DP IB Environmental Systems & Societies (ESS): SL

Your notes

Energy & Equilibria

Contents

Laws of Thermodynamics & Environmental Systems

Your notes

The First Law of Thermodynamics

- Energy exists in many different **forms**, including light energy, heat energy, chemical energy, electrical energy, and kinetic energy
- The way in which energy behaves within systems can be explained by the laws of thermodynamics
  - There are two laws of thermodynamics
- The first law of thermodynamics is as follows:

Energy can neither be created nor destroyed, it can only be transformed from one form to another

- This is also known as the principle of conservation of energy
  - It means that the energy entering a system **equals** the energy leaving it
- The transfer of energy in food chains within ecosystems demonstrates the principle of conservation of energy
  - Energy enters the system (the food chain or food web) in the form of sunlight
  - Producers convert this light energy into biomass (stored chemical energy) via photosynthesis
  - This chemical energy is passed along the food chain, via consumers, as biomass
  - All energy ultimately leaves the food chain, food web or ecosystem as heat energy

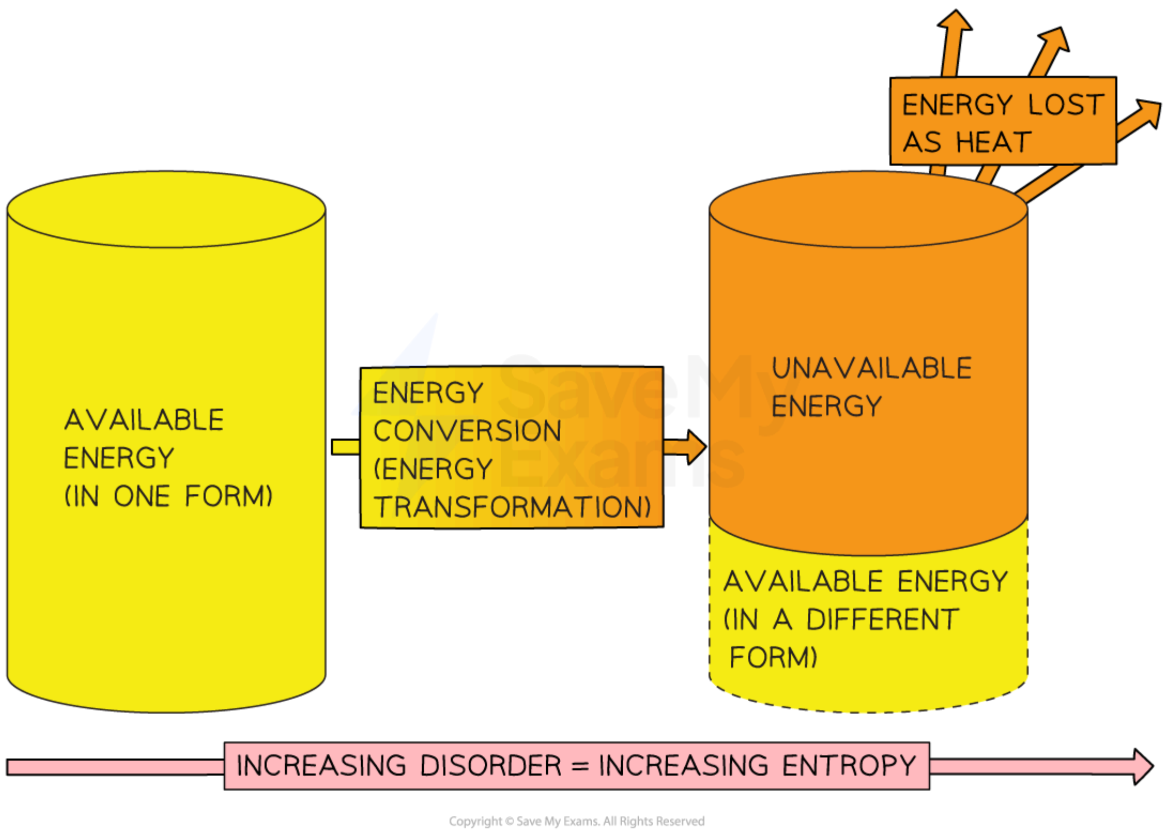
The Second Law of Thermodynamics

- The second law of thermodynamics is as follows:

