DP IB Environmental Systems & Societies (ESS): HL

Your notes

2.2 Energy & Biomass in Ecosystems

Contents

Energy Flow in Ecosystems

- Ecosystems rely on a constant supply of **energy** and **matter** to maintain their structure and function
    - Energy is essential for driving biological processes, while matter cycles through the ecosystem, being reused and recycled
- Ecosystems are considered **open systems**, meaning they exchange both energy and matter with their surroundings
    - Energy enters ecosystems primarily from the sun, entering as sunlight and being converted into chemical energy by producers through photosynthesis
        - This energy is then **transferred between trophic levels** as organisms consume one another, with some energy lost as **heat** at each transfer
        - Decomposers break down organic matter, releasing energy and returning nutrients to the environment
    - Matter, such as nutrients and water, flows into and out of ecosystems through various processes like decomposition, nutrient cycling and precipitation

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
    - It means that as energy flows through **ecosystems**, it can only change from one form to another
- 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 states that:

Energy transfers in ecosystems are inefficient

- This is because energy transfers in **any system** are **never 100% efficient**
- The second law of thermodynamics explains the **decrease in available energy within ecosystems**:
  - In a food chain, energy is transformed from a more concentrated (ordered) form (e.g. light energy from the Sun), into a more dispersed or disordered form (heat energy lost by organisms)
  - Initially, light energy from the Sun is absorbed by producers
    - However, even at this initial stage, energy absorption and transfer by producers is **inefficient**
    - This is 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 due to **respiration** and the production of **waste** heat energy
    - In ecosystems, the biggest losses occur during cellular respiration
    - When energy is transformed, some must be degraded into a less useful form, such as heat
  - As a result of these inefficient energy transfers, food chains are often **short** (they rarely contain more than five trophic levels)

Photosynthesis

Photosynthesis

What is photosynthesis?

- Primary producers in the majority of ecosystems convert **light energy** into **chemical energy** in the process of photosynthesis
  - Producers are typically plants, algae and photosynthetic bacteria that produce their **own food** using photosynthesis
    - They are also known as autotrophs
  - Producers form the **first** trophic level in a food chain
  - The photosynthesis reaction is:

Photosynthesis word equation

- The inputs and outputs are:
  - **Inputs**: sunlight as an energy source, carbon dioxide, and water
  - **Processes**: inside chloroplasts, chlorophyll captures certain visible wavelengths of sunlight energy and stores this as chemical energy
  - **Outputs**: glucose and oxygen
  - **Transformations**: light energy is transformed into stored chemical energy (in the form of glucose)
- Photosynthesis produces the raw material for producing **biomass**
  - The glucose produced during photosynthesis is used as an energy source for the plant but also as the basic starting material for other organic molecules (e.g. cellulose and starch)
- In ecosystems where sunlight and water are available, the process of photosynthesis enables plants to synthesise these organic compounds (glucose and other sugars) from carbon dioxide

- Most of these sugars synthesised by plants are used by the plant as **respiratory substrates**
    - A respiratory substrate is a molecule (such as glucose) that can be used in **respiration**, to release **energy** for **growth**

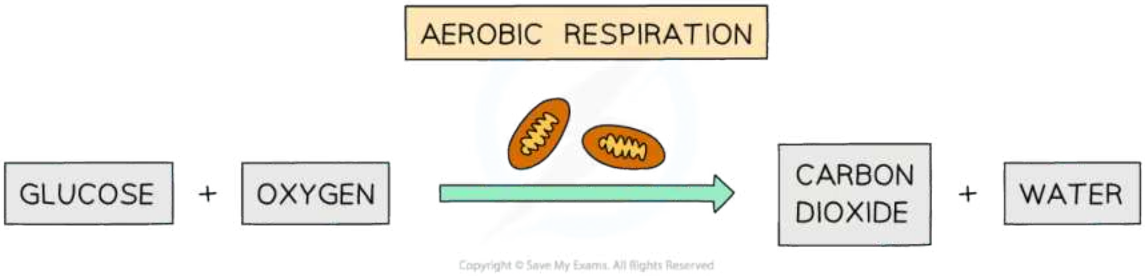
Examiner Tips and Tricks

You are not required to know the biochemical details of photosynthesis, just remember that photosynthesis is the conversion of light energy to chemical energy in the form of glucose, some of which can be stored as biomass by producers.

Respiration

Respiration

- Respiration is the conversion of organic matter into carbon dioxide and water in all living organisms, releasing **energy**
    - Cellular respiration releases energy from **glucose** by converting it into a chemical form that can easily be used in carrying out **active processes** (such as growth and repair) within **living cells**
    - The **aerobic respiration** reaction is:



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Aerobic respiration

- The inputs and outputs are:
    - **Inputs**: organic matter (glucose) and oxygen
    - **Processes**: oxidation processes inside cells
    - **Outputs**: release of energy for work (movement) and heat
    - **Transformations**: stored chemical energy is transformed into kinetic energy and heat
- Some of the chemical energy released during cellular respiration is transformed into **heat**
    - Heat is generated by cellular respiration because it is **not 100% efficient** at transferring energy from substrates, such as carbohydrates, into the chemical form of energy used in cells
    - Heat generated within an individual organism **cannot** be transformed back into chemical energy and is ultimately lost from the body
    - The heat energy released increases the **entropy** in the ecosystem, following the second law of thermodynamics, while enabling organisms to maintain relatively low entropy (high organisation)

Examiner Tips and Tricks

You are not required to know that adenosine triphosphate (ATP) is the readily usable energy currency of cells, just remember that the energy released by respiration is used in carrying out active processes within living cells.

Trophic Levels & Food Chains

What are trophic levels?

- The trophic level is the **position** that an organism occupies in a food chain (or food web)
  - If multiple organisms occupy the same position in a food chain, they are in the same trophic level

Trophic Levels

Trophic Level	Name of Trophic Level	Description of Organisms in Trophic Level
1	Producers	Plants and algae—produce their own biomass using energy from sunlight
2	Primary consumers	Herbivores—feed on producers
3	Secondary consumers	Predators—feed on primary consumers
4	Tertiary consumers	Predators—feed on secondary consumers

- **Producers** are typically plants or algae and produce their own food using photosynthesis
  - They form the **first trophic level** in a food chain
- The chemical energy stored in producers is then transferred to **primary consumers** as they **consume** (eat) producers
- The chemical energy is then transferred from one consumer to the next as they eat one another
- Consumers have diverse strategies for obtaining energy-containing carbon compounds

Consumer Strategies

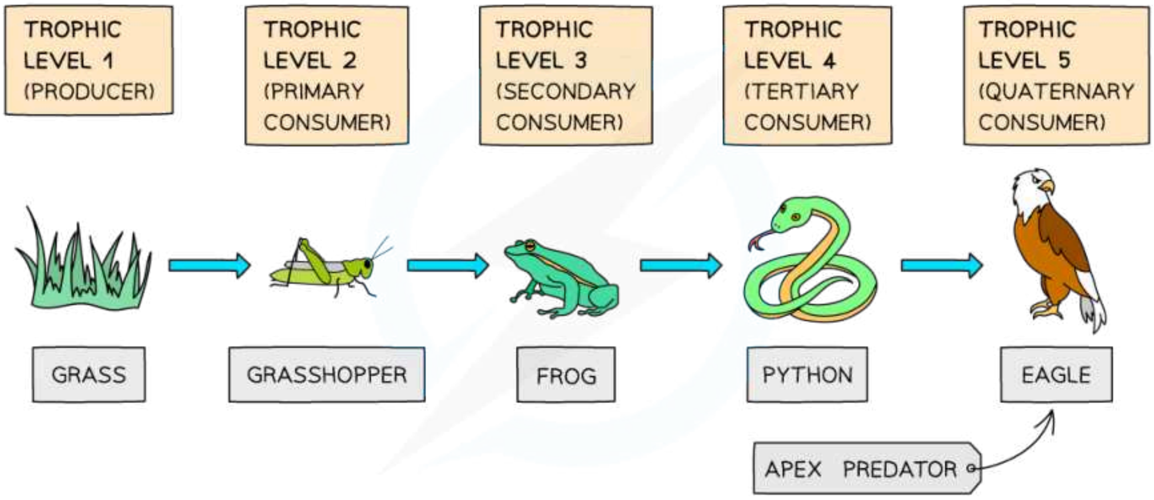
Type of Consumer	Description	Examples

Herbivores	Feed primarily on plants and plant-derived material	Deer: graze on grasses, leaves, and shrubs Rabbits: consume grasses, herbs, and vegetables
Detritivores	Consume decomposing organic matter (detritus) and help break it down further	Earthworms: feed on decaying plant material and enhance soil structure Dung beetles: consume animal dung, aiding in nutrient recycling
Predators	Hunt and consume other organisms (prey) for food	Lions: prey on various herbivores such as gazelles and zebras Wolves: hunt animals like deer and elk in packs
Parasites	Depend on a host organism for survival, often harming but not immediately killing it	Tapeworms: live in the intestines of mammals, absorbing nutrients from the host's food Mosquitoes: feed on the blood of animals, including humans, for nourishment
Saprotrophs and decomposers	Saprotrophs: decompose dead organic matter externally and absorb nutrients Decomposers: break down organic matter into simpler substances, playing a vital role in nutrient recycling	Fungi: break down dead plant material, such as fallen leaves and wood, into simpler compounds Bacteria: decompose organic matter, releasing nutrients for plant uptake
Scavengers	Consume dead animal carcasses, helping to clean up ecosystems	Vultures: feed on the remains of dead animals, scavenging carrion Hyenas: opportunistic scavengers known to consume a wide range of animal remains

Food chains

- Feeding relationships in ecosystems can be modelled using food chains

- Because producers in ecosystems make their own carbon compounds by photosynthesis, they are at the start of food chains
- Consumers obtain carbon compounds from producers or other consumers, so are placed in the higher trophic levels
- In a food chain, carbon compounds and the energy they contain are passed from primary producers to primary consumers to secondary consumers, and so on
- Apex predators are at the very top of the food chain—they are carnivores or omnivores with no predators
  - The chemical energy stored within apex predators can be passed on to **decomposers** when apex predators die and are decomposed
  - Traditionally, decomposers are not included in food chains as they gain carbon compounds from a variety of trophic levels

