DP IB Environmental Systems & Societies (ESS): SL

Your notes

Flows of Energy & Matter

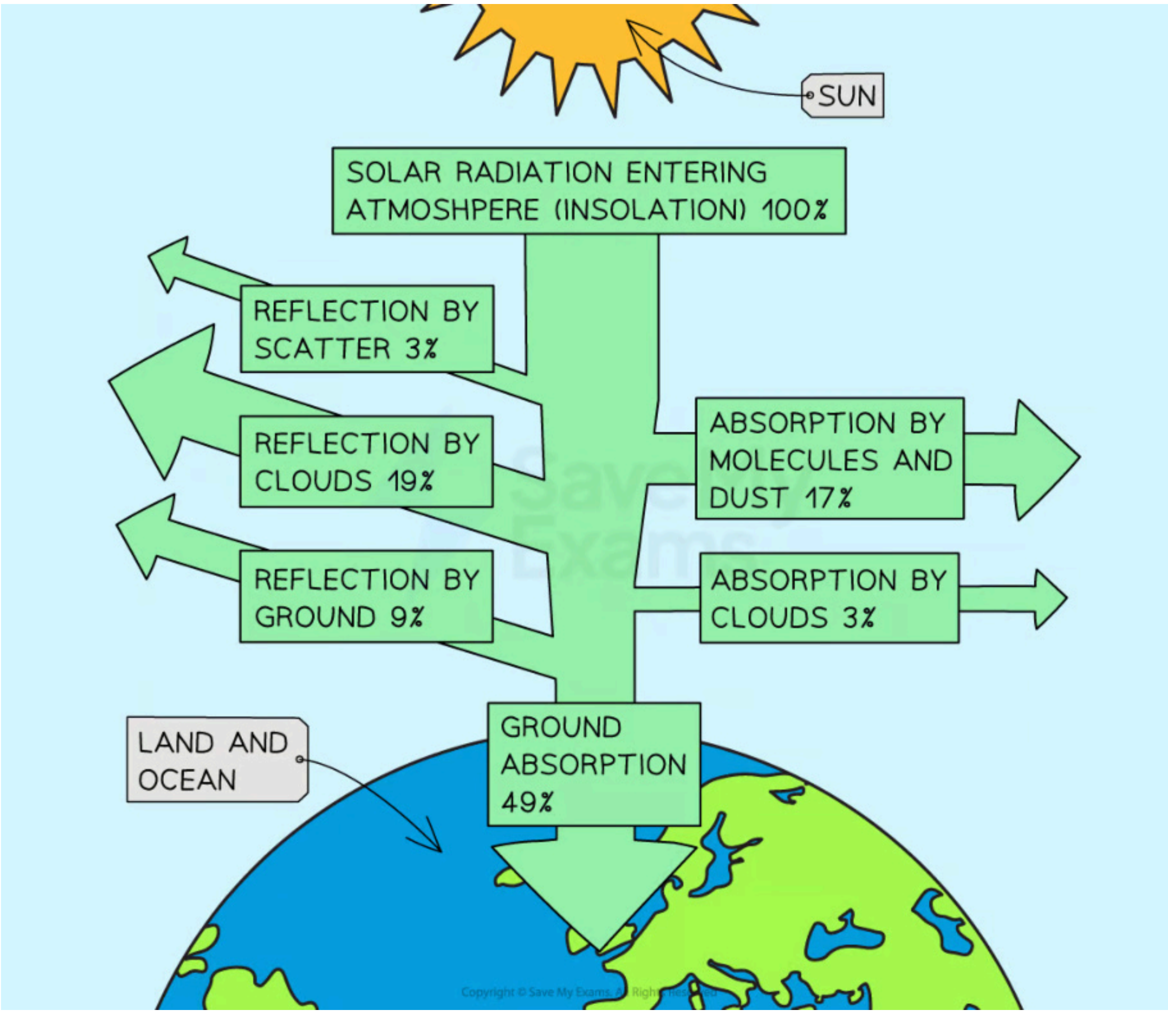
Contents

Pathways of Energy Entering the Atmosphere

Your notes

Pathways of Energy Entering the Atmosphere

- When solar radiation (**insolation**) enters the Earth's atmosphere, some of the energy becomes **unavailable for ecosystems** due to being:
  - Absorbed by inorganic matter
  - Reflected back into the atmosphere
- This means **very little** of the sunlight available from the Sun is **converted into biomass** in ecosystems
  - About 51% of the available energy from the Sun never reaches **producers**
- The pathway of radiation through the atmosphere involves a loss of radiation through **reflection** and **absorption**, with the following (approximate) percentage losses:
  - Reflection from clouds ~ 19%
  - Absorption of energy by clouds ~ 3%
  - Reflection by scatter from aerosols and atmospheric particles ~ 3%
  - Absorption by molecules and dust in the atmosphere ~ 17%
  - Reflection from the surface of the Earth ~ 9%
    - The ability of clouds and reflective surfaces on Earth (such as snow and ice) to reflect solar radiation is known as **albedo**
- Of the 49% of solar radiation absorbed by the ground, only a small proportion ends up in producers
  - Most incoming solar radiation fails to enter chloroplasts in leaves because it is **reflected**, **transmitted** (passes straight through the leaf), or is the **wrong wavelength** to be absorbed
  - Of the radiation captured by leaves, only a small percentage ends up as biomass in growth compounds because the **conversion** of light to chemical energy is **inefficient**
  - In total, only around **0.06%** of all solar radiation falling on Earth is captured by plants