The entropy of a system increases over time

- **Entropy** is a measure of the amount of **disorder** in a system
- As entropy increases (through inefficiencies in energy transformations) the energy available to do **work** decreases
- This is because the transformation and transfer of energy is any system is never 100% efficient
  - In other words, in any energy conversion, the amount of useable energy at the end of the process is always **less** than the amount of energy available at the start
- The second law of thermodynamics explains the decrease in available energy within ecosystems

- In a food chain, for example, energy is transformed from a more concentrated (ordered) form (e.g. light energy the Sun), into a more dispersed (disordered) form (heat energy)
- Initially, light energy from the Sun is absorbed by producers
- However, even at this initial stage, energy absorption and transfer by producers is **inefficient** due to reflection, transmission (light passing through leaves) and inefficient energy transfer during photosynthesis
- The energy that is converted to plant biomass is then inefficiently transferred along the food chain through respiration and production of **waste** heat energy
- As a result of these inefficient energy transfers, food chains are often **short** (they rarely contain more than five trophic levels)



The laws of thermodynamics – energy cannot be created or destroyed (it can only be transformed), and energy is always lost from systems when work is done, bringing about disorder (increasing entropy)

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Worked Example

Explain the implications of the first and second laws of thermodynamics for a named ecological system.

Answer

The implications of the first and second laws of thermodynamics on the Arctic tundra ecosystem can be explained as follows:

First Law of Thermodynamics:

The first law states that energy cannot be created or destroyed, only transformed from one form to another. In the Arctic tundra ecosystem, solar energy is the primary source of energy, which is captured by the plants through photosynthesis and transformed into chemical energy.

The herbivores then consume the plants and obtain the chemical energy stored in the plants, while the carnivores consume the herbivores and obtain the chemical energy stored in their bodies. Therefore, in the Arctic tundra ecosystem, the energy flow follows the principle of the first law of thermodynamics.

Second Law of Thermodynamics:

The second law states that in every energy transfer or transformation, some energy is lost as unusable energy, such as heat or waste. In the Arctic tundra ecosystem, energy loss occurs at every trophic level due to inefficient energy conversion and energy loss as heat during respiration. As a result, the amount of energy available to the next trophic level decreases, leading to a decrease in the number of individuals in higher trophic levels.

This also means that the energy available to the top predators in the Arctic tundra ecosystem is much lower than that available to the producers, and the number of predators is limited due to the scarcity of energy. Therefore, the second law of thermodynamics limits the complexity and carrying capacity of the Arctic tundra ecosystem

The Nature of Equilibria

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Equilibria

- An equilibrium refers to a **state of balance** occurring between the separate components of a system
- Open systems (such as ecosystems) usually exist in a **stable** equilibrium
  - This means they generally stay in the same state over time
  - They can be said to be in a state of balance
  - A stable equilibrium allows a system to return to its original state following a **disturbance**

