# The stored carbon crisis

***We always hear there is too much carbon in the atmosphere – can nature put it back in the ground?***

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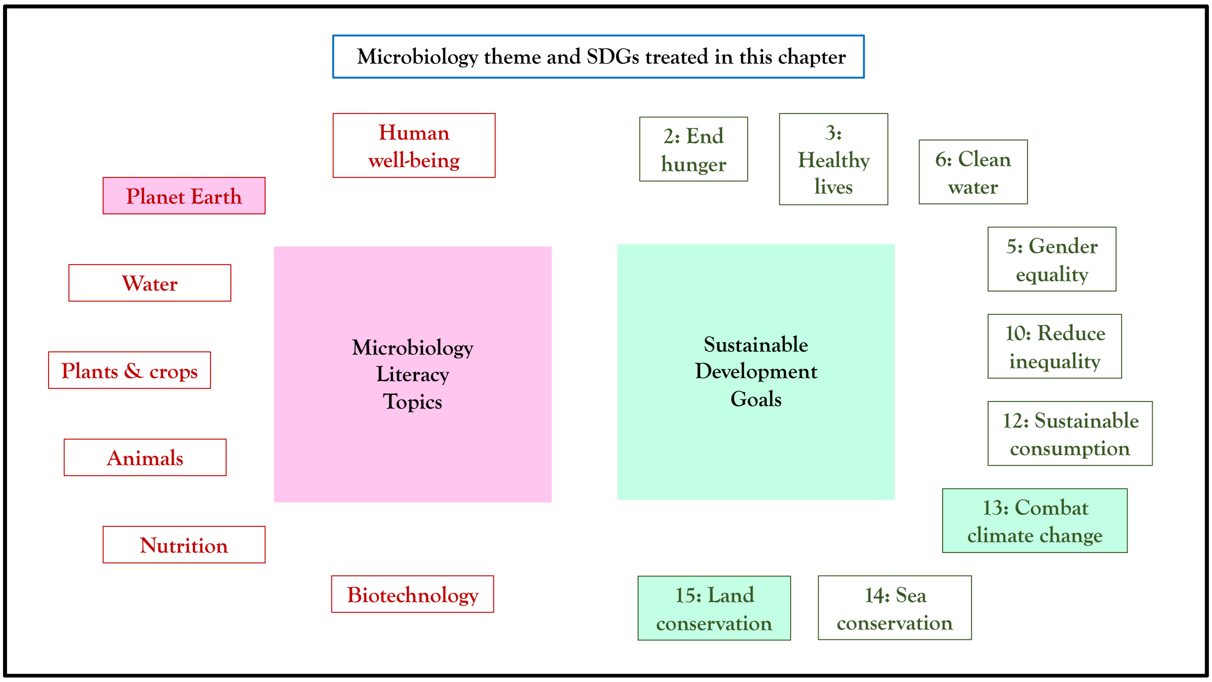
## The Stored Carbon Crisis

### Storyline

The concentration of carbon-containing gases in Earth's atmosphere is a current issue of global concern. It is therefore critical to understand where carbon is stored in the Earth system and which processes act to either add or remove it from the atmosphere. Here we discuss the different pools of carbon on Earth and the role of microorganisms in transforming this carbon into greenhouse gases that can warm the atmosphere. In particular, we focus on peatland ecosystems (e.g. bogs, fens, mires) as a key mechanism of trapping carbon from the atmosphere and demonstrate how microorganisms are key to carbon emission or trapping, both in healthy peatlands and in those facing anthropogenic challenges.

### The Microbiology and Societal Context

*The microbiology context:* microbial metabolisms; environmental microbes; redox reactions. *Environmental science context:* carbon cycle; nutrient cycling; atmospheric processes. *Sustainability issues:* global warming; environmental protection; habitat restoration.