From the sun to producers – the pathway of solar energy entering the atmosphere

Your notes

Energy Transfer & Transformation

Your notes

Transfer & Transformation of Energy

- Pathways of energy through an ecosystem include:
  - Conversion of light energy to chemical energy
  - Transfer of chemical energy from one trophic level to another with varying efficiencies
  - Overall conversion of ultraviolet and visible light to **heat energy** by an ecosystem
  - Re-radiation of heat energy to the atmosphere
- A food chain experiences a loss of chemical energy from one trophic level to the next
  - **Ecological efficiency** is the percentage of energy transferred from one trophic level to the next, and varies from 5% to 20%, with an average of **10%**
- Energy losses occur due to various reasons, such as movement, inedible parts (e.g. bone, teeth, fur), waste products (e.g. faeces), and the inefficient energy conversions that occur during the process of **respiration**
  - Ultimately, energy is lost as heat due to the second law of thermodynamics
- An ecosystem converts light energy into heat and chemical energy
  - Energy is converted from one form to another but cannot be created or destroyed due to the first law of thermodynamics
  - The inputs of the system as a whole, and of any individual trophic level, are **equal** to the outputs

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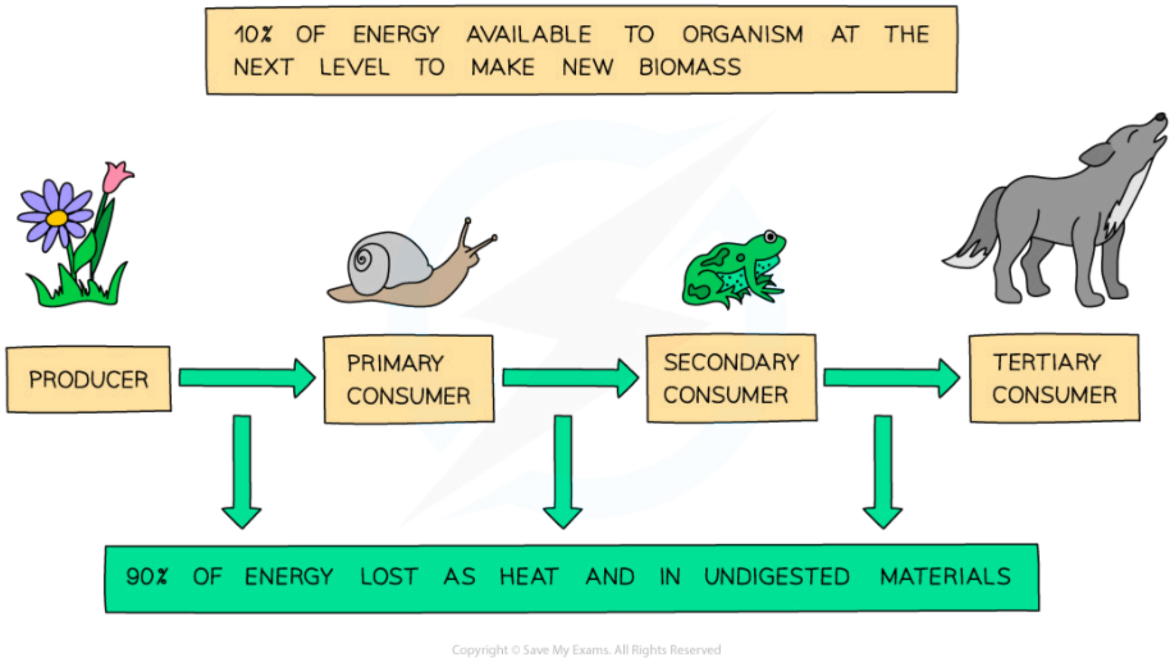


Energy is lost to the environment at every trophic level of a food chain

Calculating Ecological Efficiency

- Given the appropriate data, it is possible to calculate the efficiency of **energy transfer** from one trophic level to the next as a percentage
- This value is known as the ecological efficiency
- The equation for calculating ecological efficiency is shown below:

Ecological efficiency = (energy used for new biomass ÷ energy supplied) × 100

Worked Example

A butterfly lays an egg on a blackberry bush. In its first day, the caterpillar that hatches consumes blackberries containing a total of 35 J of energy. 4.1 J of this energy are used to form new caterpillar biomass. Calculate the ecological efficiency of this step of the food chain.