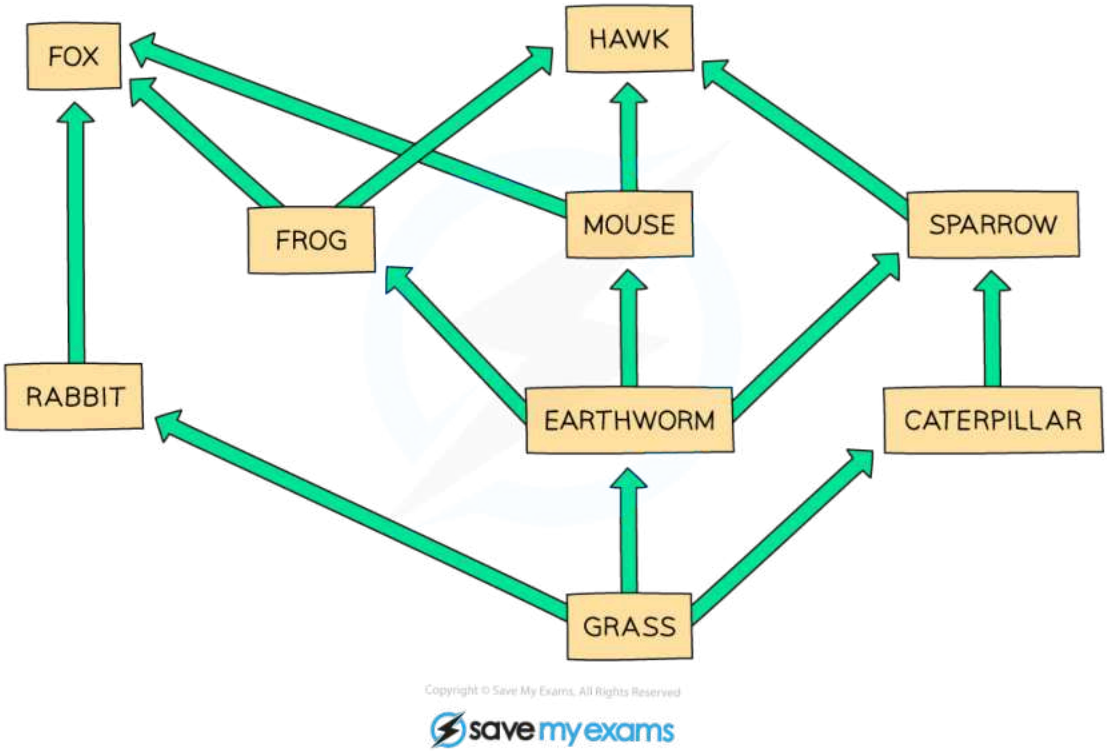


Trophic levels for a simple food chain—the blue arrows show how the chemical energy originally produced by the primary producer (grass) is transferred to other organisms in the community

Food Webs

Food Webs

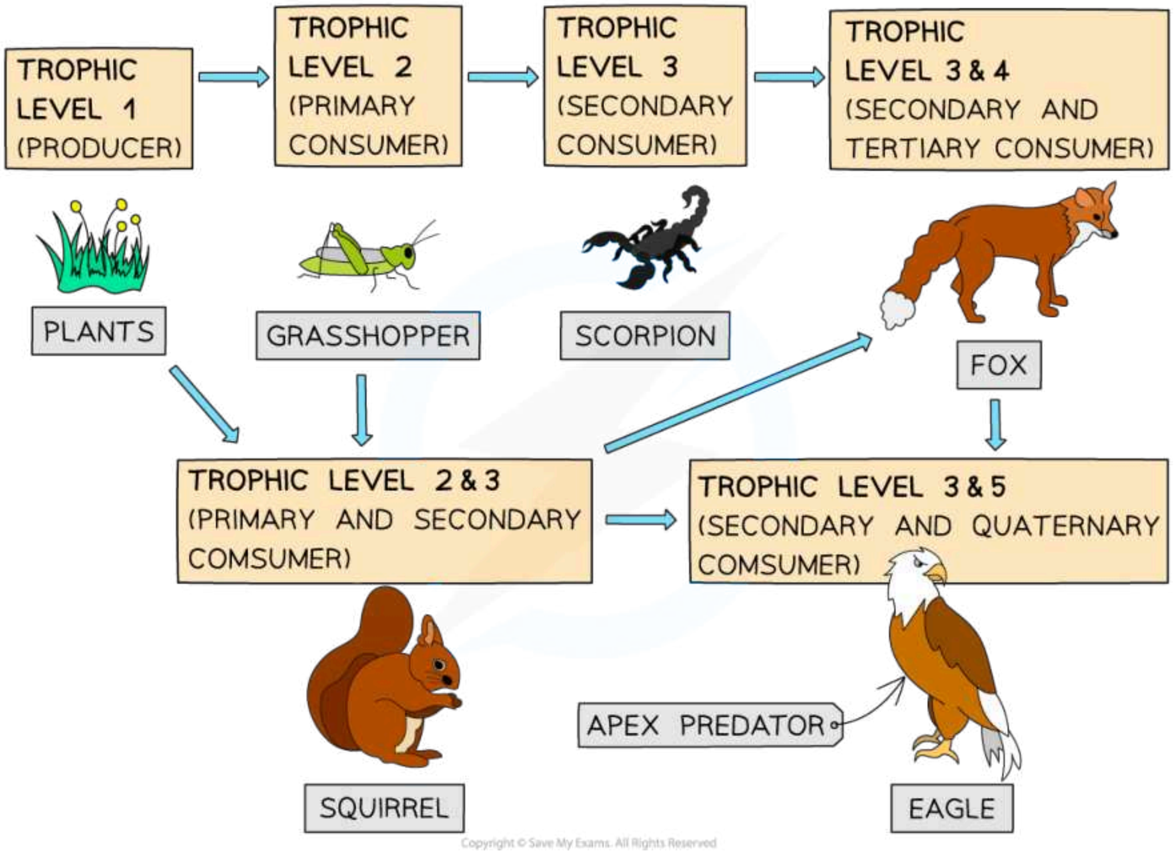
- A food web is a network of **interconnected food chains**
- Food webs are more realistic ways of showing connections between organisms within an ecosystem as **consumers rarely feed on just one type of food source**



A food web shows the interdependence of organisms

- Compared to food chains, food webs give us a lot more information about the transfer of energy in an ecosystem
- They also show **interdependence** (how a change in one population can affect others within the food web)
- For example, in the food web above, if the **population of earthworms decreased**:
    - The population of **grass plants would increase** as there are now fewer species feeding off them

- The populations of **frogs and mice would decrease significantly** as earthworms are their only food source
- The population of **sparrows would decrease slightly** as they eat earthworms but also have another food source to rely on (caterpillars)



Trophic levels for a simple food web—note that some organisms can belong to more than one trophic level (such as the squirrel, fox and eagle in this food web)

Examiner Tips and Tricks

Remember—the arrows in food chains and food webs indicate the direction of energy flow and transfer of biomass.

Energy Losses in Food Chains

Energy Losses in Food Chains

- The total **organic matter** transferred from one trophic level to the next is **never 100%** because:
    1. Not all the food available to a given trophic level is harvested
    2. Of what is harvested, not all is consumed
    3. Of what is consumed, not all is absorbed
    4. Of what is absorbed, not all is stored
- For example, if we take the example of caterpillars (the primary consumer) eating the leaves of an oak tree (the producer):
    1. The caterpillars do not eat every leaf available to them (there may simply be too many leaves, not enough caterpillars, or some leaves may be in locations that are difficult for the caterpillars to access)
    2. The caterpillars may not eat the entire leaf (they might eat only the softer, more nutritious parts and leave behind tougher portions or parts with toxins)
    3. Once the caterpillars eat the leaves, not all of the nutrients are absorbed by their bodies (some parts of the leaves may be indigestible or contain compounds that the caterpillars cannot process, which are then egested by the caterpillars)
    4. When the caterpillars digest the leaves and convert the nutrients into energy, not all of the energy from the leaves is stored for growth and development, as some of that energy is lost as heat during cellular respiration

Productivity & Biomass

Productivity

- **Gross productivity** (GP) is the **total gain in biomass** by an organism or community in a given area or time period
  - It includes all the energy captured by organisms
  - E.g. by plants through photosynthesis or by consumers feeding on other organisms
    - For example, in a pond ecosystem, the total amount of energy captured by the aquatic plants and other species in the pond represents the gross productivity of that ecosystem
- **Net productivity** (NP) is the amount of energy or biomass remaining **after losses due to cellular respiration**
  - These energy losses are **subtracted** from the gross productivity
  - Net productivity reflects the energy available for **growth** and **reproduction**
    - For example, if a plant has captured 1 000 kJ of energy through photosynthesis (gross productivity) but has used 300 kJ for cellular respiration, its net productivity would be 700 kJ
- Losses due to cellular respiration are usually **greater in consumers** than in producers
  - This is due to the more energy-requiring activities of consumers
    - For example, herbivores need to spend energy on activities such as digestion and movement, resulting in higher respiratory losses compared to plants

Net productivity and sustainable yield

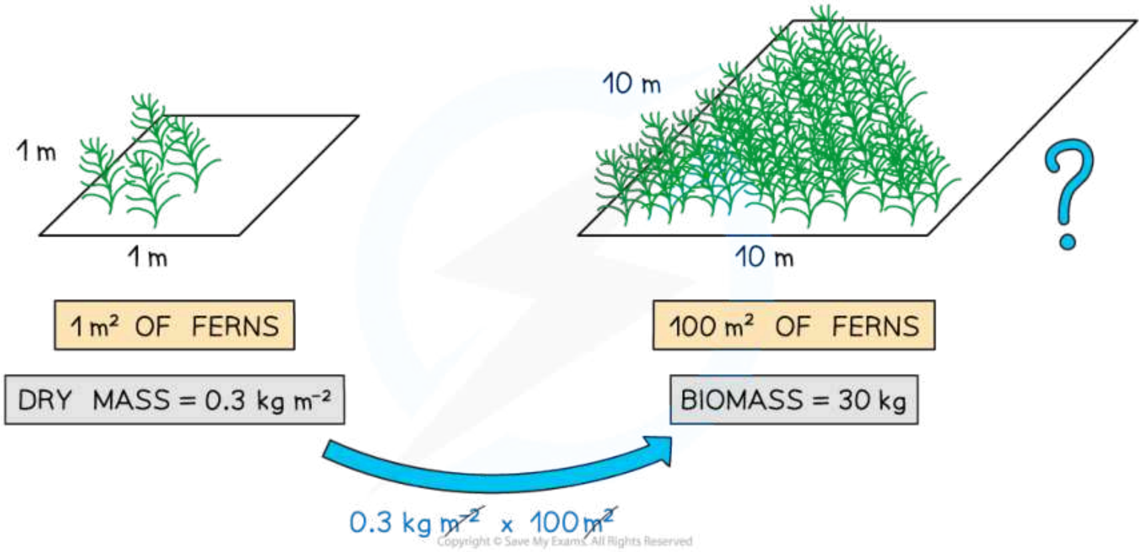
- The NP of any organism or trophic level represents the maximum sustainable yield that can be harvested without decreasing the availability of resources for the future
  - To maintain ecosystem stability and biodiversity, it is important to **avoid harvesting beyond the sustainable yield** of populations
    - For example, in fisheries management, the sustainable yield of fish populations is determined by considering the net productivity of the fishery
    - Harvesting beyond the sustainable yield can lead to overexploitation and depletion of fish stocks
    - This affects both the ecosystem itself and human livelihoods