Stable Equilibria

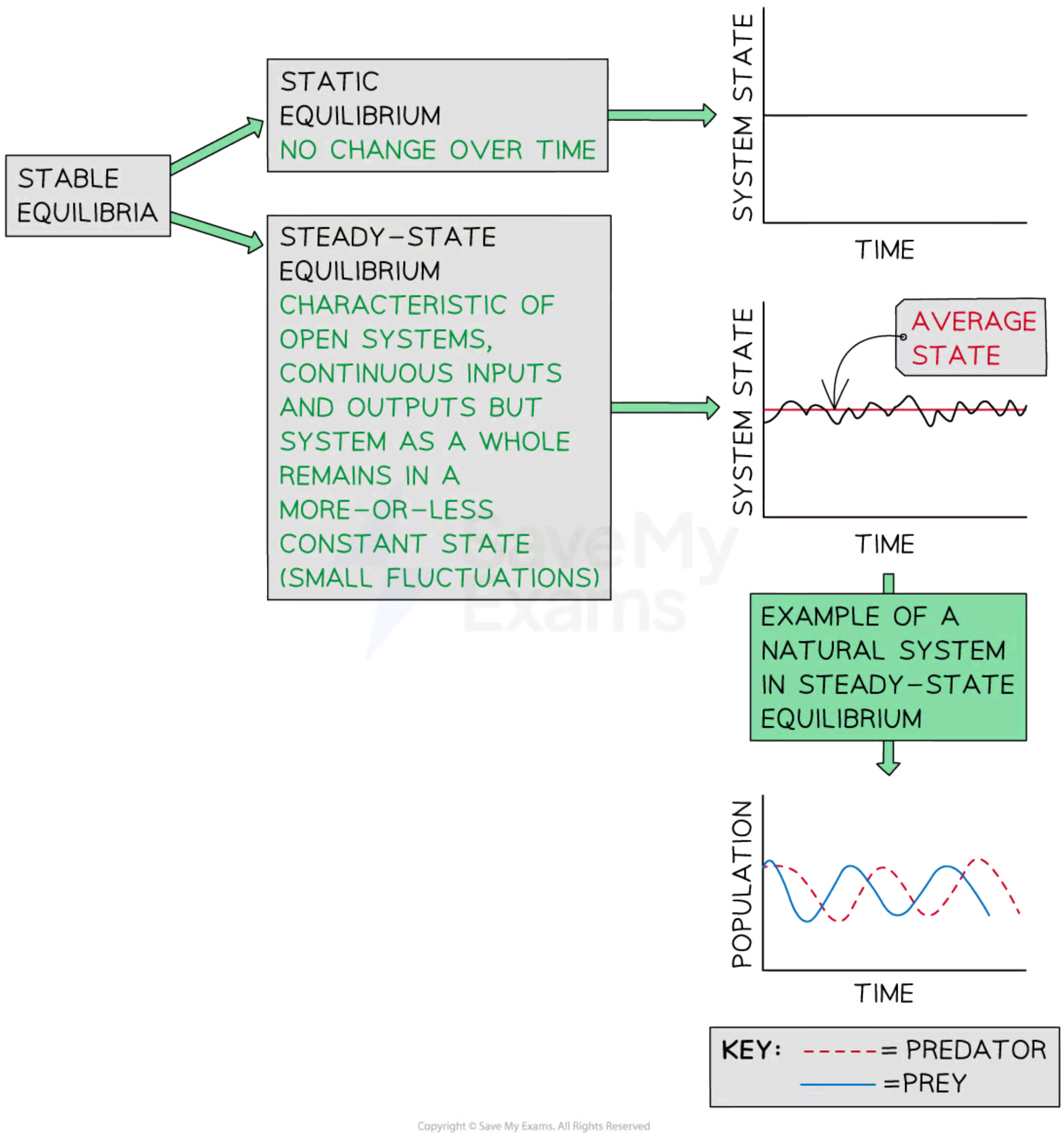
- The main type of stable equilibrium is known as **steady-state** equilibrium
  - A steady-state equilibrium occurs when the system shows no major changes over a longer time period, even though there are often small, oscillating changes occurring within the system over shorter time periods
  - These slight fluctuations usually occur within **closely defined limits** and the system always return back towards its average state
  - Most open systems in nature are in steady-state equilibrium
  - For example, a forest has constant inputs and outputs of energy and matter, which change over time
  - As a result, there are short-term changes in the population dynamics of communities of organisms living within the forest, with different species increasing and decreasing in abundance
  - Overall, however, the forest remains stable in the long-term

Photo by Rodion Kutsaiev on Unsplash

A patch of sky can be considered a steady state if the amount of cloud cover remains the same. The rate of formation and dispersion of clouds is equal, but the system is open as air flows in and out of our view

- Another type of stable equilibrium would be **static** equilibrium
  - There are no inputs or outputs (of energy or matter) to the system and therefore the system shows no change over time
  - No natural systems are in static equilibrium - all natural systems (e.g. ecosystems) have inputs and outputs of energy and matter

- Inanimate objects such as a chair or desk could be said to be in static equilibrium



