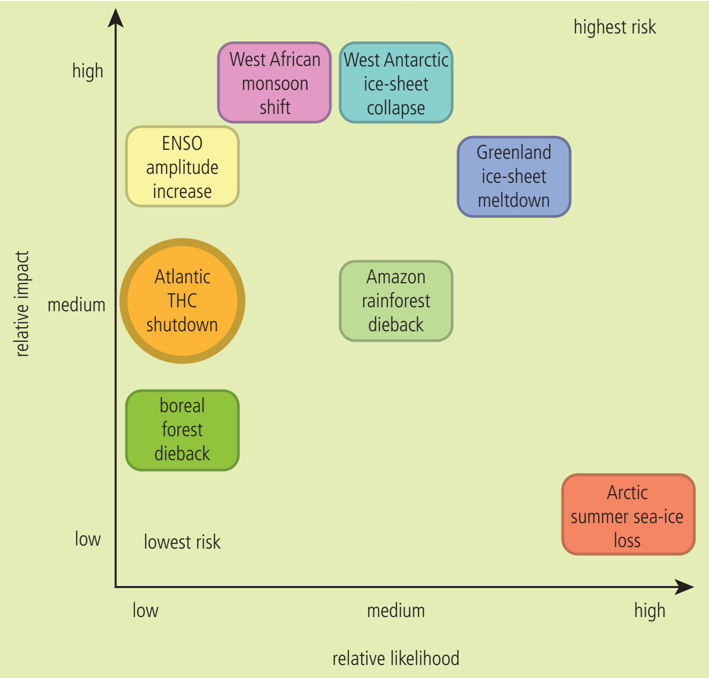
Amazon rainforest

Increased temperatures due to climate change, and the effects of deforestation through logging and land clearance, could lead to a tipping point in the Amazon. Rainforest creates its own weather patterns, with high levels of **transpiration** (evaporation of water from leaves) leading to localized rainfall. Drier condition would lead to increased likelihood of forest fires, and reduced forest extent through forest dieback: loss of trees would result in less transpiration, with more water ending up in rivers and ultimately the sea rather than in the forest. The ultimate decrease in water circulating locally would result in a tipping point being reached, leading to the desertification of the Amazon basin.

Boreal forest

Boreal forest, or Taiga (Chapter 2, page 76), is characterized by coniferous trees such as pines. It is the Earth’s most extensive biome and is found throughout the northern hemisphere. Research suggests that a 3 °C increase in mean global temperature may be the threshold for loss of the boreal forest, caused by increased water stress, decreased tree reproduction rates, increased vulnerability to disease, and fire.

Figure 1.26 Likelihood and possible and impacts of tipping points resulting from climate change



The likelihood and possible impacts of these tipping points are shown in Figure 1.26.

Models are used to predict tipping points and, as you have already seen, such models have strengths and limitations (page 25). The delays involved in feedback loops make it difficult to predict tipping points and add to the difficulty of modelling systems. Other problems with predicting tipping points include:

- There is no globally accepted definition of what is meant by the term *tipping point*: how different do two system states need to be to say that a tipping point has been reached?
- Not all properties of a system will change abruptly at one time, and so it may be difficult to say when a tipping point has been reached.
- The exact size of the impacts resulting from tipping points have not been fully identified for all systems.

To learn more about climate tipping points, go to www.pearsonhotlinks.co.uk, enter the book title or ISBN, and click on weblink 1.4.

You need to be able to evaluate the possible consequences of tipping points, and have explored various examples of human impacts and possible tipping points.

- It may be difficult to determine the causes of a tipping point – whether it has been reached because of the inherent nature of the system or external factors such as human activity, for example.
- It is difficult to determine the conditions under which ecosystems experience tipping points, because of their complexity.
- Not all systems that could be affected by tipping points have been examined or possibly even identified.
- No one may know the exact tipping point until long after it has happened.

The costs of tipping points, both from environmental and economic perspectives, could be severe, so accurate predictions are critical. Models that predict tipping points are, therefore, essential and have alerted scientists to potential large events. Continued monitoring, research, and modelling is required to improve predictions.

Activities in one part of the globe may lead to a tipping point which influences the ecological equilibrium elsewhere on the planet. For example, fossil fuel use in industrialized countries can lead to global warming which has impact elsewhere, such as desertification of the Amazon basin.

Resilience and diversity in systems

The **resilience** of a system, ecological or social, refers to its tendency to avoid tipping points, and maintain stability through steady-state equilibrium. Diversity and the size of storages within systems can contribute to their resilience and affect the speed of response to change. Large storages, or high diversity, will mean that a system is less likely to reach a tipping point and move to a new equilibrium. Humans can affect the resilience of systems through reducing these storages and diversity. Tropical rainforests, for example, have high **diversity** (i.e. a large number and proportions of species present – see page 138) but catastrophic disturbance through logging (i.e. rapid removal of tree biomass storages) or fires can lower its resilience and can mean it takes a long time to recover. Natural grasslands, in contrast, have low diversity but are very resilient, because a lot of nutrients are stored below ground in root systems, so after fire they can recover quickly (case study).

CONCEPTS: Biodiversity

Ecosystems with high biodiversity contain complex food webs which make them resistant to change – species can turn to alternative food sources if one species is reduced or lost from the system.

You need to be able to discuss resilience in a variety of systems.

Complex ecosystems such as rainforests have complex food webs which allow animals and plants many ways to respond to disturbance of the ecosystem and thus maintain stability. They also contain long-lived species and dormant seeds and seedlings that promote steady-state equilibrium. Rainforests have thin, low-nutrient soils, however, and although storage of biomass in trees is high, nutrient storage in soils is low. Nutrients are locked-up in decomposing plant matter on the surface and in rapidly growing plants within the forest, so when the forest is disturbed, nutrients are quickly lost (e.g. leaf layer and topsoil can be washed away). Ecosystems with higher resilience have nutrient-rich soils which can promote new growth.

Case study

Disturbance of tall grass prairie

Tall grass prairie is a native ecosystem to central USA. High diversity, complex food webs and nutrient cycles in this ecosystem maintain stability. The grasses are between 1.5 and 2 m in height, with occasional stalks as high as 2.5 or 3 m. Due to the build-up of organic matter, these prairies have deep soils and recover quickly following periodic fires which sweep through them; they can quickly return to their original equilibrium. Plants have a growth point below the surface which protects them from fire, also enabling swift recovery.

Tall grass prairie

North American wheat farming has replaced native ecosystems (e.g. tall grass prairie) with a monoculture (a one-species system). Such systems are prone to the outbreak of crop pests and damage by fire – low diversity and low resilience combined with soils that lack structure and need to be maintained artificially with added nutrients lead to poor recovery following disturbance.

Prairie wheat farming

You need to understand the relationships between resilience, stability, equilibria, and diversity, using specific examples to illustrate interactions.

Exercises

1. Summarize the first and second laws of thermodynamics. What do they tell us about how energy moves through a system?
2. What is the difference between a steady-state equilibrium and a static equilibrium? Which type of equilibrium applies to ecological systems and why?
3. **a.** When would a system not return to the original equilibrium, but establish a new one? Give an example and explain why this is the case.
   b. Give an example of a system that undergoes long-term change to its equilibrium while retaining the integrity of the system.
4. Give an example of how an ecosystem's capacity to survive change depends on diversity and resilience.
5. Why does a complex ecosystem provide stability? Include information regarding the variety of nutrient and energy pathways, and the complexity of food webs, in your answer.