Answer

Step 1: Ensure both units are the same

Your notes

In this case, both are expressed in joules so the units do not need to be converted

Step 2: Substitute the values into the equation

Ecological efficiency = (energy used for new biomass ÷ energy supplied) × 100

Ecological efficiency = (4.1 ÷ 35) × 100

Ecological efficiency = **11.7 %**

Worked Example

A wheat farmer decides to use biological control against insect pests that are eating her wheat crop. The farmer introduces a species of toad. By eating the insect pests the toads ingest 10 000 kJ m^{-2} yr^{-1} of energy. The toads lose 7 000 kJ m^{-2} yr^{-1} of this energy as heat from respiration and 2 000 kJ m^{-2} yr^{-1} of energy in faeces and urine. Calculate the ecological efficiency of energy transfer from the insects to the toads.

Answer

Step 1: Calculate the energy used for toad growth (new biomass)

Toad energy received = 10 000 kJ m^{-2} yr^{-1}

Toad energy losses = 7 000 + 2 000 = 9 000 kJ m^{-2} yr^{-1}

Energy for growth = 10 000 - 9 000 = 1 000 kJ m^{-2} yr^{-1}

Step 2: Substitute the values into the equation

Ecological efficiency = (energy used for new biomass ÷ energy supplied) × 100

Ecological efficiency = (1 000 ÷ 10 000) × 100

Ecological efficiency = **10 %**

Productivity & Maximum Sustainable Yield

Your notes

Primary Productivity

- During photosynthesis, primary producers (such as plants and algae) convert light energy to chemical energy stored within biological molecules
- Gross primary production can be defined as the amount of **chemical energy** stored in the carbohydrates within plants (during photosynthesis)
  - Roughly only 1% of the light falling on a plant is used in photosynthesis to produce glucose
  - 99% of the light either passes through the leaf without hitting chloroplasts, is reflected off of the leaf, or is transferred to heat energy
  - After that 1% is successfully absorbed and used to form glucose, the quantity of energy now stored in glucose is the gross primary production

Gross Primary Productivity

- The **rate** at which plants are able to store chemical energy via photosynthesis is referred to as **gross primary productivity (GPP)**
- Gross primary productivity can be expressed in units of **energy** per unit **area** per unit **time**, for example:
  - **$J\ m^{-2}\ yr^{-1}$** (joules per square metre per year)
  - **$kJ\ km^{-2}\ yr^{-1}$** (kilojoules per square kilometre per year)
  - In this case, 'area' refers to the area of land that is being studied (this land contains the primary producers that are producing the biomass - if there are no primary producers present in this area of land, there will be no gross primary production)
- Gross primary productivity can also be expressed in units of **mass** per unit **area** per unit **time**, for example
  - **$g\ m^{-2}\ yr^{-1}$** (grams per square metre per year)
  - **$kg\ km^{-2}\ yr^{-1}$** (kilograms per square kilometre per year)
- In aquatic environments, it may be more suitable to measure gross primary production per unit volume
  - For example, for aquatic algae, gross primary productivity could be given in $kg\ m^{-3}\ yr^{-1}$ (kilograms per cubic metre per year) or $kJ\ m^{-3}\ yr^{-1}$ (kilojoules per cubic metre per year)

Your notes

Worked Example

The total chemical energy contained within the grass that grows in a 200 m^2 field over the course of one year is found to be 1 000 kJ. Calculate the gross primary productivity of the grass field. Give appropriate units.

Answer

Step 1: Calculate the total chemical energy contained within the grass in 1 m^2 of the field over the course of one year

1 000 ÷ 200 = 5 (kJ)

Step 2: Give the appropriate units

5 kJ m^{-2} yr^{-1}

Worked Example

On average, a patch of arctic tundra covering an area of 1 km^2 is estimated to produce a total biomass of 1,500 kg per year. Calculate the gross primary productivity of this patch. Give your answer in g m^{-2}.