Static and steady-state equilibria are both types of stable equilibria

Stable vs Unstable Equilibria

- A system can also be in an **unstable** equilibrium

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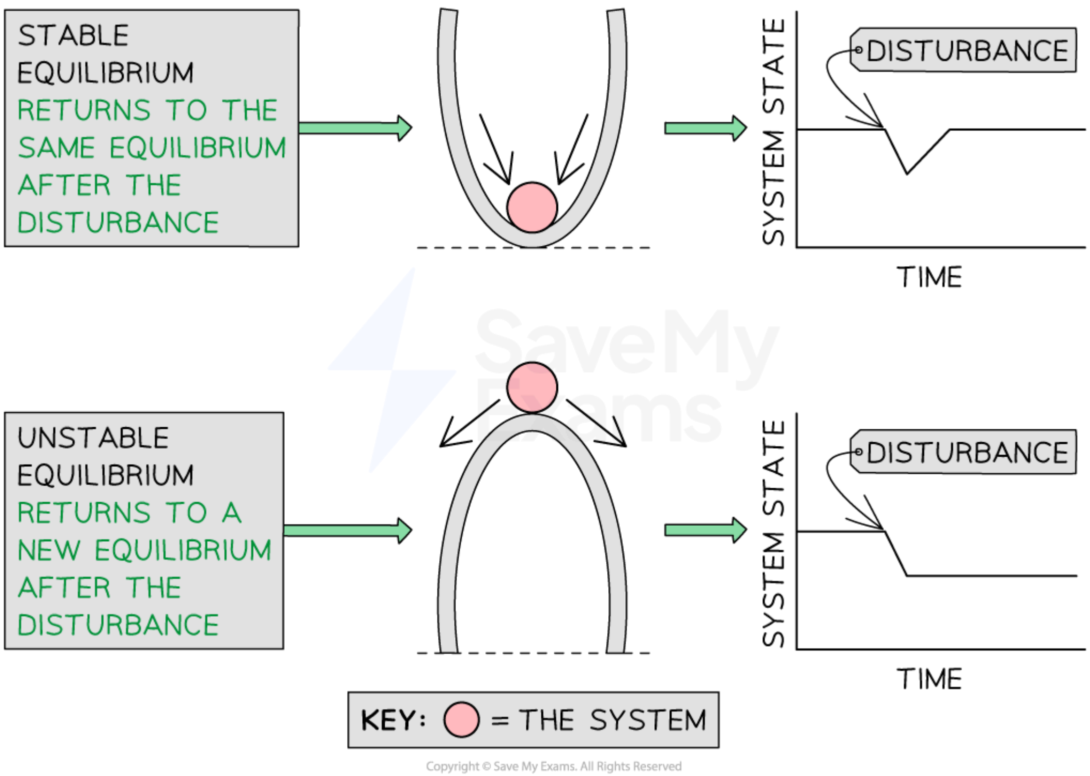
- Even a small disturbance to a system in unstable equilibrium can cause the system to suddenly **shift** to a new system state or average state (i.e. a new equilibrium is reached)



A system can be in a stable equilibrium or an unstable equilibrium

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Positive & Negative Feedback

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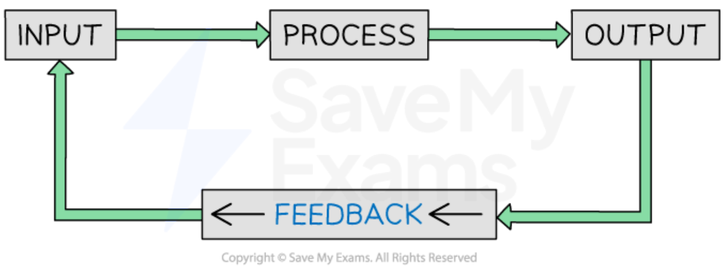
Positive & Negative Feedback

- Most systems involve **feedback loops**
- These feedback mechanisms are what cause systems to react in response to disturbances
- Feedback loops allow systems to **self-regulate**

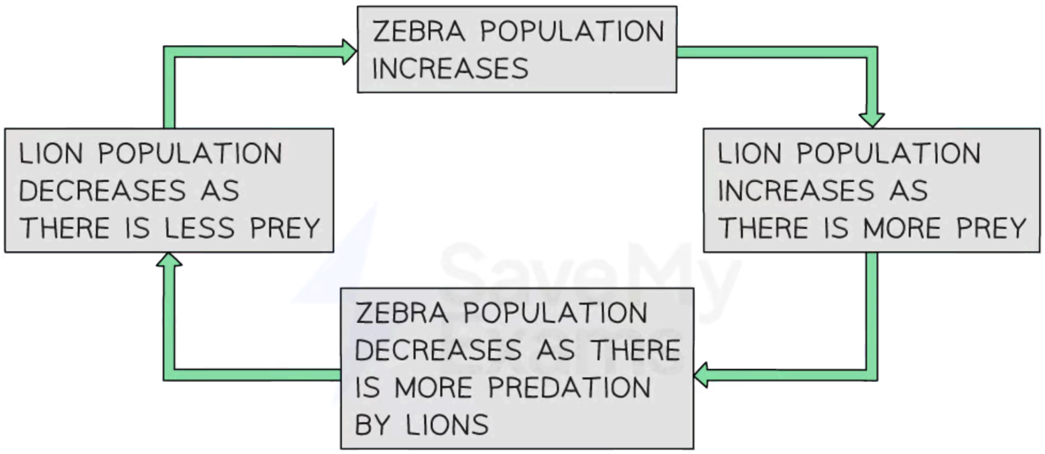


Changes to the processes in a system (disturbances) lead to changes in the system's outputs, which in turn affect the inputs

