D4.3 Climate change

Continuity and change—Ecosystems

Standard level and higher level: 3 hours

Additional higher level: 1 hour

Guiding questions

• What are the drivers of climate change?

• What are the impacts of climate change on ecosystems?

SL and HL

D4.3.1—Anthropogenic causes of climate change
Limit to anthropogenic increases in atmospheric concentrations of carbon dioxide and methane.

- The **greenhouse effect** is a natural process by which atmospheric gases maintain warm temperatures on Earth for liquid water & living organisms
  - The **sun** emits **short-wave radiation** which passes through the atmosphere
    - Most of this radiation is absorbed by Earth's surface, serving as a source of heat & energy that sustains food webs
  - The earth reemits the absorbed energy back towards space as **long-wave radiation**
  - **Greenhouse gases**, like carbon dioxide (CO_2), methane (CH_4), water vapour (H_2O), absorb some of this long-wave radiation & reemit it back in all directions, including towards Earth's surface
  - This slows down the loss of heat to space & warms Earth
- The **enhanced greenhouse effect** refers to additional warming resulting from increased concentrations of greenhouse gases caused by human activities
  - It causes **global warming**, which is the rise in the average temperature of Earth
- **Climate change** is the long-term shift of weather and temperature patterns
  - It represents the wider set of changes that happen to temperatures, weather patterns, sea levels, ice melting, and frequency or intensity of natural disasters
  - It has consequences on climatic variables remaining within tolerance levels for organisms
- **Anthropogenic** (human-driven) factors that cause climate change:
  - Fossil fuel combustion (release carbon dioxide)
  - Deforestation (decreases carbon fixation)
  - Livestock farming (animals release methane)

NOS: Students should be able to distinguish between positive and negative correlation and should also distinguish between correlation and causation. For example, data from Antarctic ice cores shows a positive correlation between global temperatures and atmospheric carbon dioxide concentrations over hundreds of thousands of years. This correlation does not prove that carbon dioxide in the atmosphere increases global temperatures, although other evidence confirms the causal link.

- A **correlation** shows how two variables change together; data from Antarctic ice cores shows positive correlations between global temperatures & atmospheric CO_2 over many years, but it does not prove that CO_2 causes changes to temperatures
- A **causation** shows how one variable causes change to the other variable; multiple pieces of evidence confirm the causal link between CO_2 & temperature (**1.** modelling data showing that natural factors cannot explain the rising temperatures **2.** past climate records **3.** the ability of gases to absorb radiation)

D4.3.2—Positive feedback cycles in global warming

Include release of carbon dioxide from deep ocean, increases in absorption of solar radiation due to loss of reflective snow and ice, accelerating rates of decomposition of peat and previously undecomposed organic matter in permafrost, release of methane from melting permafrost and increases in droughts and forest fires.

- Global warming causes initial rises in temperatures that produce further warming
  - This is a **positive feedback mechanism** because the initial change (rise in temperature) is amplified
- Positive feedback cycles in global warming depend on:
  1. Increasing trapped radiation:
  - **Albedo effect**: **albedo** measures the amount of energy/radiation a surface can reflect
    - White surfaces (like ice & snow) reflect more radiation (i.e. have higher albedo) than darker ones
    - Global warming causes melting of reflective snow & ice, which exposes darker land surfaces that have lower albedo & thus absorb more solar radiation, leading to additional warming
  2. Increasing the release of carbon from natural storages **(Dogs Make Funny Pets)**:
  - **Deep ocean release**:
    - CO_2 becomes less soluble in water as temperatures rise
    - Global warming increases ocean temperatures, so more CO_2 is released from oceans, which leads to further warming
  - **Melting of permafrost**:
    - **Permafrost** is ground containing dead organic matter that has remained frozen & undecomposed for many years
    - Global warming leads to melting of permafrost, which exposes the organic matter to heterotrophs for decomposition
    - Decomposers produce CO_2, which strengthens the greenhouse effect & leads to more melting
    - Melting of permafrost also releases methane due to the presence of **methanogenic archaea**
  - **Fires & Drought**:
    - Higher temperatures increase drought, which raises the risk of wildfires that release carbon from lost vegetation & thus lowers rates of carbon fixation, leading to more greenhouse gases
  - **Peat loss**:
    - **Peat** is ground containing dead organic matter that is **partially decomposed** due to **waterlogged soil** conditions
    - Higher temperatures increase the rate of decomposition in peat, which releases CO_2 & leads to further warming

D4.3.3—Change from net carbon accumulation to net loss in boreal forests as an example of a tipping point
Include warmer temperatures and decreased winter snowfall leading to increased incidence of drought and reductions in primary production in taiga, with forest browning and increases in the frequency and intensity of forest fires, which result in legacy carbon combustion.