Answer

Step 1: Calculate the average yearly biomass of 1 m^2 of the arctic tundra patch (1 km^2 = 1 000 000 m^2)

1 500 ÷ 1 000 000 = 0.0015 (kg yr^{-1})

Step 2: Convert this into grams

0.0015 × 1,000 = **1.5 g m^{-2} yr^{-1}**

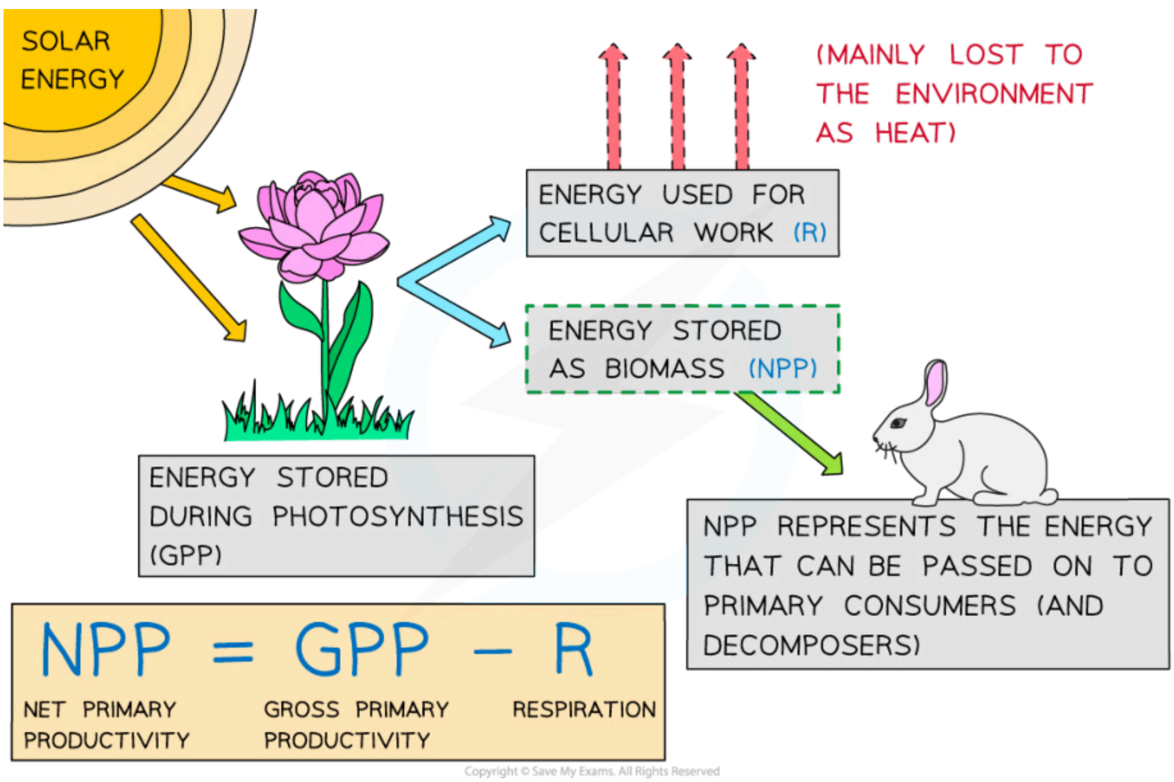
Net Primary Productivity

- **Net primary productivity (NPP)** is the **GPP minus plant respiratory losses (R)**
  - Of the total energy stored in glucose during photosynthesis, 90 % will be released from glucose during **respiration**
  - 90% of the energy originally converted by the plant will therefore **not be stored as new plant biomass** and will **not be available** to be passed on to herbivores **(primary consumers)**
- NPP can therefore be defined as the **rate at which energy is stored in plant biomass, allowing for respiratory losses**

- NPP is important because it represents the energy that is available to organisms at **higher trophic levels** in the ecosystem, such as **primary consumers** and **decomposers**
- Net primary productivity can be calculated using the equation:

$$NPP = GPP - R$$

- NPP is expressed in **units of biomass or energy per unit area or volume per unit time** e.g.
  - Using area: g m^{-2} yr^{-1} (grams per square metre per year) or J m^{-2} yr^{-1} (joules per square metre per year)
  - Using volume: kg m^{-3} yr^{-1} (kilograms per cubic metre per year) or kJ m^{-3} yr^{-1} (kilojoules per cubic metre per year)
  - As with GPP, volume would be used when calculating NPP in **aquatic habitats**



Net primary productivity, or NPP, is the rate at which energy is stored in plant biomass and made available to primary consumers

Your notes

Worked Example

The grass in a meadow habitat converts light energy into carbohydrates at a rate of 17 500 kJ m^{-2} yr^{-1}. The grass releases 14 000 kJ m^{-2} yr^{-1} of that energy during respiration. Calculate the net primary productivity of the grass in the meadow habitat.

