DP IB Environmental Systems & Societies (ESS): SL

1.2 Systems

Contents

The Systems Approach

The Systems Approach

- A systems approach is the term used to describe a method of simplifying and understanding a complicated set of **interactions**
    - **Systems** and the interactions they contain can be **environmental** or **ecological** (e.g. the water cycle or predator-prey relationships), **social** (e.g. how we live and work) or **economic** (e.g. financial transactions or business deals)
- There are two ways of studying systems:
    - A **reductionist approach** means breaking a system down into its **parts** and studying each one individually
        - This can be useful for studying specific interactions in detail but it doesn't show what's going on in the system as a whole
    - A **holistic approach** looks at all of the system's processes and interactions as a **whole**
- For example, sustainability or sustainable development depends on a highly complex set of interactions between **many different factors**
    - These include environmental, social and economic factors (sometimes referred to as the three pillars of sustainability).
    - A systems approach is required in order to understand how these different factors **combine** and **interact** with one another, as well as how they all work **together** as a whole (the holistic approach)

Components & Interactions in Systems

Storage and flow

- A system is comprised of storages and flows
  - The flows provide **inputs** and **outputs** of energy and matter
- The flows are processes that may be either:
  - **Transfers**
  - **Transformations**

Transfers and transformations

- These are two fundamental concepts in systems (and systems diagrams) that help to understand how **matter** and **energy** move through a system
- Transfers are the movement of matter or energy from one component of the system to another **without** any change in form or quality
  - For example, water flowing from a river to a lake is a transfer
- Transformations, on the other hand, involve a **change** in the form or quality of matter or energy as it moves through the system
  - For example, when sunlight is absorbed by plants, it is transformed into chemical energy through the process of photosynthesis
- Transfers and transformations are often represented in systems diagrams by **arrows** that connect the different components of the system
  - Arrows that represent transfers are usually labelled with the quantity of matter or energy being transferred (e.g., kg of carbon, kJ of energy), while arrows that represent transformations may include additional information about the process involved (e.g., photosynthesis, respiration)
- Systems diagrams can help identify the key transfers and transformations that occur within a system and how they are **interconnected**
- By understanding these processes, it is possible to identify opportunities to improve the **efficiency** or **sustainability** of the system
- Transfers and transformations can occur at **different scales** within a system, from the molecular level to the global level
  - For example, at the molecular level, nutrients are transferred between individual organisms, while at the global level, energy is transferred between different biomes

Systems diagrams

- Systems are often represented as simplified diagrams made up of storages and flows
  - Storages are commonly drawn as shapes with defined boundaries (such as a circle or rectangle)
  - Flows are commonly drawn as arrows
    - These arrows represent the various inputs and outputs occurring within a system

- The size of the shapes and arrows can be representative of the size of the particular storage or flow (although often they are not drawn this way)

Emergent properties

- The interactions within a system, when looked at as a whole, produce the **emergent properties** of the system
- Emergent properties are properties of a system that appear as individual system components interact; the components themselves do not have these properties
  - For example, in an ecosystem, all the different ecological interactions occurring within it shape how that ecosystem looks and behaves
- If the interactions **change** for some reason (e.g. a new predator is introduced), then the emergent properties of the ecosystem will change too
- Predator–prey cycles and trophic cascades are good examples of emergent properties, where patterns of change occur that would not occur in the isolated components

Types of Systems

Open & Closed Systems

- There are three main types of systems—these are:
  - **Open** systems
  - **Closed** systems
  - **Isolated** systems
- The category that a system falls into depends on how **energy** and **matter** flow between the system and the **surrounding environment**

Open systems

- Both energy and matter are exchanged between the system and its surroundings
- Open systems are usually **organic** (living) systems that interact with their surroundings (the environment) by taking in energy and new matter (often in the form of biomass), and by also expelling energy and matter (e.g. through waste products or by organisms leaving a system)
- An example of an open system would be a particular **ecosystem** or **habitat**
- Your body is also an example of an open system—energy and matter are exchanged between you and your environment in the form of food, water, movement and waste

Closed systems

- Energy, but not matter, is exchanged between the system and its surroundings
- Closed systems are usually **inorganic** (non-living)
- The Earth (and the atmosphere surrounding it) could be viewed as a closed system
  - The main **input** of energy occurs via **solar radiation**
  - The main **output** of energy occurs via **heat** (re-radiation of infrared waves from the Earth's surface)
  - Matter is recycled completely **within** the system
  - Although, technically, very small amounts of matter enter and leave the system (in the form of meteorites, spaceships or satellites), these are considered **negligible**
- Global geochemical cycles are approximated to closed systems due to the continuous recycling and redistribution of elements and compounds within the Earth's various natural "reservoirs", such as the atmosphere, hydrosphere, lithosphere, and biosphere
  - The overall quantities of elements remain **relatively constant** over geological timescales
  - For example, carbon moves between the atmosphere, oceans and terrestrial ecosystems through processes like photosynthesis, respiration and oceanic absorption, maintaining a dynamic equilibrium
  - The Earth's geochemical cycles operate on vast scales and with **long-term stability**, resembling closed systems on a global scale
- Artificial and experimental ecological closed systems can also exist