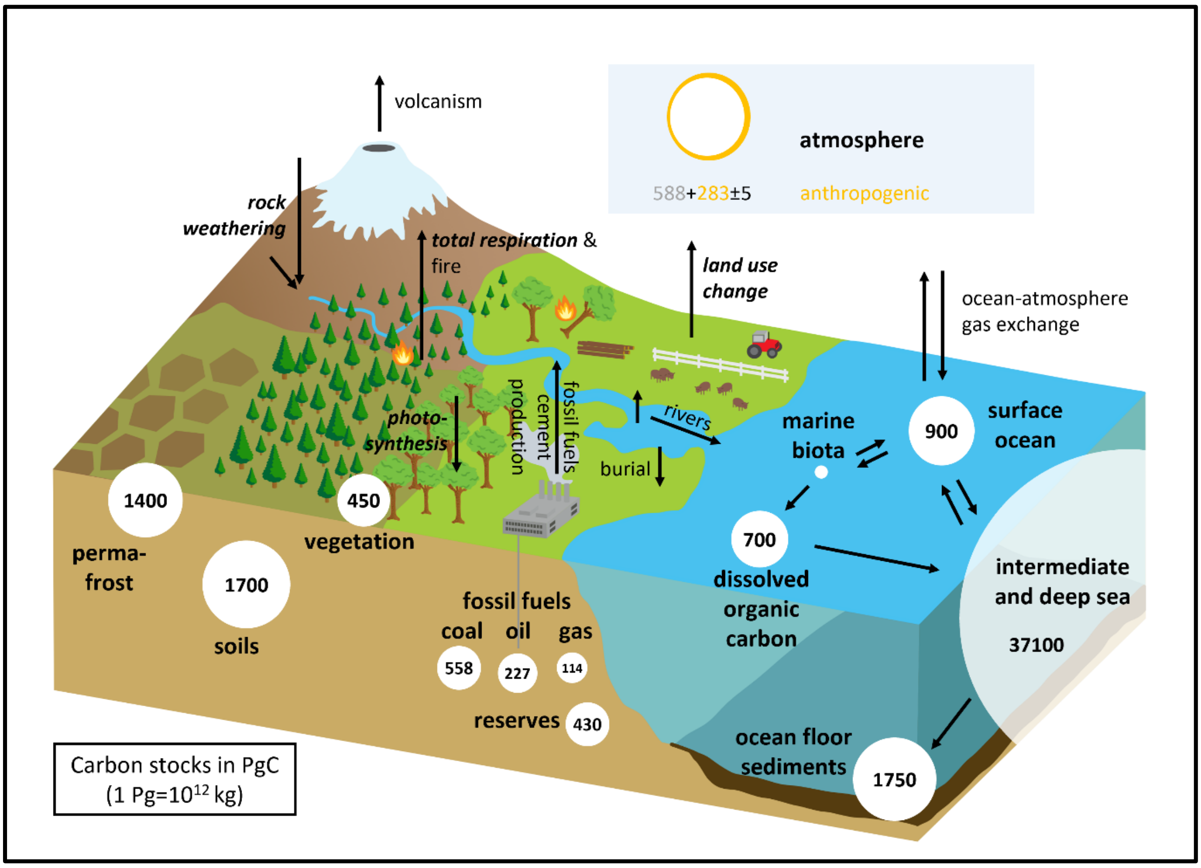


## The Stored Carbon Crisis: The Microbiology

1. ***Where is Earth's carbon?*** The habitability of our planet, Earth, is largely only possible because microorganisms, tiny single celled life forms, began excreting oxygen as a waste product early in Earth's history. These microorganisms changed the composition of the atmosphere and provided the air we breathe. Since this time, microbial processes on the Earth's surface have continued to influence the composition of our atmosphere, in particular by producing carbon-containing gases like carbon dioxide ($CO_2$) and methane ($CH_4$). These gases have the ability to absorb heat, trap it and keep it from escaping into space. This so-called "greenhouse effect" warms our planet and without it temperatures would be too low for humans to survive.