- **Boreal forests (taiga)** are the world's largest land biome & function as carbon sinks
  - Their climate is characterized by long & cold winters, short mild summers, & evergreen trees
- Warmer temperatures decrease the frequency of snowfall, which reduces the amount of water available when snow melts in the spring & summer
  - This raises incidence of drought & leads to **forest browning** (reduction of primary production) due to lower water availability (positive feedback)
- Drought increases the frequency and intensity of forest fires, which results in the combustion of **legacy carbon** (carbon that has been trapped in ecosystems for many years)
- Climate change is causing taiga to shift from carbon sinks to carbon sources due to reduced primary production & combustion from forest fires, which is an example of a tipping point

D4.3.4—Melting of landfast ice and sea ice as examples of polar habitat change
Include potential loss of breeding grounds of the emperor penguin (*Aptenodytes forsteri*) due to early breakout of landfast ice in the Antarctic and loss of sea ice habitat for walruses in the Arctic. *Note: When students are referring to organisms in an examination, either the common name or the scientific name is acceptable.*

- Climate change is altering how organisms interact with their environments
- **Landfast ice** is stationary sea ice that is anchored to the seashore
  - **Emperor penguins** use landfast ice for breeding and hunting grounds
  - Climate change leads to early breakout of landfast ice, which reduces breeding & hunting success due to habitat change
- **Sea ice** forms & floats on the ocean surface
  - **Arctic walruses** are mammals that use sea ice for resting, breeding, feeding, & caring for offspring
  - Loss of sea ice due to climate change forces walruses to leave their offspring on the seacoast to go hunt for food
    - This makes the offspring more vulnerable to attack and increases energy expenditure as parents have to swim for longer periods of time without rest

D4.3.5—Changes in ocean currents altering the timing and extent of nutrient upwelling

Warmer surface water can prevent nutrient upwelling to the surface, decreasing ocean primary production and energy flow through marine food chains.

- **Ocean currents** are large-scale movements of seawater that redistribute heat, nutrients, & marine life across the globe
- **Water density** affects ocean currents; colder water is denser & tends to sink
  - Surface water is warmer than deep water due to direct sunlight exposure, so water temperature & density both change with depth
  - These temperature & density gradients lead to **ocean stratification** (layering) that reduces mixing between surface water & deep water
- **Nutrient upwelling** is the movement of cold, nutrient-rich deep water to the surface
  - It occurs when natural forces (like wind) move surface water away from an area, so deep water rises to replace it
  - Nutrients are concentrated in deep water because dead organisms sink to the ocean floor & decompose, so upwelling provides nutrients for aquatic primary producers (like phytoplankton) that live in surface water
- Global warming is causing ocean temperature & density gradients to become steeper, so ocean strata become more resistant to mixing from natural forces like wind
  - This reduces nutrient upwelling which decreases ocean primary production & energy flow through marine food chains
- Climate change is also altering the timing of nutrient upwelling, creating temporal mismatches for marine food webs that reduce primary production

D4.3.6—Poleward and upslope range shifts of temperate species

As evidence-based examples, use upslope range shifts for tropical-zone montane bird species in New Guinea and range contraction and northward spread in North American tree species.

- Climate change leads to **range shifts** as species migrate to remain within their tolerance levels
- Tropical-zone **montane** (living in mountains) bird species in New Guinea are shifting **upslope** (towards higher elevation) as lower mountain areas become warmer
- North American tree species are shifting **polewards** (towards higher latitudes) because seedling success is higher in northern areas with lower temperatures than southern areas with warmer weather
- Range shifts increase the risk of **range contraction** (loss of geographic space)
  - In upslope shifts, this is because mountain area decreases towards the summit
  - In poleward shifts, this is because the amount of land with suitable temperatures decreases

D4.3.7—Threats to coral reefs as an example of potential ecosystem collapse

Increased carbon dioxide concentrations are the cause of ocean acidification and suppression of calcification in corals. Increases in water temperature are a cause of coral bleaching. Loss of corals causes the collapse of reef ecosystems.