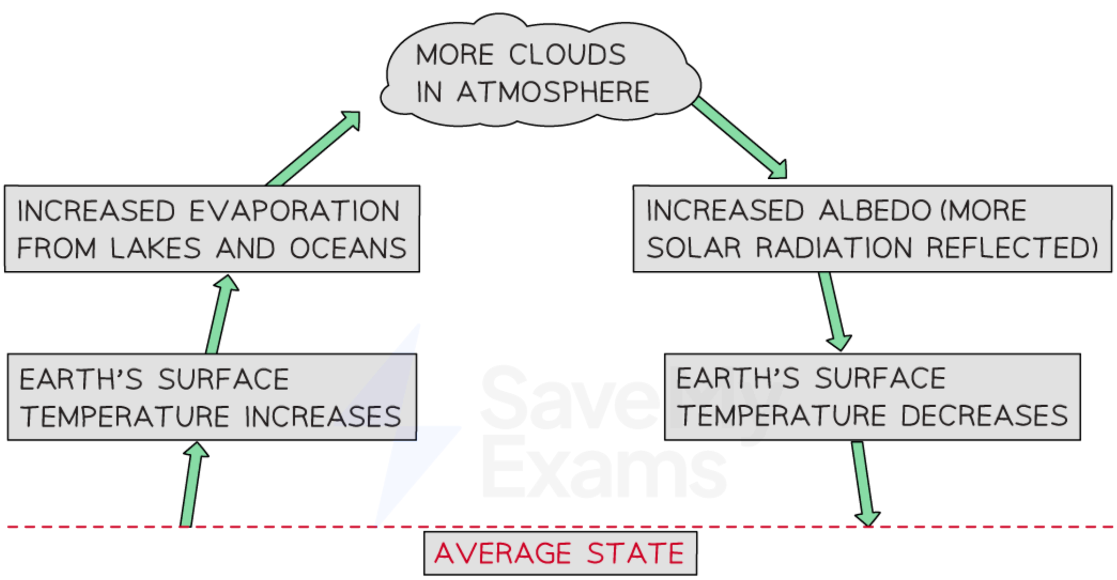
- There are two types of feedback loops:
  - Negative feedback
  - Positive feedback

Negative Feedback

- Negative feedback is any mechanism in a system that **counteracts** a change away from the equilibrium
- Negative feedback loops occur when the output of a process within a system **inhibits** or **reverses** that same process, in a way that brings the system back towards the average state
- In this way, negative feedback is **stabilising** - it counteracts deviation from the equilibrium
- Negative feedback loops stabilise systems



PREDATOR–PREY RELATIONSHIPS WITHIN ECOSYSTEMS ARE OFTEN DRIVEN BY NEGATIVE FEEDBACK.