However, the amounts of these gases in the atmosphere must be delicately balanced. Too little and we lose the warm blanket of our greenhouse; too much and the Earth becomes warmer and warmer, throwing the climate out of balance.

Rocks, soil, water, plants, animals and air all contain carbon either in solid form, dissolved in water or as a gas. Most of this carbon is safely stored away but some will transform from one form to another. For example, volcanoes transform carbon that was stored in rocks to $CO_2$ that escapes to the atmosphere.




**The global carbon cycle with sources and sinks.** Carbon can be found in all the different compartments of our planet. Stocks of carbon measured in petagrams (Pg) are depicted as circles with sizes proportional to the carbon stocks. Source and sink processes that emit or take up carbon are shown as arrows. The natural carbon cycle can buffer some of the carbon emitted by human activities. However, these systems have limitations such as solubility of $CO_2$ in water, vegetation growth and burial rates of carbon. In addition, climate warming may unlock previously stored carbon through increase of emissions e.g. from thawing permafrost soils or wildfires. (Figure adapted from IPCC 2013 and 2021)

Plants consume $CO_2$ through photosynthesis and use it to build tissue. Animals eat plants and breathe out $CO_2$, and when plants or animals die their remains are decomposed by microorganisms, turning them into part of the soil carbon, or back to $CO_2$.

2. ***How is carbon storage connected to the climate emergency?*** For a long time, these natural processes have controlled the cycling of carbon through different stores, with a rather balanced cycle of carbon release to the atmosphere and carbon uptake that helps to keep the climate stable. However, since the industrial revolution, humans have altered the carbon cycle by extracting and burning fossil fuels (oil, coal and gas), deforestation, and farming e.g. rice or livestock farming which produces a lot of methane. This imbalance is leading to an increase in global temperatures that could influence many important processes such as global weather (i.e. increased risk of floods, droughts and extreme events), fire, sea level and the health of the oceans.

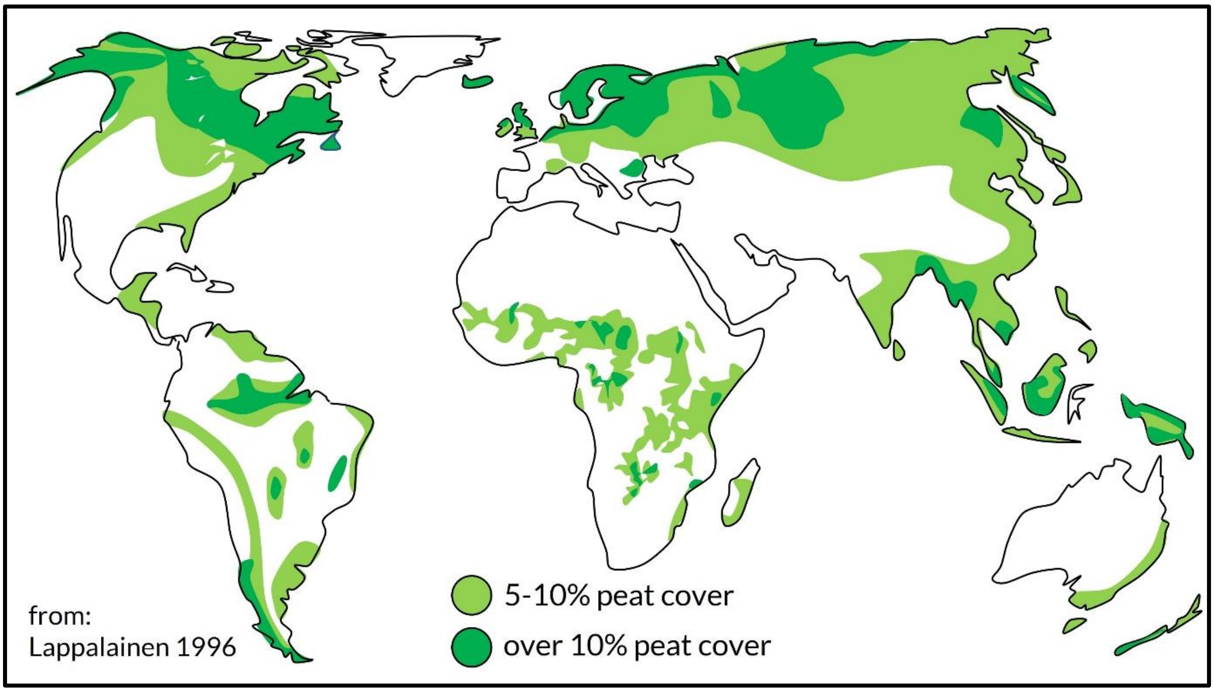
Some of these processes represent a positive climate feedback: processes occurring as a result of global warming which in turn cause further warming by e.g. greenhouse gas emissions or increase of water vapour in the atmosphere. Feedback processes are often associated with so-called "tipping points" where the changing climate could push parts of the Earth system into abrupt or irreversible changes.