- Climate change has the potential to lead to ecosystem collapse
- Coral reefs are threatened by ocean acidification & ocean warming due to climate change
- **Ocean acidification** is the reduction in pH of Earth's oceans due to excess absorption of CO_2
  - It is a result of rising atmospheric CO_2 due to anthropogenic factors
  - Higher amounts of dissolved CO_2 **increase carbonic acid ($H_2CO_{3(aq)}$)** levels & **decrease bicarbonate ion ($HCO_3^-{}_{(aq)}$)** levels
  - Since corals depend on carbonate ions for **calcification** (a process used to build coral exoskeletons), reduced **carbonate ($CO_3^{2-}{}_{(aq)}$)** availability leads to suppression of calcification, which weakens corals

$$CO_{2(g)} + H_2O_{(l)} \rightarrow H_2CO_{3(aq)} \rightarrow HCO_3^-{}_{(aq)} + H^+{}_{(aq)} \rightarrow 2H^+{}_{(aq)} + CO_3^{2-}{}_{(aq)}$$

- **Ocean warming** is a cause of coral bleaching (other causes include pollution & high sun exposure)
  - Rising water temperatures cause bleaching by disrupting symbiosis between coral & algae
  - Algae live in coral tissue, represent the coral's primary source of food, & give coral their color
  - Thermal stress due to ocean warming causes corals to expel algae from their tissue, leading to **coral bleaching** (loss of color), starvation & eventual death
  - Since corals are keystone species & provide shelter for many organisms due to their exoskeleton, loss of corals causes the collapse of reef ecosystems

D4.3.8—Afforestation, forest regeneration and restoration of peat-forming wetlands as approaches to carbon sequestration

NOS: There is active scientific debate over whether plantations of non-native tree species or rewilding with native species offer the best approach to carbon sequestration. Peat formation naturally occurs in waterlogged soils in temperate and boreal zones and also very rapidly in some tropical ecosystems.

- **Carbon sequestration** is the uptake and storage of carbon by natural or artificial (human) processes
  - It can occur naturally by photosynthesis, buried undecomposed organic matter, or growth biomass
  - It can occur artificially to combat climate change by removing carbon from the atmosphere to reduce the levels of greenhouse gases, for example:
    - **Afforestation** is the process of planting trees on land where forests do not exist
    - **Forest regeneration** is the regrowth of trees in forests, typically after wildfires or logging
      - It can occur naturally (through seed dispersal) or artificially (by planting)
    - **Restoration of peat-forming wetlands** by stopping drainage, restoring water levels, & introducing native species
      - Peat formation naturally occurs in waterlogged soils in temperate and boreal zones and also very rapidly in some tropical ecosystems, so it can sequester carbon relatively quickly
- There is scientific debate over the best approach to carbon sequestration
  - Plantations of **non-native tree species** are cost effective & efficient, but they may become invasive & not fully restore the previous complexity of the ecosystem or its biodiversity
  - Plantations of **native tree species** restore natural food webs & biodiversity, but are more expensive & outcomes usually can take long to manifest

Additional higher level

D4.3.9—Phenology as research into the timing of biological events
Students should be aware that photoperiod and temperature patterns are examples of variables that influence the timing of biological events such as flowering, budburst and bud set in deciduous trees, bird migration and nesting.

- **Phenology** is the research into the timing of biological events
  - Some biological events react to environmental cues in a predictable pattern, for example:
    - **Flowering** in plants is timed to when pollinators are active
    - **Budburst** (emergence of new leaves or stems at the start of the growing season) is timed to when weather becomes warm in deciduous trees
    - **Bud set** (end of the growing season when trees prepare for winter) is timed to when weather becomes colder in deciduous trees
    - **Bird nesting** (seasonal breeding activities like nest building, egg-laying, chick-rearing) is timed to ensure abundant food & favorable conditions are present during chick development
    - **Bird migration** is timed to suitable weather & food availability
- Variables that affect the timing of biological events include (**PowerPoinT**):
  - **Photoperiod**: the period of time in a day that an organism is exposed to light
  - **Precipitation**: seasonal rainfall can help plants reach a moisture threshold for growth
  - **Temperature**: warmer temperatures in spring trigger flowering

D4.3.10—Disruption to the synchrony of phenological events by climate change
Students should recognize that within an ecosystem temperature may act as the cue in one population and photoperiod may be the cue in another. Include spring growth of the Arctic mouse-ear chickweed (*Cerastium arcticum*) and arrival of migrating reindeer (*Rangifer tarandus*) as one example. Also include a suitable local example or use the breeding of the great tit (*Parus major*) and peak biomass of caterpillars in north European forests as another. *Note: When students are referring to organisms in an examination, either the common name or the scientific name is acceptable.*