Answer

Step 1: Work out which numbers correspond to which parts of the equation

The meadow grass converts 17 500 kJ m^{-2} yr^{-1} into carbohydrates; this is GPP

The meadow grass releases 14 000 kJ m^{-2} yr^{-1} of that energy in respiration; this is R

Step 2: Substitute numbers into the equation

NPP = GPP - R

NPP = 17 500 - 14 000

Step 3: Complete calculation

17 500 - 14 000 = 3 500

NPP = **3 500 kJ m^{-2} yr^{-1}**

Secondary Productivity

- Gross secondary productivity (GSP) is the total energy/biomass assimilated by consumers and is calculated by subtracting the mass of faecal loss from the mass of food eaten
- Gross secondary productivity can be calculated using the equation:

GSP = food eaten – faecal loss

- Net secondary productivity (NSP) is calculated by subtracting respiratory losses (R) from GSP
- Net secondary productivity can be calculated using the equation:

NSP = GSP – R

- As with gross primary productivity and net primary productivity, GSP and NSP are expressed in **units of biomass or energy per unit area or volume per unit time** e.g.
  - Using area: g m^{-2} yr^{-1} (grams per square metre per year) or J m^{-2} yr^{-1} (joules per square metre per year)
  - Using volume: kg m^{-3} yr^{-1} (kilograms per cubic metre per year) or kJ m^{-3} yr^{-1} (kilojoules per cubic metre per year)
  - Volume would be used when calculating GSP or NSP in **aquatic habitats**

Your notes

Worked Example

In a patch of woodland, caterpillars ingest 2 000 kJ m^{-2} yr^{-1} of chemical energy from the biomass of oak leaves. The caterpillars lose 1 200 kJ m^{-2} yr^{-1} of this energy in faeces. They lose a further 600 kJ m^{-2} yr^{-1} of this energy through respiration. Calculate the net secondary productivity of the caterpillars.

Answer

Step 1: Calculate GSP

GSP = food eaten - faecal loss

GSP = 2 000 - 1 200

GSP = 800 kJ m^{-2} yr^{-1}

Step 2: Calculate NSP

NSP = GSP - R

NSP = 800 - 600

NSP = **200 kJ m^{-2} yr^{-1}**

Maximum Sustainable Yield

- The **annual yield** for a natural resource (such as a forest) is the annual **gain** in **biomass** or **energy,** through growth
- The **maximum sustainable yield** is the maximum amount of a renewable natural resource that can be harvested annually without compromising the long-term productivity of the resource (i.e. without a reduction in natural capital)
- It is the level of **harvest** that can be maintained **indefinitely**
- The concept of maximum sustainable yield applies to various resources, such as crops, fish, timber, and game animals
  - For example, in fisheries, the concept of maximum sustainable yield is used to determine the maximum amount of fish that can be harvested sustainably from a given population
  - This is calculated based on the population size, growth rate, and reproduction rate
  - If the fishing rate exceeds the maximum sustainable yield, the population may decline, and the long-term productivity of the fishery may be compromised

- Similarly, in forestry, the concept of maximum sustainable yield is used to determine the maximum amount of timber that can be harvested sustainably from a forest
- This is calculated based on the growth rate and regeneration capacity of the trees
- If the harvesting rate exceeds the maximum sustainable yield, the forest may become depleted, and the long-term productivity of the forest may be compromised

- In this way, maximum sustainable yield is **equivalent** to the net primary productivity (NPP) or net secondary productivity (NSP) of a system (as these values represent the amount of energy stored and new plant or animal biomass per year)

Your notes

Examiner Tips and Tricks

When answering questions on GPP or NPP, make sure you give the appropriate units. GPP and NPP can either be expressed in terms of **biomass** (per unit area per unit time) or **chemical energy** (per unit area per unit time). The biomass of an organism is effectively a measure of how much chemical energy is stored within it!

The worked example for calculating NPP uses the equation in its basic form, but you may also be expected to rearrange the equation e.g. to calculate GPP or R

If a question provides you with the NPP and R and asks you to calculate GPP, you will need to use the following equation:

GPP = NPP + R

If a question provides you with the NPP and the GPP and asks you to calculate R, you will need to use the following equation:

R = GPP – NPP

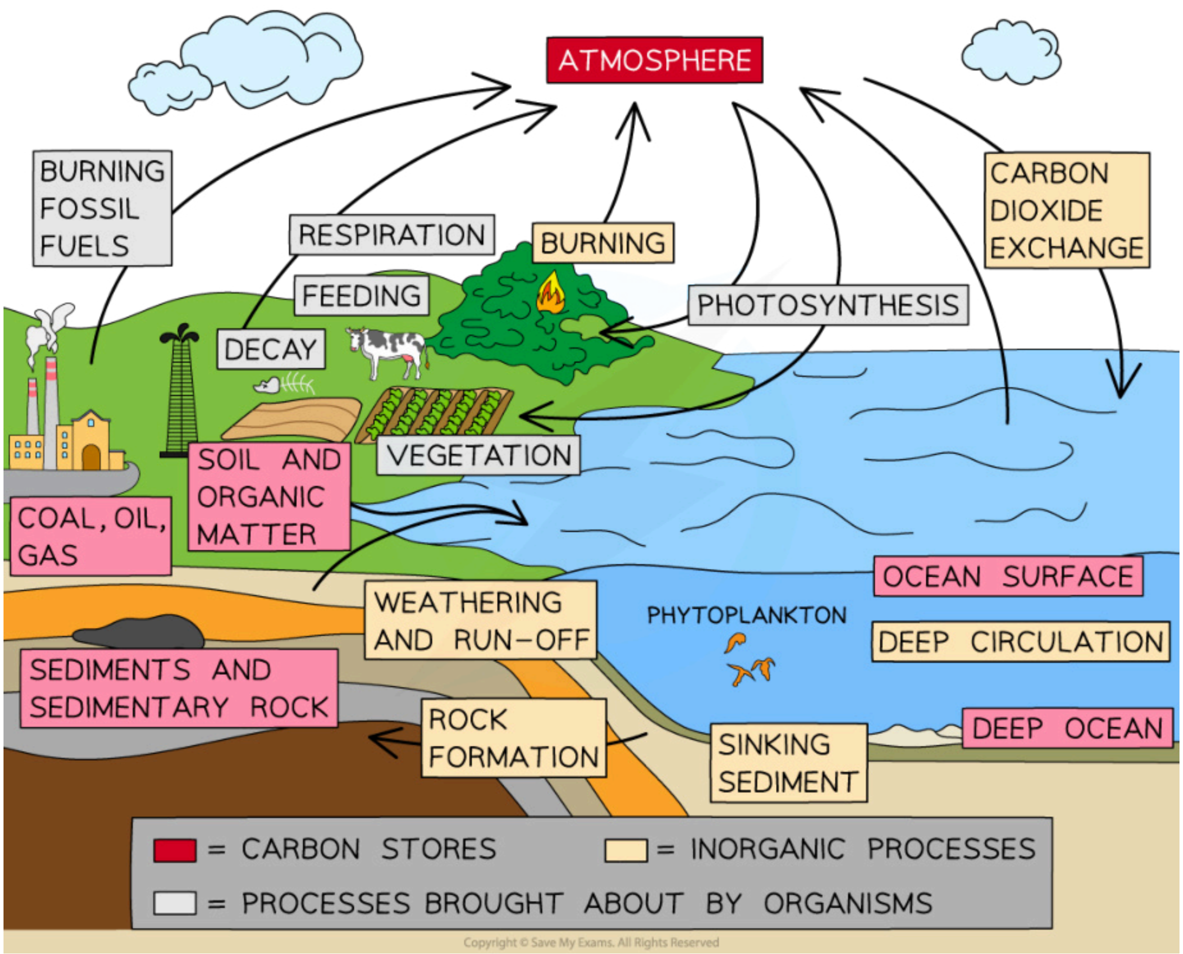
What is the Carbon Cycle?

Your notes

The Carbon Cycle

What is the carbon cycle?

- Carbon is constantly being recycled around the biosphere so that the number of carbon atoms in the biosphere is essentially constant; carbon atoms merely swap from one compound to another by the various processes in the carbon cycle



Carbon cycle diagram

Storage and Flows in the Carbon Cycle

Your notes

- Storages in the carbon cycle include:
  - The atmosphere (as CO_2)
  - Sedimentary rocks
  - Fossil fuels like coal, oil, and gas; coal is largely carbon
  - Soil and other organic matter
  - Vegetation (e.g. as cellulose)
  - Animals
  - Dissolved in the oceans (as CO_2)
- Flows in the carbon cycle include:
  - Consumption (feeding)
  - Death and decomposition
  - Photosynthesis
  - Respiration
  - Dissolving
  - Fossilisation

Photosynthesis

- **Autotrophs** use the energy of sunlight to 'fix' carbon dioxide, turning its carbon into sugars and other organic molecules
- This removes carbon from the atmosphere
- Terrestrial plants use gaseous CO_2 directly from the air
- Aquatic organisms use CO_2 dissolved in water
- As much CO_2 is fixed from ocean microorganisms, as from terrestrial plants

Sedimentation

- Plants that die are not fully decomposed by saprobionts; their bodies form layers of sediment that can accumulate over millions of years, locking carbon into the ground
- This sediment is a store of energy and can form fossil fuels like peat and coal
- Aquatic organisms that die also form sediments on the sea bed; these can go on to form other fossil fuels like oil and gas

- Shells and other calcium-containing body parts can form sedimentary rocks such as limestone
- The existence of life forms over billions of years has shaped the biosphere, in that their remains are still being recycled

Respiration

- All life forms respire, including autotrophs
- Heterotrophs rely on respiration for all their energy needs
- Respiration puts CO_2 into the atmosphere, in the opposite direction to photosynthesis
- Anaerobic respiration also releases CO_2 into the atmosphere, via fermentation by yeast, moulds and bacteria

Feeding

- Carbon is passed from autotroph to **heterotroph** during feeding
- Carbon is also passed from primary consumer to secondary consumer
- Biomass transfer always includes the transfer of carbon, the main element in biomass

Decay & Decomposition

- Dead plants and animals are fed upon by detritivores and decayed by saprophytes
- Releasing carbon into the surroundings
- Supplying carbon to the detritivores
- Supplying carbon to the saprophytes
- Waste matter such as faeces and urine is used by decaying saprobionts
- Such processes can release CO_2 back into the air

Human Impacts on the Carbon Cycle

What is the human impact on the carbon cycle?