Measuring Biomass

- Estimating the biomass and energy of trophic levels in a community is an important step in understanding the structure and function of an ecosystem
- There are several methods for measuring the biomass of a particular trophic, including:
    - Measurement of dry mass
    - Controlled combustion
    - Extrapolation from samples

Measurement of dry mass

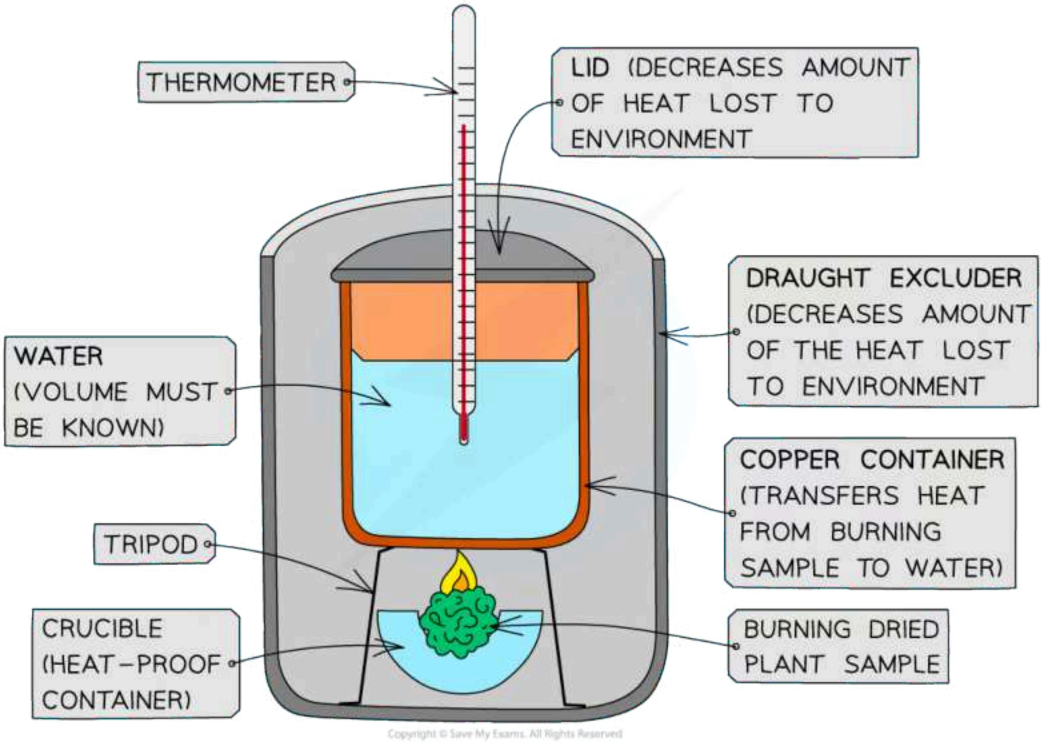
- One common method for estimating biomass is to measure the dry mass of organisms
- This involves collecting samples of organisms from a particular **trophic level** and drying them in an oven to **remove all water** within the tissues
- The dry weight of the sample is then measured
- This can then be used to estimate the **total biomass** of the populations that have been sampled
    - Dry mass of samples is approximately equal to the mass of organic matter (biomass) since water represents the majority of inorganic matter in most organisms
- For example:
    - If the dry mass of one daffodil plant is found to be 0.1 kg, then the dry mass (i.e. the biomass) of 200 daffodils would be 20 kg (0.1 x 200 = 20)
    - If the dry mass of the grass from 1 m^2 of a field is found to be 0.2 kg, we can say that the grass has a dry mass (i.e. biomass) of 0.2 kg m^{-2} (this means 0.2 kg per square metre)
    - If the grass field is 200 m^2 in size, then the biomass of the whole field must be 40 kg (0.2 x 200 = 40)



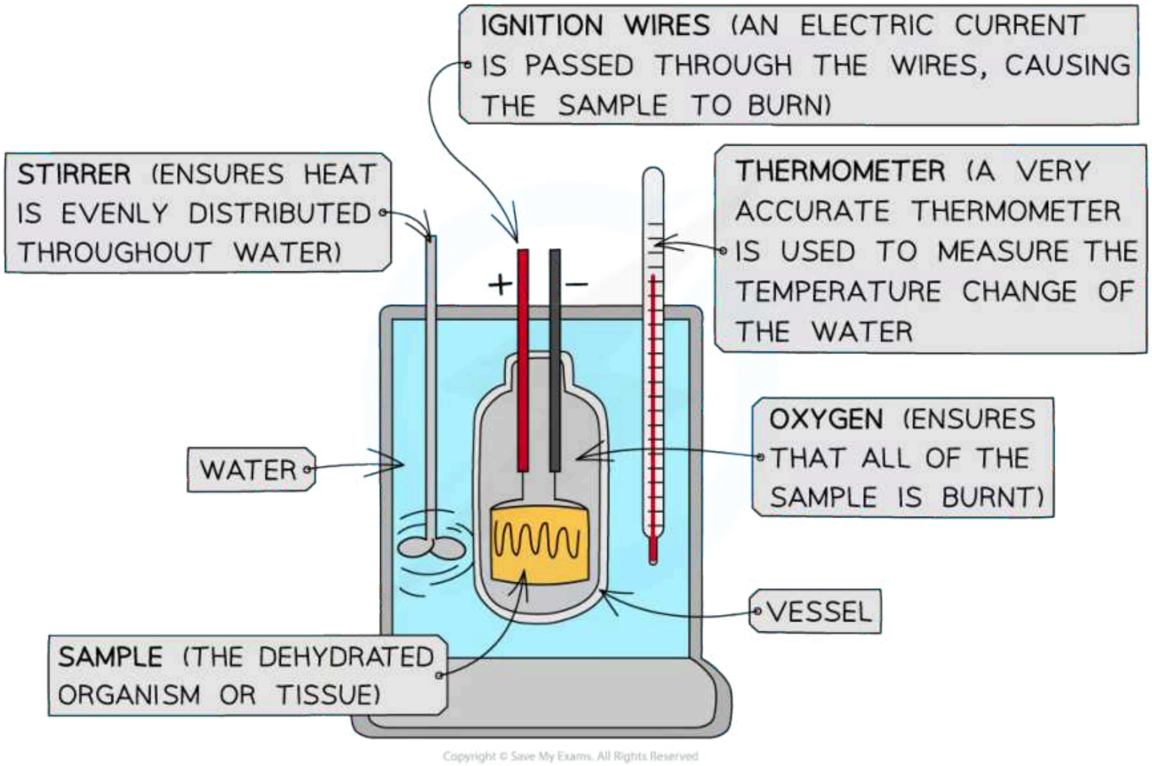
It is possible to estimate the biomass of organisms in a larger area if you know the dry mass of the organisms in a given (smaller) area

Controlled combustion

- Another method for estimating biomass is controlled combustion
- This involves burning a known quantity of biomass and measuring the **heat produced**
- By knowing the heat value of the biomass, it is possible to estimate the total biomass of a population or trophic level, based on the amount of heat produced
- A piece of equipment known as a **calorimeter** is required for this process
  - The burning sample heats a **known volume** of **water**
  - The **change in temperature** of the water provides an estimate of the chemical energy the sample contains



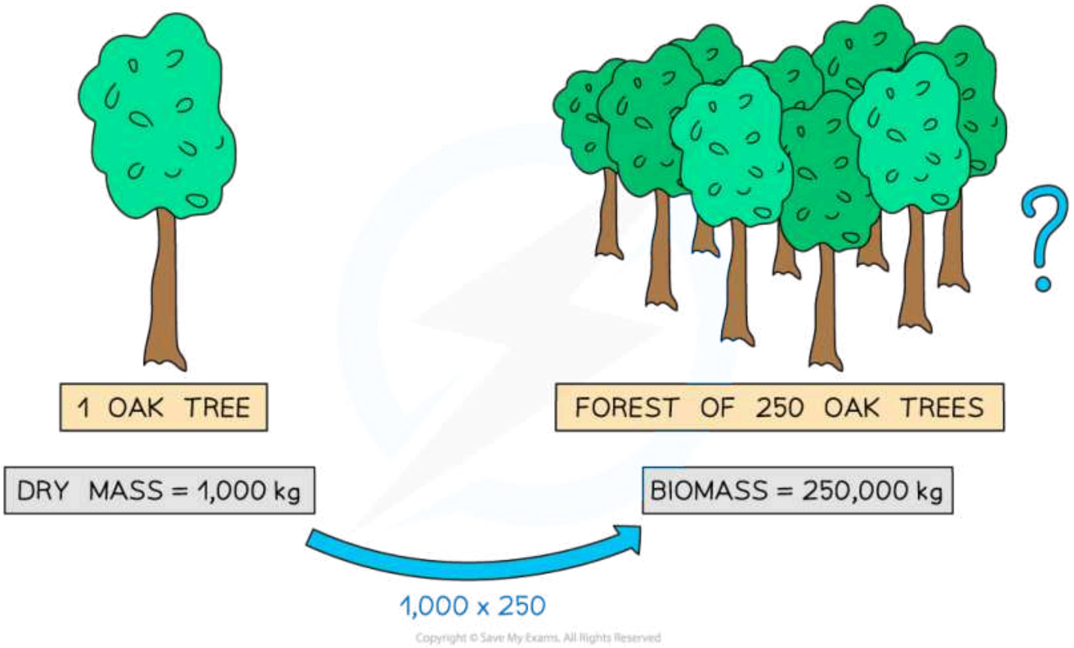
A simple, inexpensive version of a calorimeter that can be set up using classroom equipment



An example of a more precise (and much more expensive) version of a calorimeter known as a bomb calorimeter—this type is used in professional scientific laboratories

Extrapolation from samples

- A third method for estimating biomass is to take small samples of populations and extrapolate to estimate the total biomass of a population or trophic level
- This method can be particularly useful when dealing with **large** or **difficult-to-sample** populations



It is possible to estimate the biomass of a group of organisms if you know the dry mass of a single organism

- Data obtained from these methods can be used to construct ecological pyramids
  - Ecological pyramids (such as pyramids of biomass) are very useful in visually illustrating the relationships between different trophic levels in an ecosystem and how energy and biomass are transferred through the system

Limitations of calorimetry

- It can take a **long time** to fully dehydrate (dry out) a biological sample to find its dry mass
  - This is partly because the sample has to be heated at a relatively low temperature to ensure it doesn't burn

  - Depending on the size of the sample, the drying process could take several days
- **Precise equipment** is needed, which may not be available and can be very expensive
  - A very precise digital balance should be used to measure the mass of the sample as it is drying
    - This is to detect even extremely small changes in mass
  - It is preferable to use a very precise digital thermometer when measuring the temperature change of the water in the calorimeter
    - This is to detect even very small temperature changes
- The more simple and basic the calorimeter, the less accurate the estimate will be for the chemical energy contained within the sample
  - This is due to heat energy from the burning sample being **lost** and not being **transferred efficiently** to the water
  - A bomb calorimeter ensures that almost all the heat energy from the burning sample is transferred to the water, giving a **highly accurate estimate**