It is thought that thawing of permafrost represents an example of a climatic tipping point, the consequences of which are one of the most important unknowns in global climate feedbacks. Permafrost is permanently frozen ground, which does not even thaw in summer. When frozen, carbon is preserved in the soil as the microorganisms are not active. This is the same effect that keeps food in the freezer from going off. Once the soil is thawing, the microorganisms can grow, feed on the carbon and produce a lot of $CO_2$ and $CH_4$, which is released into the atmosphere and further contributes to climate warming. This positive feedback causes further permafrost loss.

The problem of unbalanced carbon input into the atmosphere is known as the "stored carbon crisis": we are releasing carbon to the atmosphere so quickly that neither natural nor anthropogenic processes can return it to the ground quickly enough to avoid a climate emergency.

3. ***Peatlands and the stored carbon crisis.*** One system which excellently demonstrates how problems caused by humans impact natural carbon cycling and storage are peatlands. Peatlands are known by many different names such as bogs, mires, quagmires and fens. Their different names reflect their diversity, their characteristics and where they are found. But something that all peatlands share is that they are wetlands where carbon-rich dead plant material builds up. This is why peatlands are also referred to as 'carbon stores'.

Peatlands only cover around 3% of Earth's land surface, but they store 30% of the carbon in all the planet's soil. Most peatlands are found in the northerly regions of Europe, Asia and North America, but there are also peatlands in tropical regions. The wet climate of these areas is what provides the right conditions for peat to develop. The waterlogging of soil in these places means that little oxygen is present, and this protects the carbon from being broken down as normal and released as carbon dioxide. This effect can preserve carbon in peat soils for many thousands of years. Indeed, peat is famous for preserving the bodies of ancient people from up to 8000 years ago!