- Human activities such as burning fossil fuels, burning, deforestation, urbanisation and agriculture impact the balance of storages and flow within the carbon cycle

Burning fossil fuels

- Since the mid 19th century, humans have extracted and burned increasing amounts of fossil fuels from the Earth

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Your notes

- CO_2 is being returned to the atmosphere faster than it can be absorbed by plants and aquatic producers
- The CO_2 level in the atmosphere is approximately double that of 800,000 years ago
- Warmer temperatures mean that less CO_2 can be dissolved in the oceans, so is released into the air
- This has caused dramatic climate change and affected many other species, mainly through changing habitats

Photo by Renaldo Matamoro on Unsplash

Deforestation reduces the ability of forests to act as carbon sinks

Deforestation

- Mass deforestation is reducing the amount of producers available to take carbon dioxide out of the atmosphere by photosynthesis
- In many areas of the world, deforestation is taking place for land rather than for timber, and as such these forest are simply burnt down, releasing yet more carbon dioxide into the atmosphere

Urbanisation

- As well as increasing human activities such as transportation, energy use, and industrial activities in urban areas, urbanisation also affects the carbon cycle by altering land use patterns
- Forests, wetlands, and other natural ecosystems are often replaced with buildings, roads, and other infrastructure
- This reduces the amount of carbon that can be sequestered in plants and soil, and the carbon storage capacity of the land is decreased.

Worked Example

Discuss human impacts on the carbon cycle.

Answer

Humans have a significant impact on the carbon cycle, mainly through the combustion of fossil fuels and deforestation. Fossil fuels such as coal, oil, and natural gas contain carbon that has been stored underground for millions of years. When these fuels are burned, carbon is released into the atmosphere as carbon dioxide (CO_2), contributing to the greenhouse effect and climate change.

Deforestation, especially in tropical regions, also affects the carbon cycle. Trees and other plants absorb CO_2 from the atmosphere during photosynthesis, storing carbon in their biomass. When trees are cut down and burned or left to decay, the stored carbon is released back into the atmosphere as CO_2.

Other human activities that contribute to carbon emissions include agriculture, transportation, and industry. For example, livestock farming produces methane, a potent greenhouse gas, through enteric fermentation in cows, sheep, and other ruminants. Transportation, especially cars and trucks, burns fossil fuels and releases CO_2 into the atmosphere. Industry and manufacturing processes also contribute to carbon emissions through the burning of fossil fuels and other energy-intensive processes.

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What is the Nitrogen Cycle?

The Nitrogen Cycle

Nitrogen Cycle

- Nitrogen is the most abundant gas in the atmosphere, though is relatively inert. It does have a role in biology thanks to its ability to be converted (fixed) into biomass
- Bacteria and other microorganisms play a vital role in the nitrogen cycle
- Nitrogen-fixing bacteria are able to convert gaseous nitrogen into ammonium ions (NH_4^+)
- Ammonium ions are nitrified by nitrifying bacteria into nitrite (NO_2^-) and nitrate (NO_3^-), which are highly soluble and can be absorbed by roots
- Denitrifying bacteria use nitrates for respiration and return gaseous nitrogen to the atmosphere
- Other bacteria and fungi are involved in saprobiotic decomposition e.g. decay of dead biomass or excreta