  - For example, sealed terrariums, containing just the right balance of water and living organisms (such as mosses, ferns, bacteria, fungi or invertebrates), can sometimes survive for many years as totally closed systems if light and heat energy are allowed to be **exchanged** across the glass boundary
- **Biosphere 2** was an attempt to create a larger-scale artificially closed system
  - It was a self-contained experimental research facility designed to **simulate Earth's ecosystems** in a **closed environment**
  - Constructed in the late 1980s, it consisted of several interconnected ecosystems, including a rainforest, ocean, desert, savannah and agricultural area, along with living quarters for human inhabitants
  - The goal was to study the interactions between different ecosystems and humans in a controlled environment
  - To create a closed system, Biosphere 2 was sealed off from the outside world, with limited inputs of matter (energy could enter the system in the form of **sunlight** and **heat**)
  - Air and water were recycled, and food was grown within the facility to sustain the inhabitants

Isolated systems

- Neither energy nor matter are exchanged between the system and its surroundings
- Isolated systems do not exist naturally; they are more of a **theoretical concept** (although the entire Universe could be considered to be an isolated system!)

Environmental Systems

Systems at different scales

- Systems are structures made up of **interconnected parts** that work together towards a common goal or function
  - In a similar way, environmental systems are interconnected **networks** of **components** and **processes** within the environment, found at various scales from single organisms to huge

ecosystems
- These environmental systems include interactions between living organisms, their habitats and physical elements like water, air and soil, shaping Earth's environment and influencing its dynamics and functions

- Environmental systems can be observed and analysed at a **range of different scales**
  - For example, a bromeliad (a type of plant commonly found in tropical rainforests) could represent a **small-scale local ecological system**
    - Within the leaves of the bromeliad, various organisms interact, forming a microcosm of life
  - The entire rainforest itself represents a **large-scale ecosystem**, where countless species interact within a complex web of relationships
    - Within the rainforest, there are predator-prey relationships, symbiotic relationships, species competing for resources and nutrient cycles all occurring within the system
  - It could also be argued that the entire planet can be considered to be one **giant, self-contained system**
    - The Earth's atmosphere, oceans and land are highly interconnected and regulate environmental conditions to maintain conditions suitable for life

Earth as a single integrated system

- Instead of just a collection of independent parts, Earth can be seen as a complex, integrated system comprised of many interconnected components, including:
  - **Biosphere**: includes all living organisms on Earth and their interactions with the environment
  - **Hydrosphere**: includes all water bodies on Earth, including oceans, rivers, lakes and groundwater
  - **Cryosphere**: includes all forms of frozen water on Earth's surface, such as glaciers, ice caps and permafrost
  - **Geosphere:** refers to the solid Earth, including rocks, minerals and landforms such as mountains and valleys
  - **Atmosphere:** includes the layer of gases surrounding the Earth, including the troposphere, stratosphere, mesosphere, thermosphere and exosphere
  - **Anthroposphere**: represents the sphere of human influence on the environment, including human activities, infrastructure and urbanisation

Gaia hypothesis

- The Gaia hypothesis (also known as the Gaia theory), initially proposed by James Lovelock in the 1970s, presents a holistic view of the Earth as a **single, self-regulating system**

- Lovelock proposed that Earth's **biota** (living organisms) and their **environment** are closely linked and act together as an integrated system
- His theory suggests that **feedback mechanisms** within Earth's systems help maintain stability and balance on a global scale, a bit like homeostasis in living organisms

- **Variations and developments:**
  - Initially, the Gaia hypothesis was introduced to explain how the composition of the Earth's atmosphere affects global temperatures and how these two factors are connected or "controlled" via complex feedback methods
    - For example, the presence of greenhouse gases, such as carbon dioxide and methane, in the Earth's atmosphere can increase global temperatures
    - In response to these rising temperatures, feedback mechanisms, such as increased evaporation leading to more cloud cover or enhanced plant growth absorbing more carbon dioxide, may act to mitigate temperature increases
  - Over time, the Gaia hypothesis has undergone various interpretations and refinements, with contributions from scientists such as Lynn Margulis
  - Some scientists have criticised the Gaia hypothesis for its anthropomorphism, comparing the Earth to a living organism, and lack of testability, while others consider it a useful theory for understanding Earth's interconnected systems

Stable Equilibrium & Feedback Mechanisms

Stable Equilibrium

- 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**
  - A stable equilibrium allows a system to return to its original state following a **disturbance**
  - This state of balance is maintained by **stabilising negative feedback loops**

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 returns to 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

A patch of sky can be considered to be in 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 and water vapour flows in and out of our view (Photo by Rodion Kutsaiev on Unsplash)

- Another type of stable equilibrium is **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 a desk could be said to be in static equilibrium

Stable vs unstable equilibria

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

Negative & Positive 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**
- 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 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 **to its average state**
- In this way, negative feedback is **stabilising**—it counteracts deviation from equilibrium
- Negative feedback loops stabilise systems