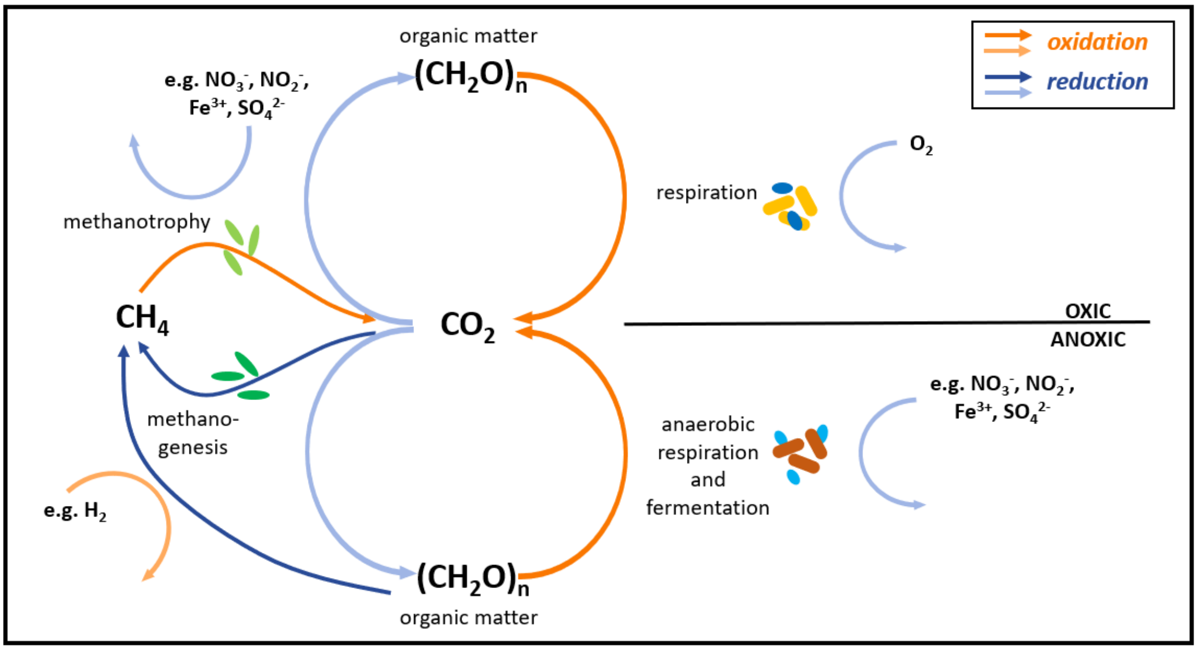

**The distribution of peatlands on our planet:** Peatlands can be found in more than 180 countries across 6 continents. Most peatlands are situated in the northern regions of the globe, as well as the tropics. The wetter climate in these places provides the conditions for peat to form and build-up. (Figure adapted from Lappalainen 1996)

***4. How are microbes involved in storing carbon?*** Microorganisms are critical for the carbon storage capabilities of peatlands. In most environments, when plants die or shed their leaves at the end of the growing season, they are broken down by microbes who use oxygen. The microbes gain their energy from this process and release lots of the carbon back into the atmosphere as carbon dioxide. However, in peatlands, the wet conditions mean there is limited oxygen and more of the plant matter can build up instead of being broken down as usual.

Despite the lack of oxygen in peat, some microbes can still live there. This is because microbes are a highly diverse range of living organisms, and many have different adaptations to survive even in environments that appear extreme to us. In peatlands, there are microbes that don't need oxygen to grow and survive. Instead they can use other substances to help them get the energy they need from the peat itself (see below for more details).

These specialist microbes break down the carbon in the peatland at a much slower rate than microbial communities in oxygen-rich environments do. The processes they carry out can produce the greenhouse gas methane as an end product. In healthy peatlands though, the amount of carbon emitted as methane and carbon dioxide is much smaller than the carbon which is being locked away.