Ecological Pyramids

Ecological Pyramids

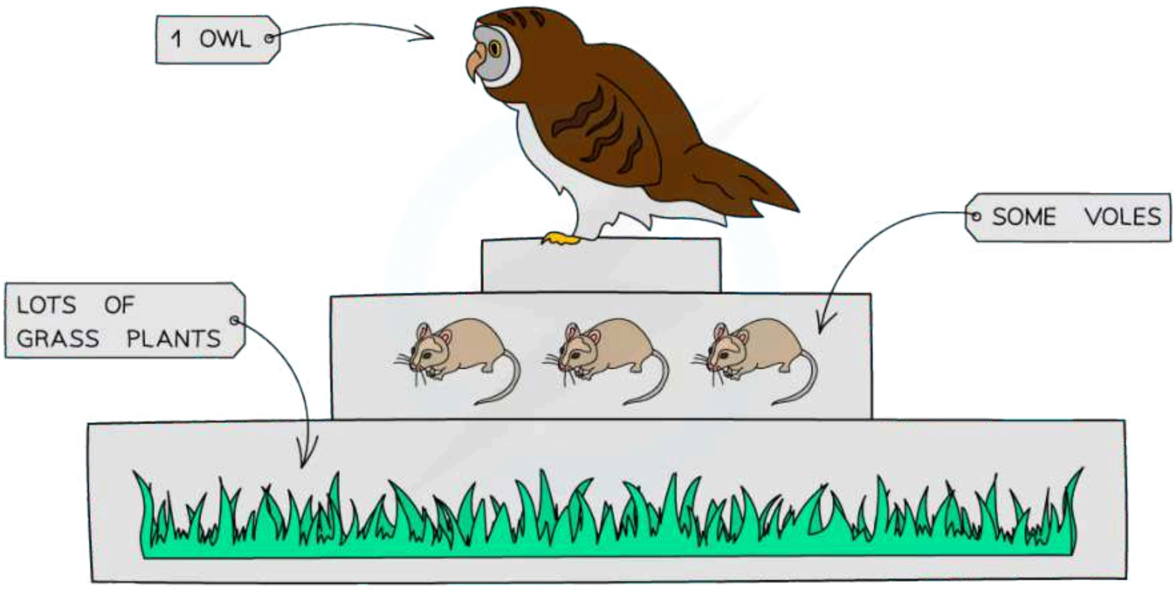
- Ecological pyramids include:
  - Pyramids of numbers
  - Pyramids of biomass
  - Pyramids of energy (also known as pyramids of productivity)
- They are quantitative models usually measured for a given **time** and **area**

Pyramids of numbers

- A pyramid of **numbers** shows how many organisms we are talking about at each level of a food chain
- The **width** of the box indicates the **number of organisms** at that trophic level
- For example, consider the following food chain:

grass → vole → owl

- A pyramid of numbers for this food chain would look like the one shown below
  - Often, the number of organisms **decreases** along food chains, as there is a decrease in available energy since some energy is lost to the surrounding environment at each trophic level
  - Therefore pyramids of numbers usually become **narrower** towards the apex (the top)

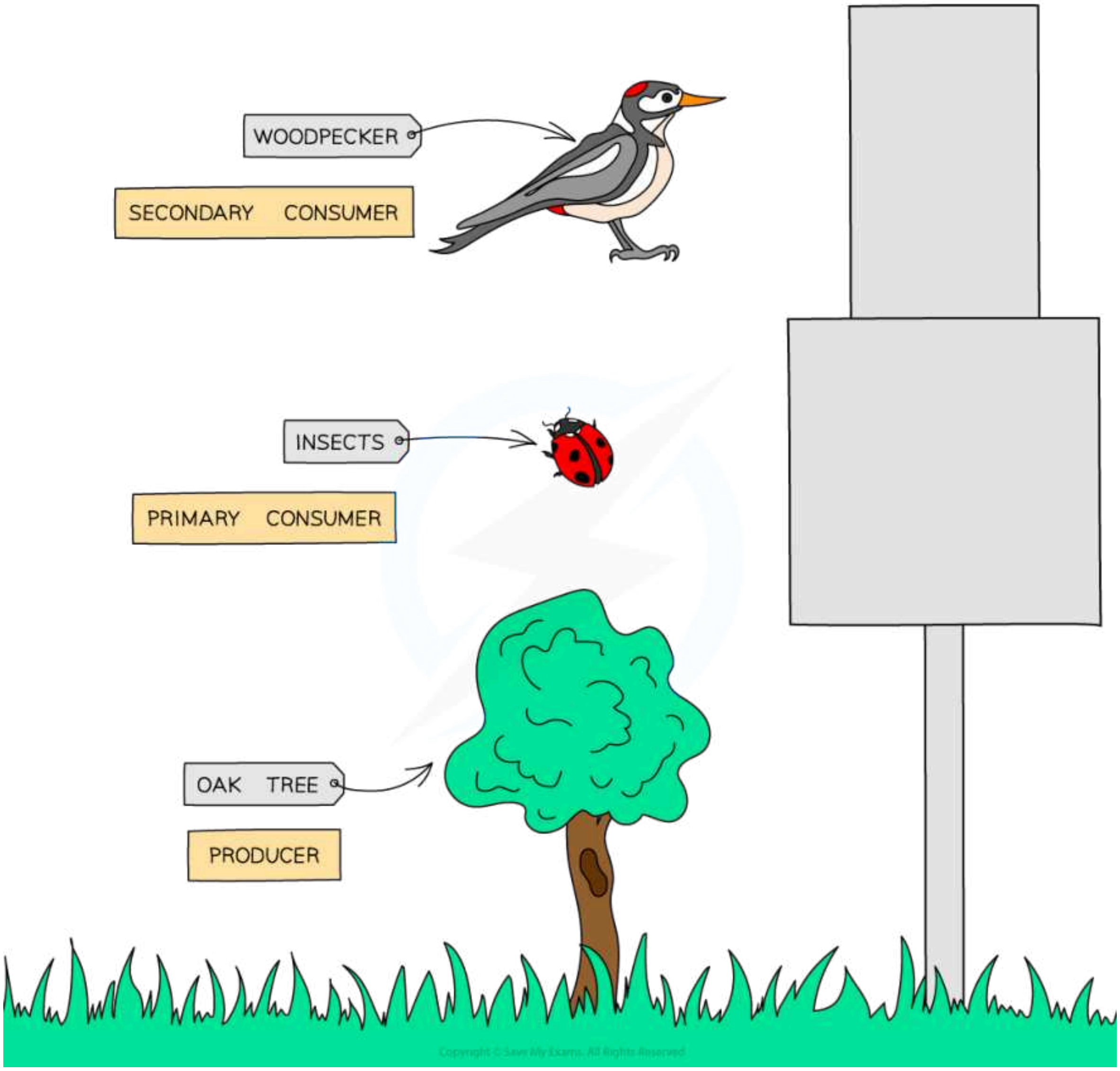


Pyramid of numbers

- Despite the name, a pyramid of numbers doesn't always have to be pyramid-shaped
- For example, consider the following food chain:

oak tree → insects → woodpecker

- The pyramids of numbers for this food chain will display a different pattern to the first food chain
- When individuals at lower trophic levels are relatively **large**, like the oak tree, the pyramid becomes **inverted**:
  - Only a single oak tree is needed to support large numbers of insects (which can then support large numbers of woodpeckers)



Pyramids of numbers are not always pyramid-shaped (they can be inverted, like the one shown above)

Pyramids of biomass

- A pyramid of biomass shows how much mass the organisms at each trophic level would have without including all the water that is in the organisms:
  - This is known as their '**dry mass**'
- As per the **second law of thermodynamics**, the quantities of biomass generally **decrease** along food chains, so the pyramids become **narrower** towards the top

  - If we take our first food chain as an example, it would be impossible to have 10kg of grass feeding 50kg of voles feeding 100kg of barn owls
- Being able to **construct** accurate pyramids of biomass from appropriate data is an important skill

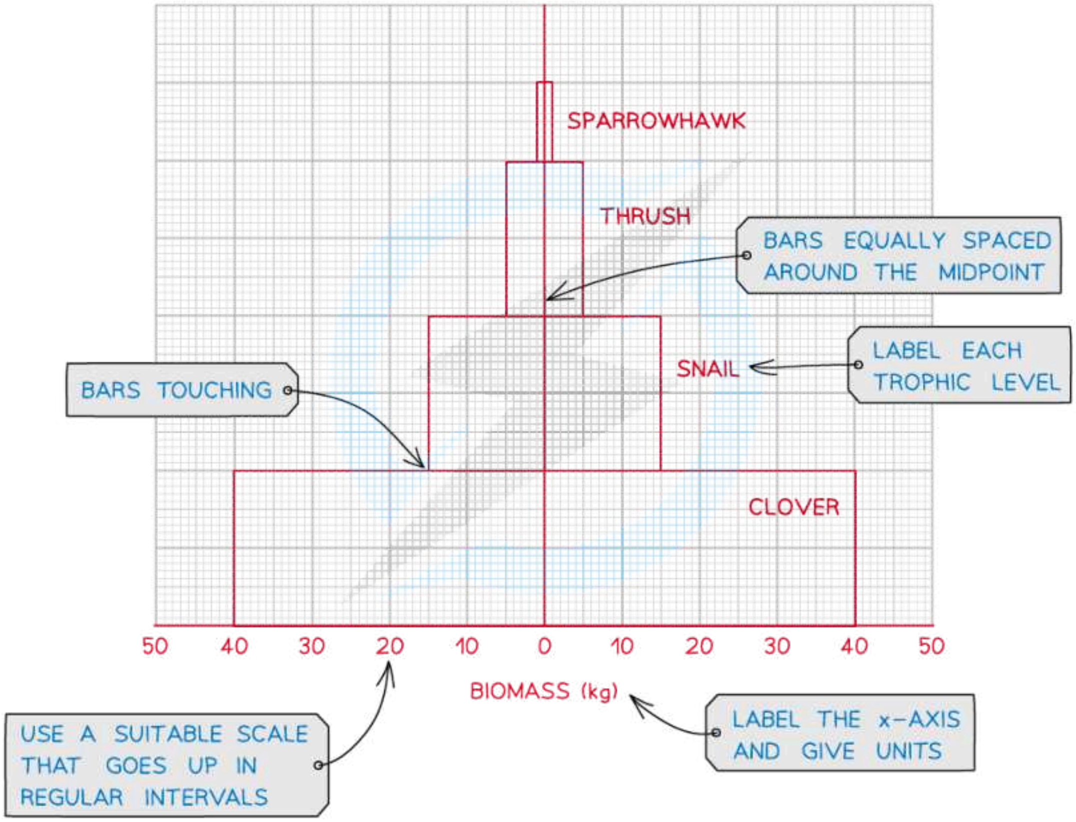
Worked Example

The table below shows:

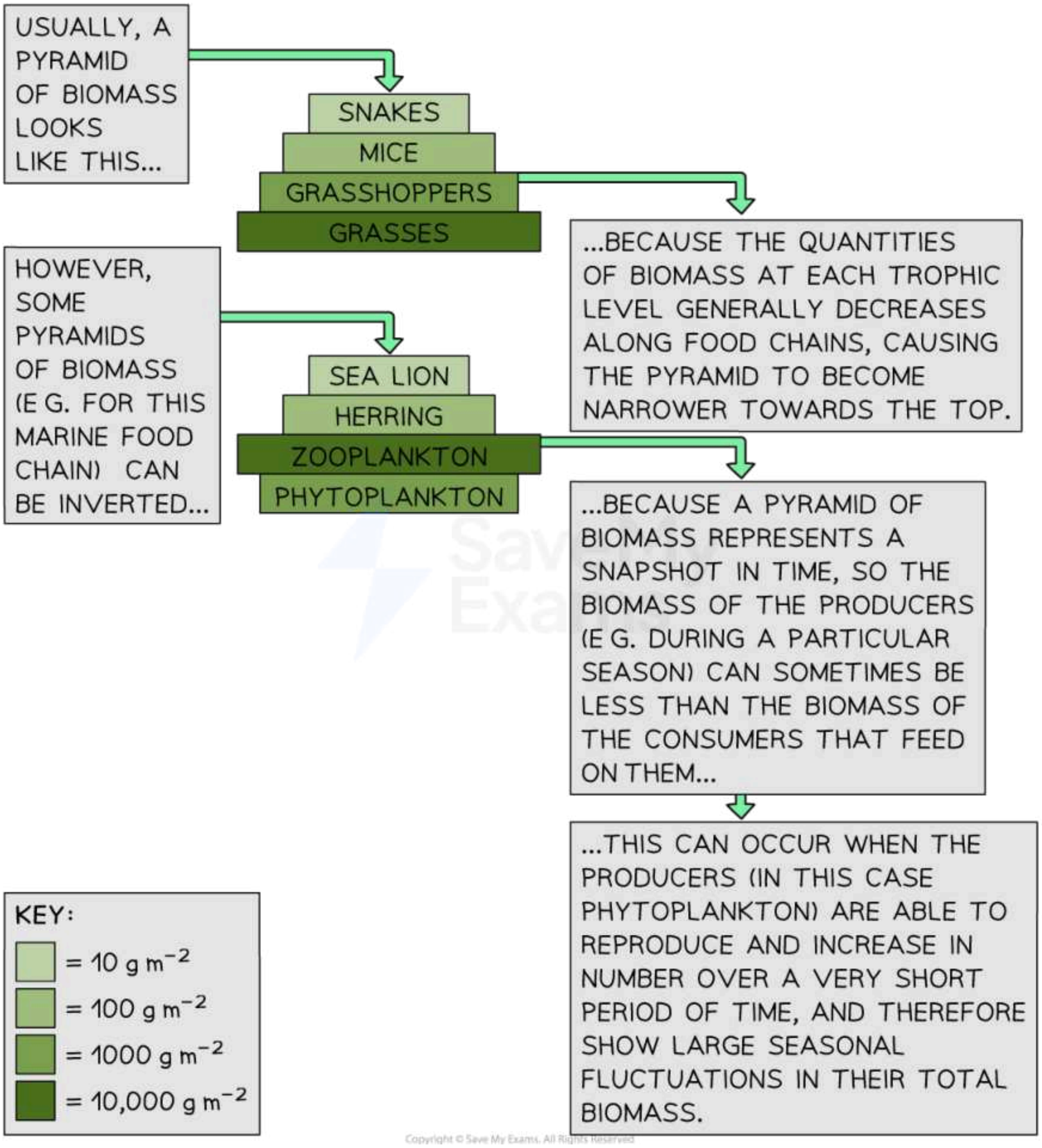
- A food chain with four trophic levels
- The total mass of organisms at each trophic level

	Clover →	**Snail →**	**Thrush →**	**Sparrowhawk**
Biomass (kg)	80	30	10	2

Draw a pyramid of biomass for the food chain in Table 1.



- Pyramids of biomass are **usually pyramid-shaped**, regardless of what the pyramid of numbers for that food chain looks like
  - However, they can occasionally be **inverted** and show higher quantities at higher trophic levels
  - These inverted pyramids sometimes occur due to marked **seasonal variations**
    - For example, in some marine ecosystems, the standing crop of phytoplankton, the major producers, is lower than the mass of the primary consumers, such as zooplankton
    - This is because the phytoplankton **reproduce very quickly** and are constantly being consumed by the primary consumers, which leads to a lower standing crop but higher productivity
    - This can occur because phytoplankton can vary greatly in productivity (and therefore biomass) depending on sunlight intensity

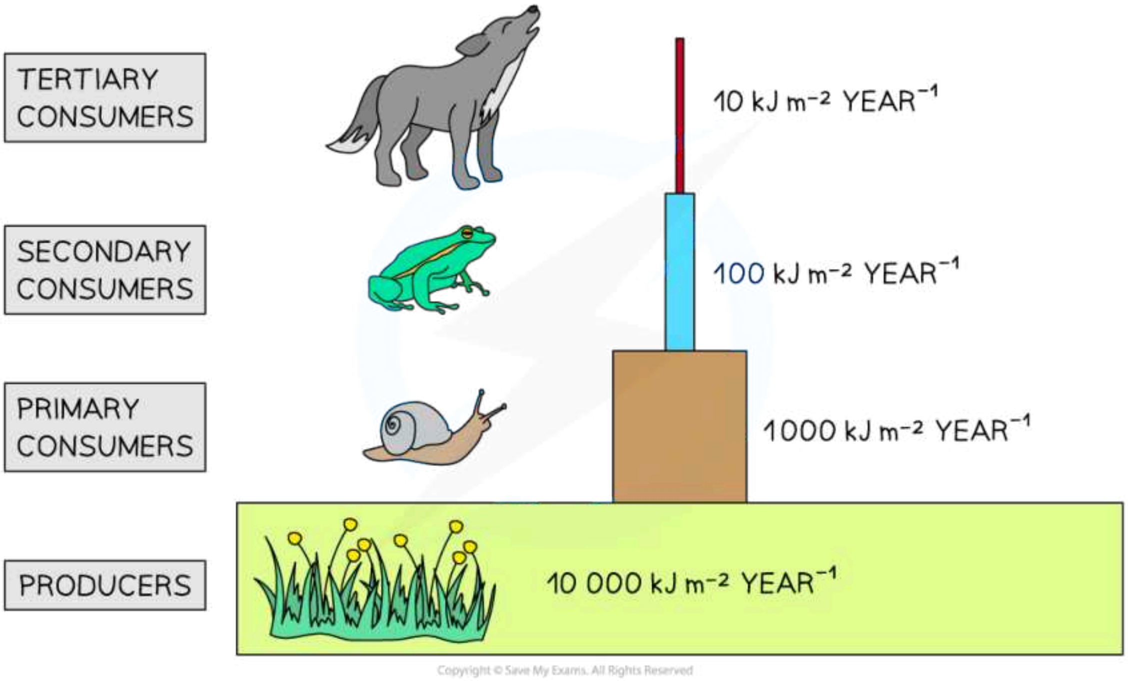


Pyramids of biomass

Pyramids of energy

- Pyramids of energy (also referred to as pyramids of productivity) show the flow of **energy** through trophic levels, indicating the **rate** at which that energy is being generated

- Pyramids of productivity illustrate the amount of energy or biomass of organisms at each trophic level per unit **area** per unit **time**
  - Productivity is measured in units of **flow**
  - The units are mass or energy per metre squared per year (g/kg m^{-2} yr^{-1} or J/kJ m^{-2} yr^{-1})
- The length of each box, or bar, represents the quantity of energy present
- These pyramids are **always** widest at the base and decrease in size as they go up
  - This is because pyramids of productivity for entire ecosystems over a year always show a decrease along the food chain, following the **second law of thermodynamics**
- The base is wide due to the large amount of energy contained within the biomass of **producers**
- As you move up the pyramid to higher trophic levels, the quantity of energy decreases as not all energy is transferred to the biomass of the next trophic level (roughly 10 % of the energy is passed on)
- Energy is **lost** at each trophic level due to:
  - Incomplete consumption
  - Incomplete digestion
  - Loss of heat energy to the environment during respiration
  - Excretion of the waste products of metabolism e.g. carbon dioxide, water, and urea



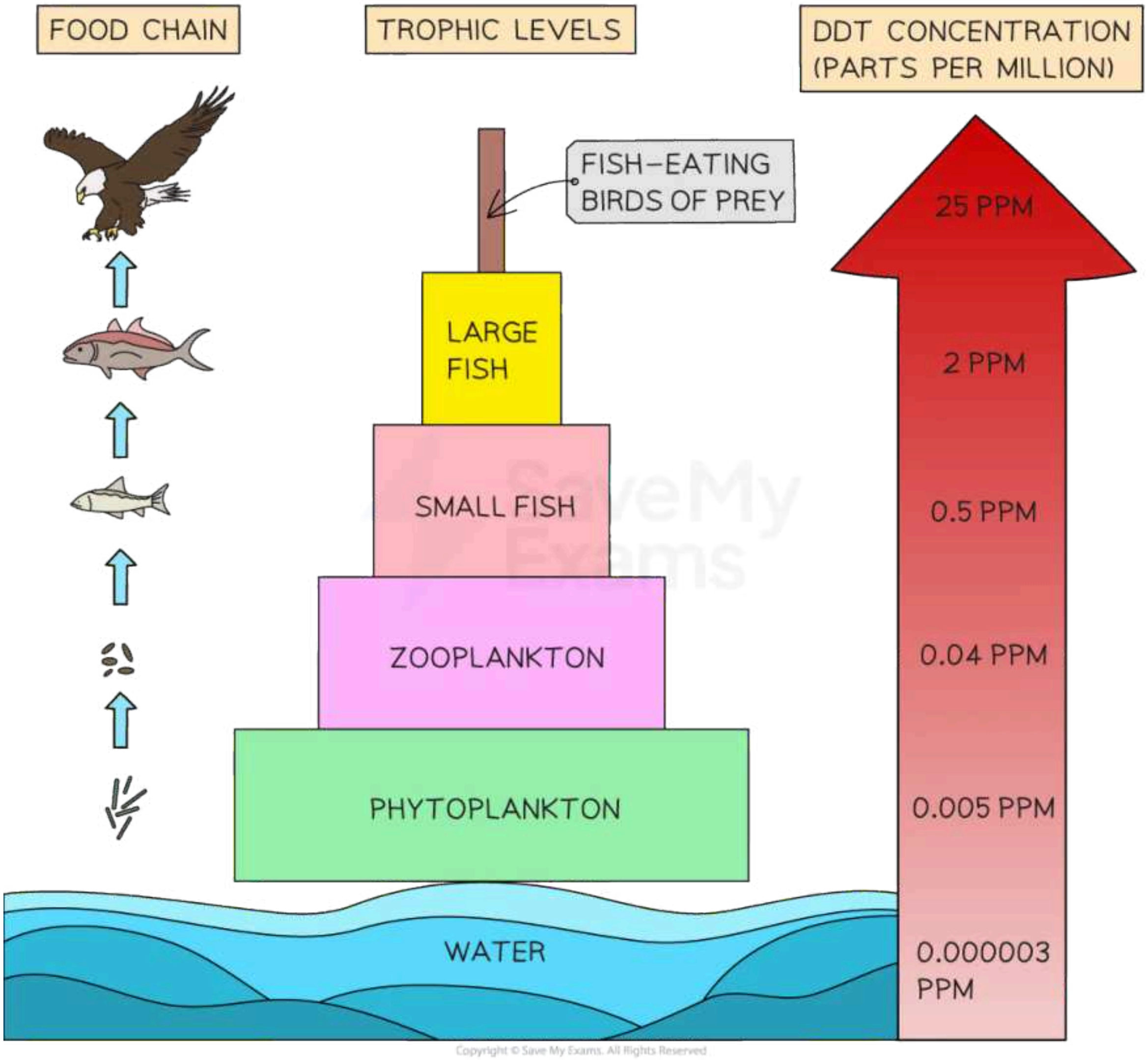
The energy stored in the biomass of organisms can be represented by a pyramid of productivity