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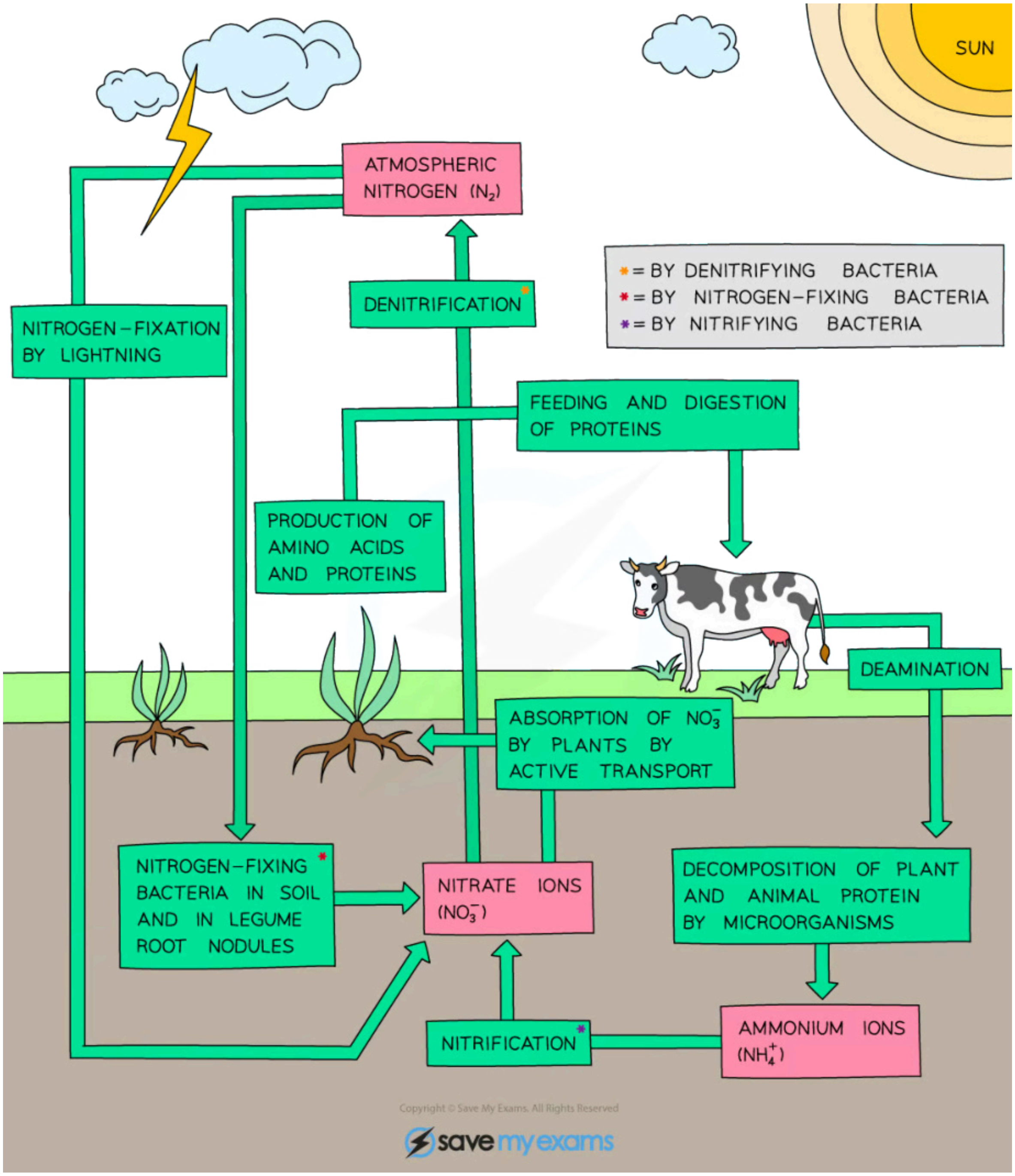

Your notes

Nitrogen cycle diagram

Storage and Flows in the Nitrogen Cycle

- Storages in the nitrogen cycle include:
  - Organisms (organic)
  - Soils (inorganic)
  - Fossil fuels (organic)
  - Atmosphere (inorganic)
  - Water bodies (inorganic)
- Flows in the nitrogen cycle include:
  - Nitrogen fixation by bacteria and lightning
  - Absorption
  - Assimilation
  - Consumption (feeding)
  - Excretion
  - Death and decomposition
  - Denitrification by bacteria in water logged soils

Human Impacts on the Nitrogen Cycle

What is the human impact on the nitrogen cycle?

- Increased use of fertilisers:
  - Fertilisers, especially nitrogen fertilisers, are widely used in agriculture to increase crop yield
  - However, excess nitrogen can leach into waterways, leading to eutrophication and harmful algal blooms
- Burning of fossil fuels:
  - Burning fossil fuels releases nitrogen oxides into the atmosphere, which can lead to the formation of acid rain
  - Acid rain can increase soil acidity, which can affect the ability of plants to take up nitrogen
- Industrial nitrogen fixation:
  - Humans have developed methods to fix nitrogen industrially, for example, in the production of fertilisers and explosives

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- This has greatly increased the amount of fixed nitrogen available for use in human activities

Photo by James Park on Unsplash

Wetlands are important nitrogen sinks

Your notes

- Land-use changes:
  - Conversion of natural landscapes, such as forests and wetlands, into agricultural or urban areas can lead to changes in nitrogen cycling
  - For example, wetlands are important nitrogen sinks, and their loss can result in nitrogen being released into waterways and the atmosphere
- Livestock farming:
  - Livestock farming produces large amounts of manure and urine, which can contribute to increased nitrogen inputs to ecosystems
  - This can lead to eutrophication and other environmental problems if not managed properly
- Wastewater treatment:
  - Wastewater treatment plants can be a source of nitrogen pollution if they do not effectively remove nitrogen from treated water before releasing it into the environment