- **Phenological synchrony** is the temporal overlap of biological events in interacting species
  - Synchrony has ecological consequences for individual survival, species fitness, & ecosystem stability
- Climate change is causing disruption to the synchrony of phenological events by altering temperature whilst leaving other environmental cues fixed (like photoperiod)
  - Photoperiod remains fixed because it depends on Earth's orbit (not climate)
  - Since different species can respond to different environmental cues, synchrony between interacting species that depend on different cues (& thus likely change at different rates) is disrupted
- Disruption of phenological synchrony can lead to **trophic mismatch**:
  - **Arctic mouse-ear chickweed** depend on temperature cues during development but **deer** depend on photoperiod to determine when to migrate
    - Chickweed is reaching peak biomass earlier (before deer migration) due to warmer temperatures, reducing food availability for deer & thus their survival
  - **Great tits** are birds that depend on **caterpillars** as a source of food for their chicks
    - Even though egg hatching and caterpillar growth both depend on temperature as a cue, caterpillars are reaching peak biomass before bird eggs hatch, reducing food availability

D4.3.11—Increases to the number of insect life cycles within a year due to climate change
Use the spruce bark beetle (*Ips typographus* or *Dendroctonus micans*) as an example. *Note: When students are referring to organisms in an examination, either the common name or the scientific name is acceptable.*

- Insects are **ectotherms**, so warmer temperatures generally increase their metabolic rate
  - Faster metabolism causes cells to divide & grow faster, so insects complete their **life cycle** more rapidly (the series of changes an organism goes through from birth until reproduction)
- The number of insect life cycles is increasing within a year (e.g. from 1 to 2) due to climate change
  - This is an issue because the insect's habitat may not be able to sustain large insect populations in a short period of time
  - For example, the **spruce bark beetle** feeds on the bark tissue of spruce trees, which weakens the tree's defenses & eventually kills it
    - Rising temperatures are increasing the number of generations that this beetle can complete in one year, which overwhelms spruce trees & raises tree mortality
    - Global warming also increases drought, which weakens spruce trees & makes them even more susceptible to beetle attacks

D4.3.12—Evolution as a consequence of climate change
Include changes in the fitness of colour variants of the tawny owl (*Strix aluco*) as a consequence of changes in snow cover. *Note: When students are referring to organisms in an examination, either the common name or the scientific name is acceptable.*

- Climate change alters environmental conditions & thus changes the strength of selection pressures
  - For example, **tawny owls** can have either **grey** or **brown plumage color**
  - Grey owls have better camouflage during harsh winters (i.e. greater snow depth)
  - Climate change is causing milder winters with declining snow depth, so the strength of selection against brown owls is weakening
  - As a result, brown owls are becoming more common in the population (i.e. evolution is occurring)

Linking questions

• What are the impacts of climate change at each level of biological organization?

• What processes determine the distribution of organisms on Earth?

Review questions

SL and HL

- Define albedo. [1]
- Distinguish between global warming and climate change. [1]
- State **two** anthropogenic factors causing climate change. [2]
- Distinguish between correlative and causative evidence of climate change. [3]
- Describe how climate change is changing the distribution of organisms on Earth. [4]
- Describe the role of carbon sequestration in combating climate change. [6]
- Explain how climate change is threatening coral reefs. [7]
- Explain the role of positive feedback cycles in driving climate change. [8]
- Describe, using examples, how climate change is affecting ecosystem stability. [8]

Additional Higher Level

- Define phenological synchrony. [1]
- Define a life cycle. [1]
- Outline **two** ways in which the survival of the spruce bark beetle has increased due to climate change. [4]
- Explain, using an example, the role of climate change in increasing insect life cycles. [4]
- Explain, using an example, how climate change is leading to evolution. [4]
- Discuss the impacts of climate change at each level of biological organization. [8]

References

Ann Clark, Mary, et al. *Biology 2e*. E-book, OpenStax, 2018, https://openstax.org/books/biology-2e/pages/1-introduction. OpenStax.

Gordon Betts, J., et al. *Anatomy and Physiology 2e*. E-book, OpenStax, 2022, https://openstax.org/books/anatomy-and-physiology-2e/pages/1-introduction. OpenStax.

Karell, P., Ahola, K., Karstinen, T. et al. Climate change drives microevolution in a wild bird. Nat Commun 2, 208 (2011). https://doi.org/10.1038/ncomms1213

Riemer K, Anderson-Teixeira KJ, Smith FA, Harris DJ, Ernest SKM. Body size shifts influence effects of increasing temperatures on ectotherm metabolism. Global Ecol Biogeogr. 2018; 27: 958–967. https://doi.org/10.1111/geb.12757