Human Impacts on Energy & Matter Flows

Human Impacts on Energy & Matter Flows

Bioaccumulation and biomagnification

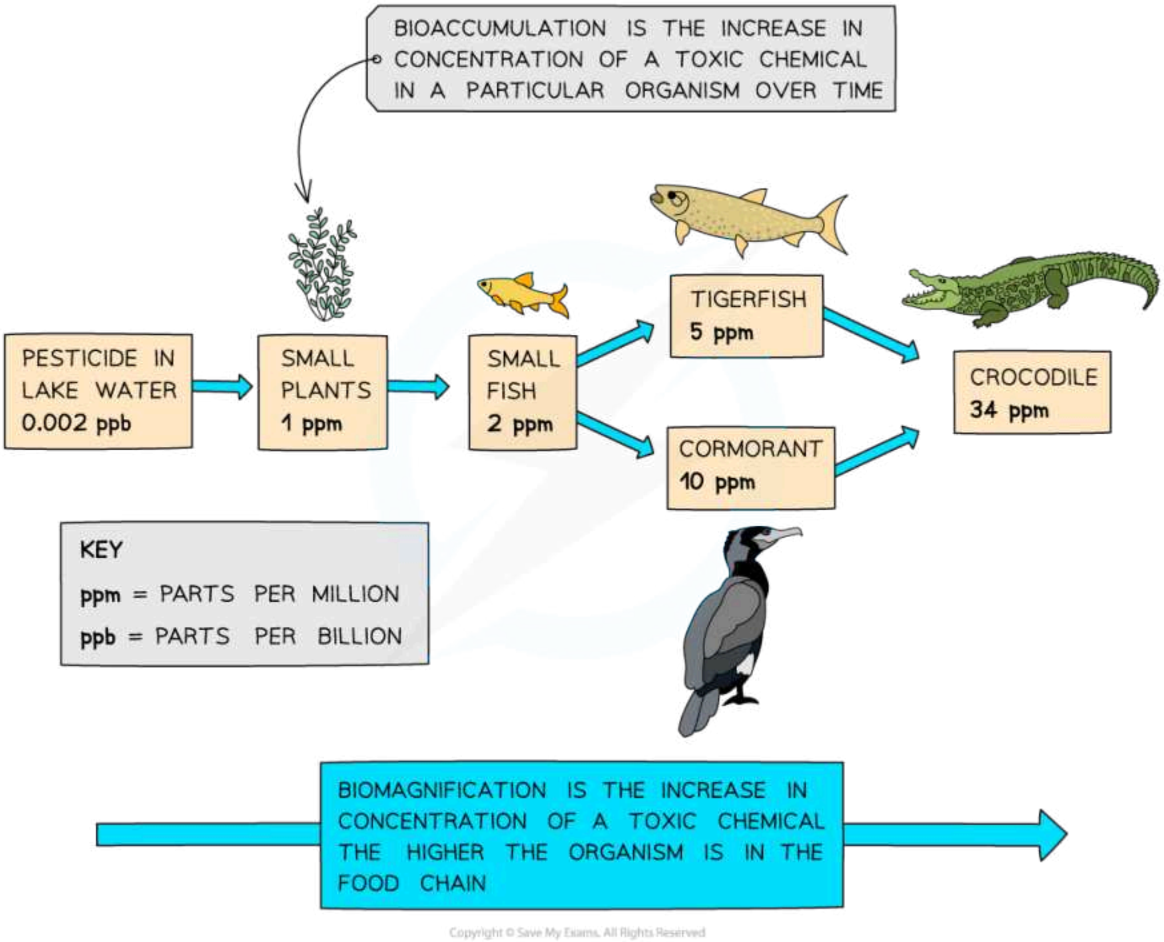
- **Bioaccumulation** is the build-up of **persistent** or **non-biodegradable pollutants** within an organism or trophic level because they cannot be broken down
- **Biomagnification** is the **increase in the concentration** of persistent or non-biodegradable pollutants along a food chain
  - As pollutants are passed up the food chain from one trophic level to the next, they become more concentrated
  - This means that organisms at higher trophic levels (such as top predators) accumulate higher concentrations of pollutants than those at lower trophic levels
  - This is due to the decrease in the total biodegradable biomass of organisms at higher trophic levels
- Pollutants that are persistent and non-biodegradable can accumulate along food chains
  - Examples include:
    - Polychlorinated biphenyl (PCB)
    - Dichlorodiphenyltrichloroethane (DDT)
    - Mercury
- They can cause changes to ecosystems through the processes of bioaccumulation and biomagnification
  - For example, **DDT** was a widely used **insecticide** in the mid-20th century that was found to have harmful effects on birds of prey such as eagles and falcons
  - When DDT was sprayed on crops, it would leach into waterways and eventually enter freshwater and marine ecosystems
  - DDT would then enter food chains (via plankton) and accumulate in the bodies of fish
  - These fish would then be eaten by birds, which would accumulate **higher concentrations** of DDT
  - Because DDT is persistent and does not break down easily, it can continue to **accumulate** in the bodies of animals at **higher trophic levels** (such as birds of prey), leading to harmful effects such as thinning of eggshells and reduced reproductive success



Through the process of biomagnification, the concentration of DDT in the tissues of organisms increases at successively higher trophic levels in a food chain

- **Mercury** is another example of a pollutant that can accumulate along food chains
  - Mercury is released into the environment through activities such as coal-fired power plants and gold mining
  - Once in the environment, mercury can be converted into a highly toxic form called **methylmercury**
  - This accumulates in the bodies of fish

- As larger fish eat smaller fish, the concentration of methylmercury within the tissues of these fish increases, leading to potential harm for **humans** who eat large predatory fish such as tuna or swordfish
  - In 1956, for example, a chemical factory released toxic methylmercury into waste water entering Minamata Bay in Japan
  - Mercury accumulation in fish and shellfish caused mercury poisoning in local people (who ate the fish and shellfish) and resulted in severe symptoms (paralysis, death, or birth defects in newborns)



Biomagnification and bioaccumulation of a pesticide in an aquatic ecosystem

Non-biodegradable pollutants and microplastics

- One concerning aspect of many non-biodegradable pollutants is that they can be **absorbed** by **microplastics**

  - This can increase the transmission of these pollutants within food chains (i.e. increase the level of biomagnification)
- Microplastics are tiny plastic particles, often less than 5mm in size
  - They come from various sources like plastic bottles, packaging and synthetic clothing
  - When in the environment, these microplastics act a bit like **sponges**, absorbing non-biodegradable pollutants such as polychlorinated biphenyls (PCBs), pesticides and heavy metals such as lead and mercury

Effect on the food chain

- Marine animals often **ingest** microplastics as they feed
- As smaller organisms consume microplastics containing pollutants, these toxins accumulate in their bodies
- Larger predators then consume these contaminated organisms, leading to biomagnification, where the concentration of toxins increases at higher trophic levels
- This can have negative consequences for organisms in food chains
  - For example, a study found that oysters exposed to microplastics containing pollutants experienced:
    - Lower feeding rates
    - Altered growth patterns
    - Reduced reproductive success
  - This was found to negatively impact the fitness of individual oysters and the success of the population as a whole

Human activities and ecosystem impacts

- Human activities can significantly change the natural flows of energy and matter within ecosystems
- **Burning fossil fuels**:
  - Releases carbon dioxide into the atmosphere, contributing to global warming
  - Increased CO_2 availability can increase photosynthesis rates
    - However, other pollutants and climate change effects (e.g. temperature rise and changing rainfall patterns) can outweigh this benefit, reducing primary productivity
  - For example, burning coal to generate electricity emits CO_2 but also releases sulfur dioxide (SO_2)
  - This pollutant contributes to acid rain and affects soil pH, which in turn impacts plant health and nutrient availability

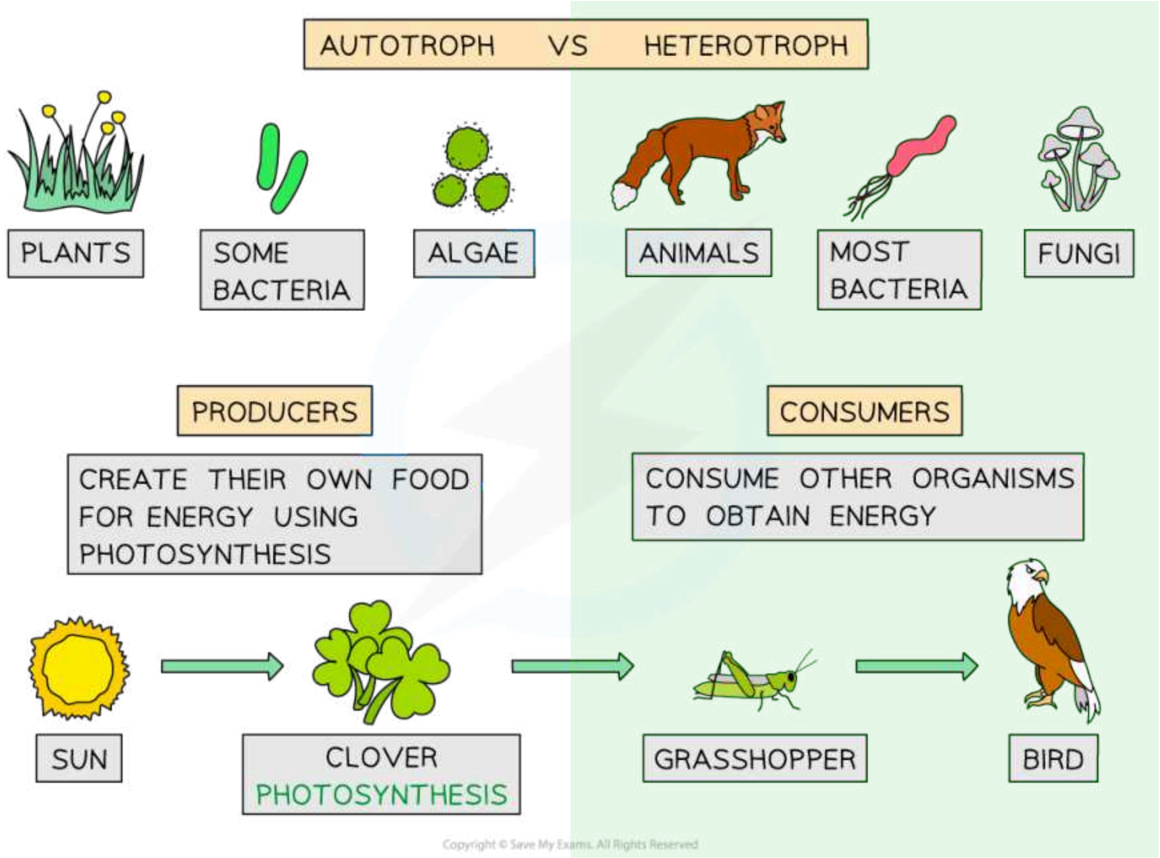
  - This further reduces photosynthesis rates
- **Deforestation**:
  - Clearing forests for agriculture, urbanisation, or logging disrupts ecosystems
    - As well as causing habitat loss and disruption of food webs, deforestation reduces the carbon sink capacity of forests
  - This contributes to climate change
- **Urbanisation**:
  - Urban development replaces natural habitats with impervious surfaces like concrete, leading to increased runoff and reduced infiltration
  - Urban areas generate "heat islands", increasing local temperatures
- **Agriculture**:
  - Intensive agriculture involves the use of fertilisers, pesticides and monoculture practices
  - This can lead to soil degradation, water pollution and loss of biodiversity