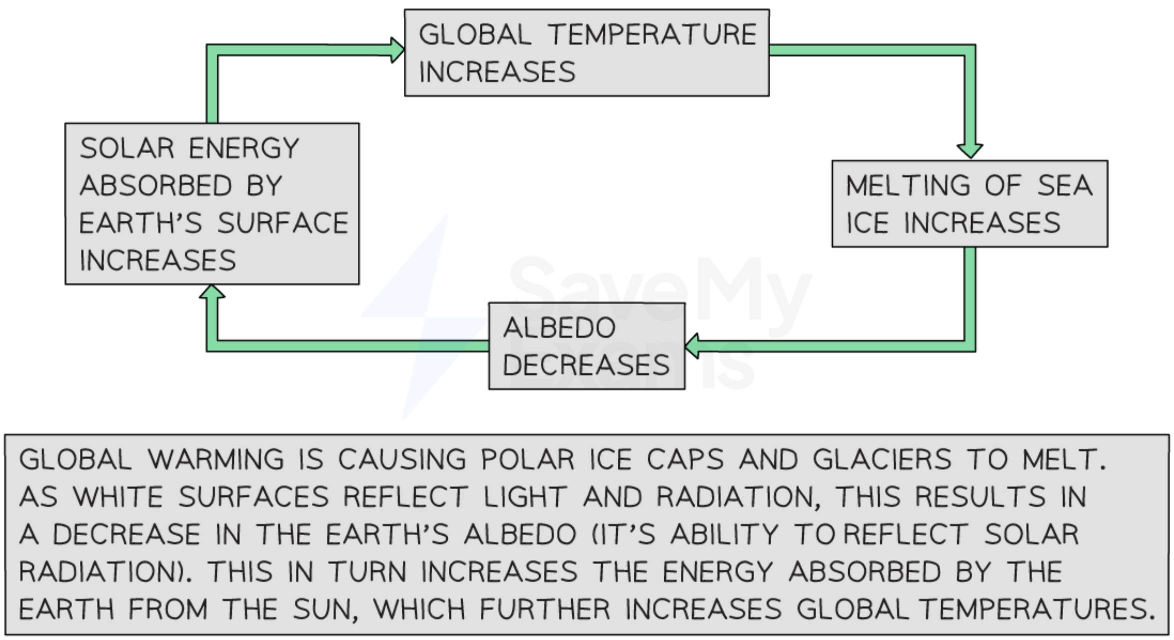


CLOUD COVER (AND IN TURN THE EARTH'S ALBEDO AND SURFACE TEMPERATURE) IS INFLUENCED BY THE HYDROLOGICAL CYCLE. INCREASING TEMPERATURES CAUSE MORE WATER VAPOUR TO BE PRODUCED, CREATING MORE CLOUDS. THE CLOUDS THEN BLOCK INCOMING SOLAR RADIATION, LOWERING THE TEMPERATURE OF THE PLANET AND STABILISING THE SYSTEM.

Examples of negative feedback include predator-prey relationships and parts of the hydrological cycle

Positive Feedback

- Positive feedback is any mechanism in a system that leads to **additional** and **increased** change away from the equilibrium
  - Positive feedback loops occur when the output of a process within a system feeds back into the system, in a way that moves the system increasingly away from the average state
  - In this way, positive feedback is **destabilising** - it amplifies deviation from the equilibrium and drives systems towards a tipping point where the state of the system suddenly shifts to a new equilibrium
  - Positive feedback loops destabilise systems



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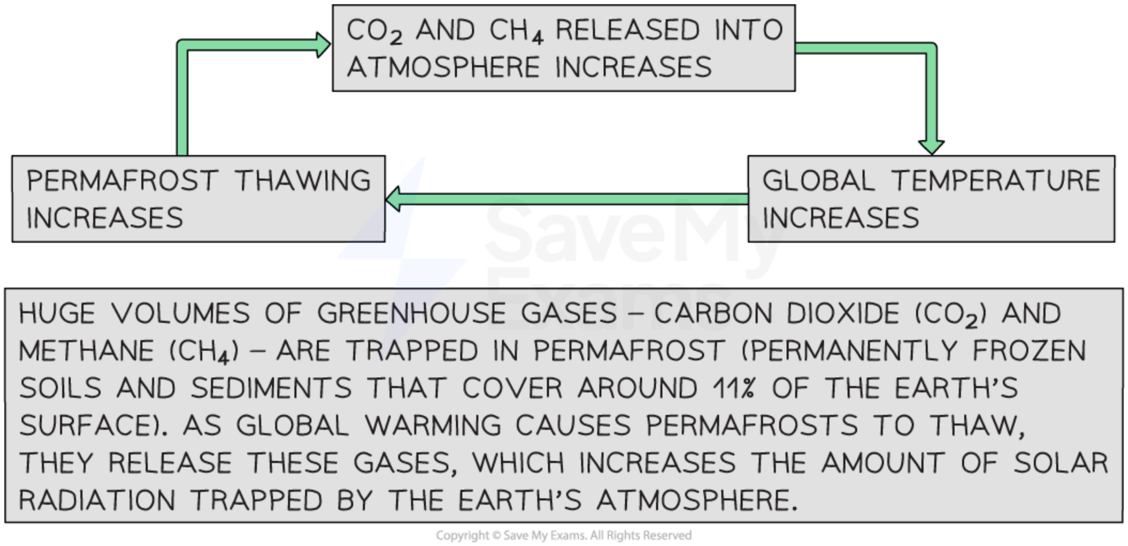