The Daisyworld model

- James Lovelock and Andrew Watson created the Daisyworld model as a computer simulation in the 1980s
  - The model was based on a theoretical planet with only two types of organisms: **black** daisies and **white** daisies
  - These daisies interacted with the environment by affecting the planet's **albedo** (the amount of solar radiation it can reflect away)
- **Global temperature regulation due to life**:
  - In the Daisyworld simulation, as the amount of sunlight (solar luminosity) is increased, black daisies thrive more due to their ability to absorb more sunlight
  - This causes the planet's albedo to **decrease**, trapping more heat and leading to an **increase** in global temperatures
  - This makes the planet more habitable for white daisies
  - The growth of white daisies causes the planet's albedo to **increase**, leading to a **decrease** in global temperatures
  - As both daisy populations compete, they eventually reach a **stable equilibrium**
  - This **steady-state equilibrium** stabilises Daisyworld's surface temperature, ensuring both populations can survive in the long-term
  - This cycle of temperature regulation serves as an example of an important **negative feedback loop**, in which processes that work to stabilise the system in one direction counteract changes in the opposite direction
- **Contrast with a dead planet**:
  - In contrast, on a dead planet without daisies, there are no negative feedback mechanisms for regulating temperature
  - Without organisms to adjust albedo and therefore trigger temperature changes, the dead planet's climate becomes **more extreme over time**, either excessively hot or cold, depending on the initial conditions, resulting in a planet that **cannot sustain life**

Positive feedback

- Positive feedback is any mechanism in a system that leads to **additional** and **increased** change **away from 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 its average state**
    - In this way, positive feedback is **destabilising**—it amplifies deviation from 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

Other examples of positive feedback

- Positive feedback loops **amplify** changes within a system
  - They can lead to either an increase or a decrease in a system component.
- ***Example:* population decline**
  - Population decline reduces reproductive potential
  - Reduced reproductive potential further decreases the population
  - This amplifying loop accelerates the **decline**
- ***Example:* population growth**
  - Population growth increases reproductive potential
  - Increased reproductive potential triggers further population growth
  - This positive feedback loop accelerates population **expansion**

Tipping Points & Resilience

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 a system to move **away** from its average state (away from 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
    - This is sometimes known as a **regime shift** to an **alternative stable state**
    - Eutrophication is a classic example of an ecological system 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 are required to identify these links
- The melting of polar ice caps and glaciers is another example of how human activities can push the Earth's systems beyond their limits and towards environmental tipping points

Perito Moreno Glacier—Argentina (Photo by Rachel Jarboe on Unsplash)

The consequences of environmental tipping points can be severe and long-lasting, with effects that extend beyond the immediate environment.

One 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:

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 the further melting of ice.

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 storage** 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 simple example of how the size of storage affects the relative stability of a system could be demonstrated by the relative **instability** of a small **pond** compared to the relative **stability** of a **lake**
    - In a larger storage system, such as a lake, changes in input or output have less immediate impacts on the overall system compared to a smaller storage system like a pond
    - For example, if pollutants enter the lake, they may become more dispersed and diluted due to its size, reducing the overall impact on water quality, whereas in a smaller storage system like a pond, pollutants can quickly accumulate, leading to more immediate and concentrated pollution

    - While evaporation still occurs in a lake, the impact on the overall water level is less noticeable due to the lake's size, providing a buffer against rapid drying, whereas for a pond, evaporation can quickly deplete the water volume, leading to more rapid drying and decreased stability of the system

- **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 is reduced, making it 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 storage (e.g. no underground seed reserves) results in a system that has **low resilience** to disturbances such as fires

Case Study

An ecological system with high resilience

Mangrove forest located in the Mida Creek—Malindi, Kenya (Photo by Timothy K on Unsplash)

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.

Case Study

An ecological system with low resilience

Coral reef—Red Sea (Photo by Francesco Ungaro on Unsplash)

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.

Models

Models

- A **model** is a **simplified version of reality**
- A model is often used to represent a system
  - The model can then be **analysed** or **tested** to learn more about how the system works and to **predict** how the system might **respond** to change
  - For example, weather models are used to predict how our weather systems change over time, allowing us to create weather forecasts
- Some models can be very **simple**, such as a child's model car, while others can be **highly complex** and require the power of supercomputers, such as the computer models that are currently being used to predict how our climate will change in the future
  - To some extent, due to their very nature, all models involve some level of **approximation** or **simplification**, and therefore some loss of accuracy (even the very powerful and complex models)
- Models have a variety of strengths and weaknesses

Strengths and Limitations of Models

Strengths	Limitations
Models simplify complex systems	Models can be oversimplified and inaccurate
Models allow predictions to be made about how systems will react in response to change	Results from models depend on the quality of the data inputs going into them
System inputs can be changed to observe effects and outputs without the need to wait for real-life events to occur	Results from models become more uncertain the further they predict into the future
Models are easier to understand than the real system	Different models can show vastly different outputs even if they are given the same data inputs
Results from models can be shared between scientists, engineers, and companies and communicated to the public	Results from models can be interpreted by different people in different ways

Results from models can warn us about future environmental issues and how to avoid them or minimise their impact	Environmental systems are often incredibly complex, with many interacting factors—it is impossible to take all possible variables into account