Autotrophs & Heterotrophs (HL)

Autotrophs & Heterotrophs

What are autotrophs and heterotrophs?

- All living organisms can be classified into two groups based on how they obtain carbon compounds: autotrophs and heterotrophs
    - **Autotrophs** synthesise carbon compounds from inorganic sources like carbon dioxide and water
    - **Heterotrophs** obtain carbon compounds by consuming other organisms (either plants, animals, or decomposing organic matter)



Autotrophs make their own carbon compounds (e.g. glucose) whereas heterotrophs obtain them from a range of food sources

Types of autotrophs

Photoautotrophs

- Photoautotrophs use light as their external energy source to produce organic compounds through **photosynthesis**
  - Examples include: green plants, algae, and some bacteria, like cyanobacteria
- They convert carbon dioxide and water into **glucose** and oxygen using light energy

Chemoautotrophs

- Chemoautotrophs use energy from exothermic inorganic chemical reactions to produce organic compounds through **chemosynthesis**
  - Examples include: some bacteria and archaea, especially those found in extreme environments, such as **hydrothermal vents** or deep-sea ecosystems
- They can oxidise substances like **hydrogen sulphide** or **ammonia** to obtain energy
  - For example, bacteria living near hydrothermal vents use sulphur compounds to produce energy in environments without sunlight
- The giant tube worm (*Riftia pachyptila*) lives on or near hydrothermal vents deep in the ocean
  - Giant tube worms have a symbiotic relationship with chemosynthetic bacteria living inside them
  - The bacteria use **hydrogen sulphide** from the vent and **oxygen** and **carbon dioxide** from the surrounding water to produce sugars through chemosynthesis
  - The tube worms rely on the bacteria for food because they lack a digestive system
  - This allows them to survive in extreme environments where light and traditional food chains do not exist
- Chemoautotrophs are the **primary producers** in these extreme environments
  - This means they create energy-rich compounds like sugars that support other organisms in these food webs

Types of heterotrophs

- **Herbivores**: obtain carbon compounds by consuming plants
- **Carnivores**: obtain carbon compounds by consuming other animals
- **Omnivores**: obtain carbon compounds by consuming both plants and animals
- **Decomposers**: obtain carbon compounds by breaking down dead organic material, returning nutrients to the ecosystem
  - Examples include: fungi, bacteria, and earthworms

Examiner Tips and Tricks

Sometimes, understanding the origin of a word can help you to remember the meaning, for example:

Autotroph comes from:

- 'auto' = 'self'
- 'trophic' = 'feeding'

Heterotroph comes from:

- 'hetero' = 'different'
- 'trophic' = 'feeding'

Primary & Secondary Productivity (HL)

Primary Productivity

- During **photosynthesis**, primary producers (such as plants and algae) convert light energy to chemical energy
  - This chemical energy is **stored** within biological molecules (biomass)
- Primary productivity can be defined as the **rate at which biomass is produced** using an **external energy source** (like sunlight) and inorganic sources of carbon and other elements

Measuring primary productivity

- Common **units** for measuring productivity are **kg carbon m^{-2} $year^{-1}$**(kilograms of carbon per square metre of ecosystem per year)
- Protocols for estimating primary productivity can vary based on the ecosystem being studied

Laboratory techniques

- In **laboratory settings**, scientists can **estimate primary productivity** by measuring the rate of photosynthesis in samples, such as plants or phytoplankton
  - **Controlled experiments** can provide data on how different conditions (like light intensity or CO_2 levels) affect productivity

Field techniques

- In **field studies**, changes in biomass can be measured over time to estimate productivity
  - For example, in grassland ecosystems, researchers may **sample vegetation** at different times to see how much biomass has increased

Gross primary productivity

- The **rate** at which plants are able to store **chemical energy** or **biomass** 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)

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})

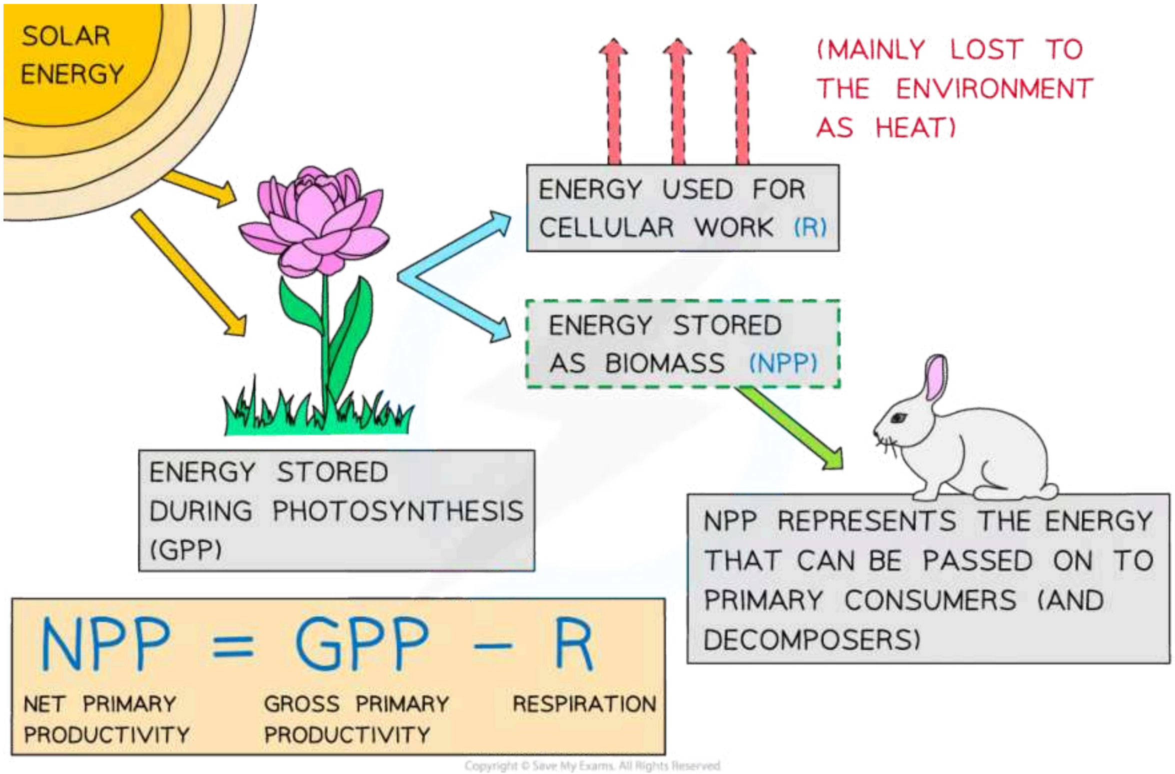
> Step 2: Convert this into grams
>
> 0.0015 × 1 000 = **1.5 g m^{-2} yr^{-1}**

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**
- NPP is the basis for food chains and food webs, as it represents the energy that supports all life forms in an ecosystem
    - NPP can be thought of as the amount of plant growth that can be **harvested** by:
        - **Primary consumers** in **natural ecosystems**
        - **Farmers** in **agricultural systems**
        - **Foresters** in **silvicultural systems**
- 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**, for example:
    - 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

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}**

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 the quantity of carbon compounds it contains, which in turn provide a good estimate 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

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**

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 - 1200

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

Step 2: Calculate NSP

NSP = GSP - R

NSP = 800 - 600

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

Sustainable Yield (HL)

Sustainable Yield

- Sustainable yield refers to the rate at which a resource can be **harvested** or **used** without compromising the ability of the system to **regenerate** or **replenish** that resource for future use
- It ensures:
  - The long-term sustainability of resources by not over-exploiting them
  - The resource remains available for future generations by allowing natural regeneration