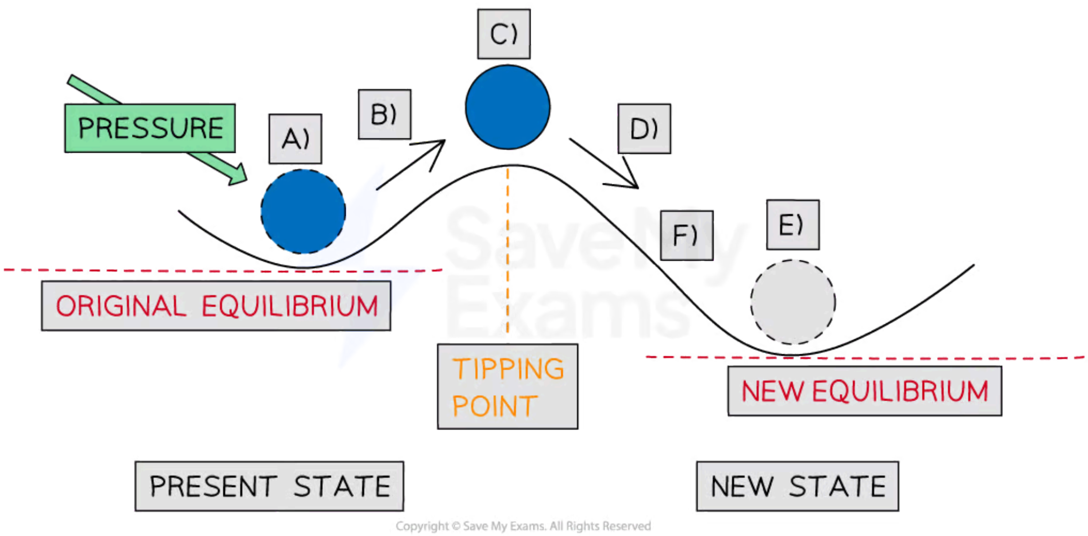
Examples of positive feedback include melting of the ice caps and thawing of permafrost

Climate Tipping Points

Your notes

Tipping Points

- A **tipping point** is a **critical threshold** within a system
  - If a tipping point is reached, any further small change in the system will have significant knock-on effects and cause the system to move **away** from its average state (away from the equilibrium)
  - In ecosystems and other ecological systems, tipping points are very important as they represent the point beyond which serious, **irreversible damage** and change to the system can occur
  - Positive feedback loops can push an ecological system towards and past its tipping point, at which point a new equilibrium is likely to be reached
  - Eutrophication is a classic example of an ecological reaching a tipping point and accelerating towards a new state
- Tipping points can be difficult to predict for the following reasons:
  - There are often **delays** of varying lengths involved in feedback loops, which add to the complexity of modelling systems
  - Not all components or processes within a system will change abruptly at the same time
  - It may be impossible to identify a tipping point until **after** it has been passed
  - Activities in one part of the globe may lead to a system reaching a tipping point elsewhere on the planet (e.g. the burning of fossil fuels by industrialised countries is leading to global warming, which is pushing the Amazon basin towards a tipping point of desertification) - continued monitoring, research and scientific communication is required to identity these links



(A) The system is subject to a pressure that pushes it towards a tipping point. (B) The system's tipping point (critical threshold) is reached. Like a ball balancing on a hill, at this stage even a minor push is enough to cross the tipping point, upon which positive feedback loops accelerate the shift (D) into a new state (E). The change to the new state is often irreversible or a high cost is required to return the system back to its previous state, which is illustrated in the figure as a ball being in a deep valley (E) with a long uphill climb back to the previous state (F)

Worked Example

Evaluate the possible consequences of environmental tipping points, using the melting of polar ice caps and glaciers as an example.

Answer

The consequences of environmental tipping points can be severe and long-lasting, with effects that extend beyond the immediate environment. One such example is the melting of polar ice caps and glaciers, which can have the following consequences:

Rising Sea Levels:

As polar ice caps and glaciers melt, the water they release adds to the volume of the ocean. This can lead to rising sea levels, which can inundate low-lying areas and cause flooding, erosion, and damage to infrastructure.

Changes in Ocean Currents:

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The melting of polar ice caps and glaciers can alter the salinity and temperature of the ocean, which can affect ocean currents. Changes in ocean currents can impact global weather patterns and have cascading effects on ecosystems.

Loss of Biodiversity:

Polar regions are home to a diverse range of species, many of which are adapted to the extreme conditions found there. The loss of polar ice caps and glaciers can lead to the loss of habitat and food sources, leading to declines in biodiversity.