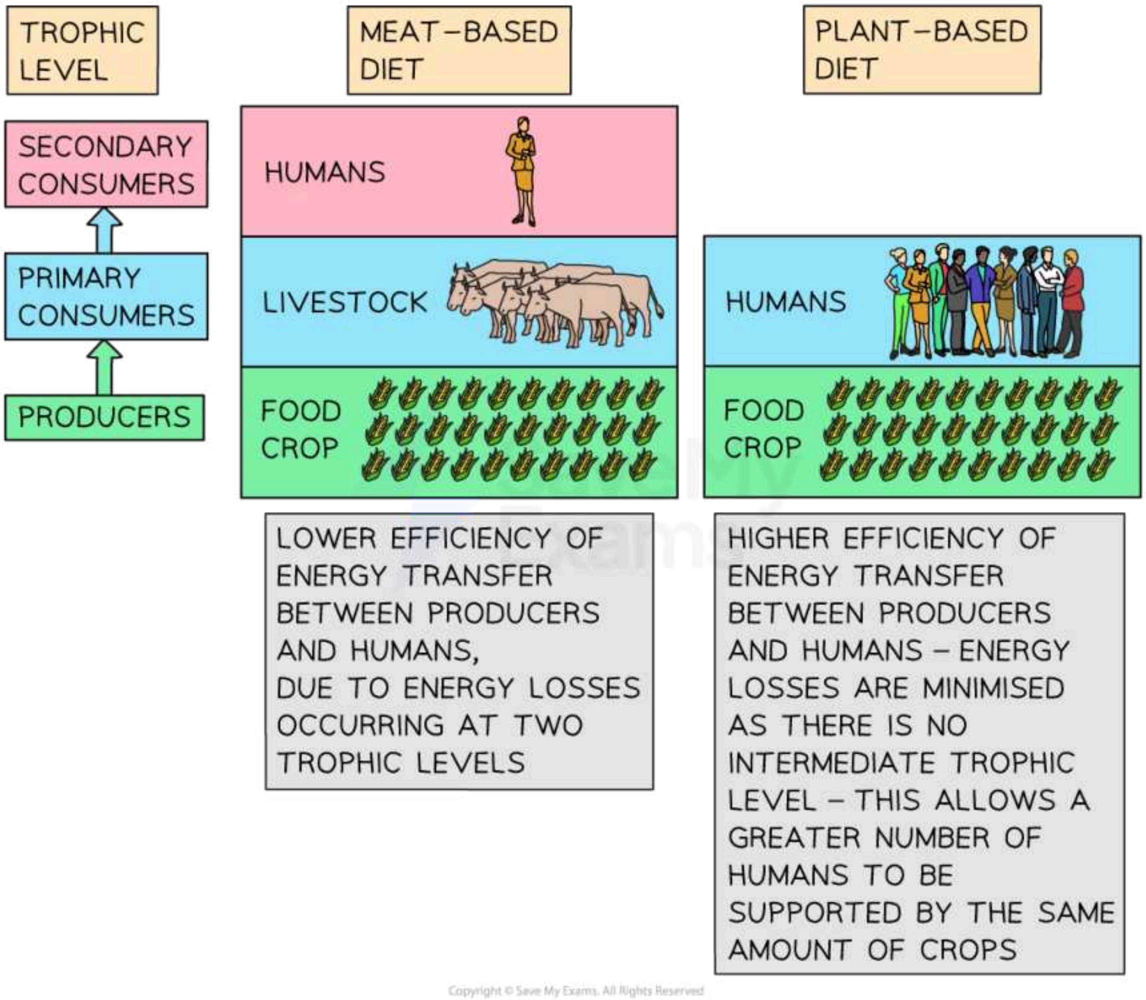
Maximum sustainable yield (MSY)

- Maximum sustainable yields (**MSYs**) are the highest rates of net primary productivity (**NPP**) or net secondary productivity (**NSP**) that can be harvested from a system **without depleting it**
  - In **agricultural**, **aquacultural** or **silvicultural systems** (farming, fish farming or forestry), MSY is the highest amount of biomass (i.e. crops, livestock, seafood or trees) that can be sustainably harvested **over time without degrading the soil, water or wider ecosystem**

Sustainable yields and trophic levels

- Sustainable yields are generally higher for organisms at **lower trophic levels**
  - These are the organisms closer to the base of the food chain, like plants or herbivores)
- This is because **less energy is lost** from the system at lower trophic levels, making them **more efficient for resource production**
  - Energy is lost as heat during the transfer between trophic levels
  - This makes higher trophic levels (like carnivores) less efficient for resource use
- **Plant-based foods** at lower trophic levels are the most energy-efficient and sustainable for human consumption
  - They require much fewer resources (e.g. land, water, and energy) to produce compared to animals at higher trophic levels
  - For example, growing crops like wheat or rice for direct human consumption is more sustainable than raising livestock for meat
- This means that **sustainability in food production** is much easier to achieve when humans consume from lower trophic levels (ideally from the first tropic level, known as producers)

- Growing crops for **direct human consumption** (plants) is **more sustainable** than raising livestock, which requires plants to be grown as **feed**



Efficiency of meat-based vs plant-based terrestrial food production systems (for the plant-based diet, note the higher number of humans supported by the same amount of crops)

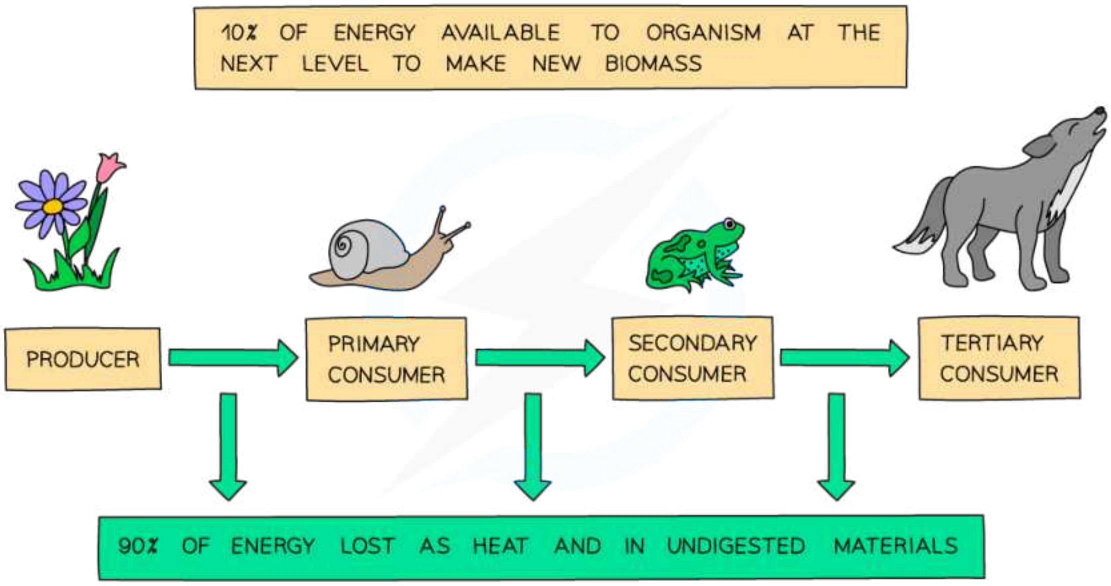
Examiner Tips and Tricks

Remember that sustainable yield is about maintaining the balance between resource use and regeneration, ideally, so that human food production can continue to feed human populations indefinitely.

Ecological Efficiency (HL)

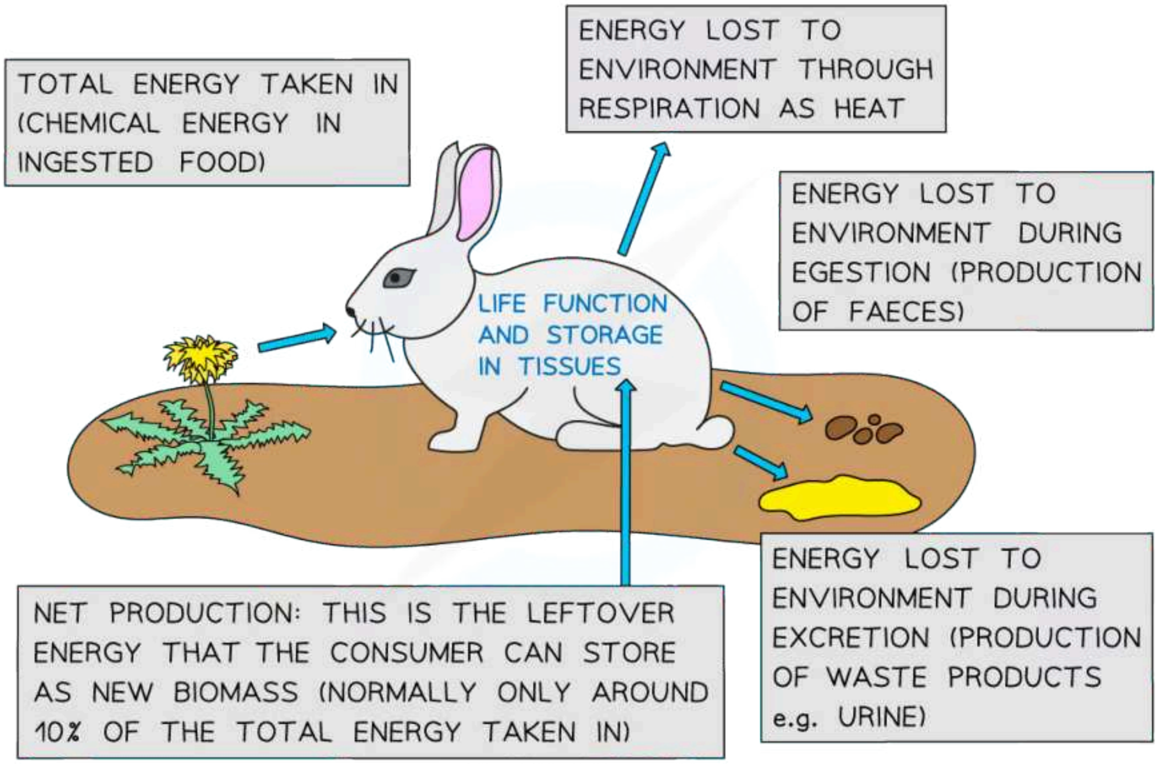
Ecological Efficiency

- The transfer of **energy** in a food chain is **not 100 % efficient**
    - Energy is **lost** to the **environment** at every trophic level
- When a consumer ingests another organism, not all the chemical energy in the consumer's food is transferred to the consumer's **biomass**
    - Only **around 10 %** of the energy is available to the consumer to store in their tissues
    - This is because around 90 % of the energy is **lost** to the **environment**



- So much energy is lost to the environment because:
    - Not every part of the food organism is eaten
        - E.g. the roots and woody parts of plants or the bones of animals
        - This means all the stored energy in these uneaten tissues is lost to the environment

- Consumers are not able to digest all of the food they ingest
  - E.g. cellulose in plants or the fur of animals
  - This means some is **egested** as faeces
  - The chemical energy in this undigested food is then lost to the environment
- Energy is lost to the environment in the form of **heat** when consumers **respire**
- Energy is lost to the environment when organisms excrete the waste products of metabolism
  - E.g. urea in urine



Energy losses by organisms at particular trophic level

- The energy that is left after these losses is available to the consumer to fuel their life functions, including being stored in biomass during **growth**
- These energy loss limit the number of trophic levels in ecosystems
  - Eventually, the amount of energy remaining becomes **insufficient** to support **further trophic levels**
  - This is why most terrestrial ecosystems are unable to support more than five trophic levels

- **Ecological efficiency** is:
  The percentage of energy received by one trophic level that is passed on to the next level
- The exact percentage varies between ecosystems, trophic levels and species
  - The percentage of energy transferred from one trophic level to the next is **very variable**
  - The commonly used value of 10% is **not** a fixed amount or a true average

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)
  - 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

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 11 000 kJ m^{-2} yr^{-1} of energy. The toads lose 7 500 kJ m^{-2} yr^{-1} of this energy as heat from respiration and 2 800 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 = 11 000 kJ m^{-2} yr^{-1}

Toad energy losses = 7 500 + 2 800 = 10 300 kJ m^{-2} yr^{-1}

Energy for growth = 11 000 - 10 300 = 700 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 = (700 ÷ 11 000) × 100

Ecological efficiency = **6.4 %**