Release of Greenhouse Gases:

Melting permafrost, which is soil that has been frozen for long periods, can release large amounts of methane and carbon dioxide, which are both potent greenhouse gases. This can contribute to climate change and lead to further melting of polar ice caps and glaciers.

Changes in Global Temperatures:

The melting of polar ice caps and glaciers can change the reflective properties of the Earth's surface. This can result in more sunlight being absorbed, leading to an increase in global temperatures and further melting of ice.

- The melting of polar ice caps and glaciers is just one example of the many ways in which human activities can push the Earth's systems beyond their limits and towards environmental tipping points
- It is important for individuals and governments to take action to reduce greenhouse gas emissions and protect the planet's natural systems

Resilience

- Any system, ecological, social or economic, has a certain amount of resilience
  - This resilience refers to the system's ability to maintain **stability** and **avoid tipping points**
- **Diversity** and the **size of storages** within systems can contribute to their resilience and affect their speed of response to change
  - Systems with higher diversity and larger storages are less likely to reach tipping points
  - For example, highly complex ecosystems like rainforests have high diversity in terms of the complexity of their food webs
  - If a disturbance occurs within one of these food webs, the animals and plants have many different ways to respond to the change, maintaining the stability of the ecosystem
  - Rainforests also contain large storages in the form of long-lived tree species and high numbers of dormant seeds
  - These factors promote a **steady-state equilibrium** in ecosystems like rainforests

- In contrast, agricultural crop systems are artificial monocultures meaning they only contain a single species. This low diversity means they have low resilience - if there is a disturbance to the system (e.g. a new crop disease or pest species), the system will not be able to counteract this

A system with high resilience (such as a tropical rainforest) has a greater ability to avoid tipping points than a system with low resilience (such as an agricultural monoculture)

- Humans can affect the resilience of natural systems by reducing the diversity contained within them and the size of their storages
    - Rainforest ecosystems naturally have very high biodiversity
    - When this biodiversity is reduced, through the hunting of species to extinction or the destruction of habitat through deforestation, the resilience of the rainforest ecosystem in reduced - it becomes increasingly **vulnerable** to further disturbances
    - Natural grasslands have high resilience, due to large storages of seeds, nutrients and root systems underground, allowing them to **recover quickly** after a disturbance such as a fire (especially if they contain a diversity of grassland species, including some which are adapted to regenerate quickly after fires)
    - However, when humans convert natural grasslands to agricultural crops, the lack of diversity and storages (e.g. no underground seed reserves) results in a system that has low resilience to disturbances such as fires

Worked Example

Giving a specific example of each, discuss an ecological system with high resilience and an ecological system with low resilience.

Answer

Mangrove forests are coastal ecosystems found in tropical and subtropical regions. They are an example of an ecological system with high resilience. This is due to several factors:

Adaptability:

Mangroves have evolved to survive in harsh coastal conditions, including saltwater inundation due to tidal flooding. They are also able to withstand and adapt to changing environmental conditions, such as sea-level rise and storm surges.

Self-regeneration:

Mangroves have a unique ability to self-regenerate through the production of propagules, which can sprout into new trees. This allows them to recover quickly from disturbances such as storms, hurricanes, and tsunamis.

Biodiversity:

Mangroves support high levels of biodiversity, with many species of plants and animals adapted to their unique ecosystem. This biodiversity provides a buffer against disturbances, as it allows for the maintenance of ecological processes and the provision of ecosystem services.

Nutrient Cycling:

Mangroves are efficient at cycling nutrients, such as nitrogen and phosphorus, within their ecosystem. This helps to maintain soil fertility and supports the growth of mangrove trees and other vegetation.

Coral reefs are an example of an ecological system with low resilience. This is due to several factors:

Multiple Simultaneous Stressors:

Coral reefs are under threat from a range of human activities, including overfishing, pollution and coastal development.

Rising Sea Temperatures:

Coral reefs are particularly vulnerable to climate change, which is causing ocean temperatures to rise and making the water more acidic. This can cause coral bleaching, which can lead to mass coral mortality and the degradation of the entire reef ecosystem.

Slow Recovery Rate:

Once coral reefs have been damaged, their recovery can be slow and difficult. This is because corals grow slowly and are vulnerable to further damage while they are recovering. If the disturbances continue, the reef may reach a tipping point beyond which it cannot recover.

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