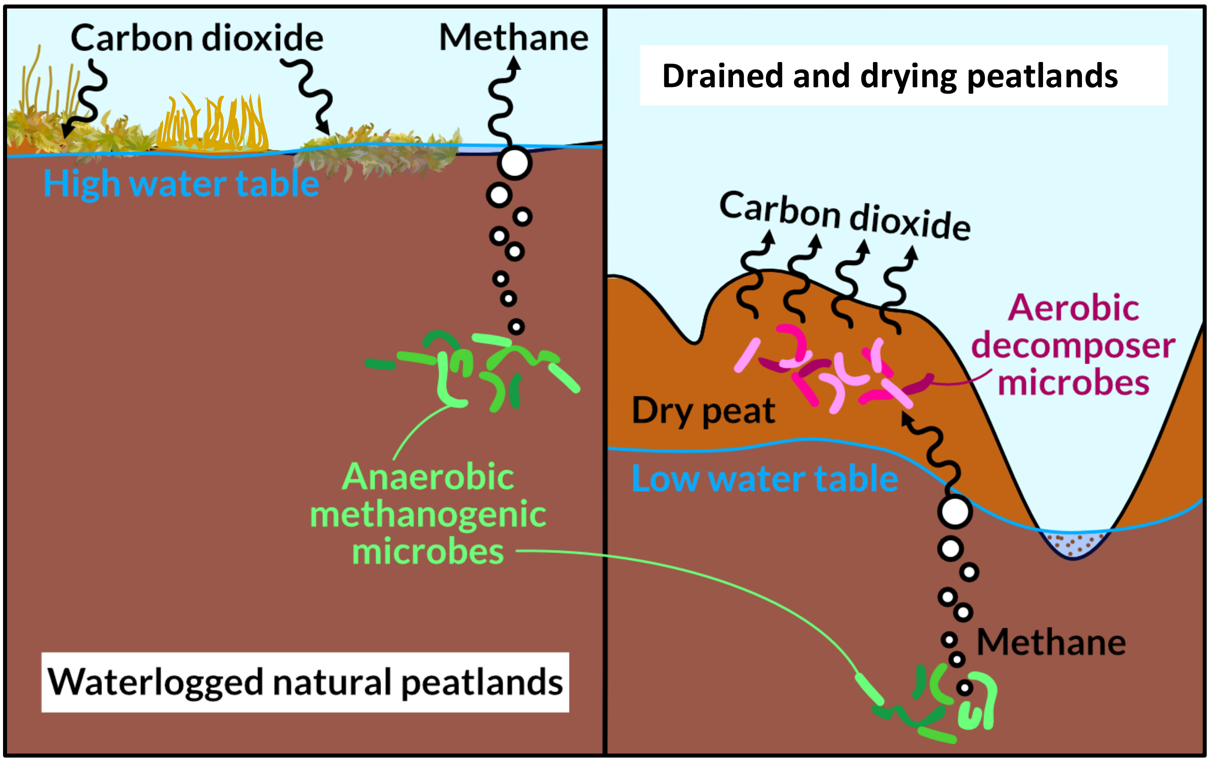
If the balance of carbon entering the peatland as dead plant material is bigger than the carbon being emitted when microbes break it down, then the peatland is a carbon store. But these carbon stores are at risk because of how they are managed by humans and because of climate change. These factors threaten to dry out peatlands, removing the water that protects the carbon from microbial breakdown. In dry peatlands oxygen enters the soil and thus microbes can use the carbon more quickly. This means they emit more carbon dioxide too, which tips the balance from a carbon store into a carbon source to the atmosphere (see Fig. **How is carbon cycled in healthy vs. drying peatlands**).




**How microbes make greenhouse gases.** Microorganisms use carbon both to gain energy and to build their cells. To gain energy reactions have to take place in cells, which consist of an oxidation reaction (whereby electrons are donated to reaction partners) and a reduction reaction (where electrons are taken up). In the process to gain energy microbes can produce greenhouse gases in several ways: microorganisms can produce $CO_2$ by respiration using organic matter such as sugars and oxygen or if no oxygen is available (anoxic conditions) some microbes can do anaerobic respiration using lower energy electron acceptors such as e.g. nitrate or sulfate or they produce $CO_2$ in fermentation. Methane can be formed from $CO_2$ or directly from organic carbon such as sugars. But $CH_4$ can also be oxidised to $CO_2$ again when reacting with electron donors such as oxygen or others like nitrate and sulfate. (Figure adapted from Brock Biology of Microorganisms)

4. ***Peatlands under threat.*** Peatlands have been impacted by human activities in many ways. Peatlands in their natural, wet state are often not considered very productive or valuable by landowners, as both crop and livestock farming are difficult due to waterlogging. Vast amounts of peatland have been drained to enable farming or cutting of peat to use as a fuel source. Despite numerous alternatives, peat is also mined around the world for production of compost as it holds water well, is high in carbon and is cheap. All of these uses of peatlands allow oxygen to enter and enable microorganisms to more rapidly degrade the peat, turning a large fraction of it into $CO_2$. It is estimated that 15% of the world's peatlands are now in a degraded state, and in some European countries such as the UK and Germany this figure is as high as 80%.

However, there is still hope for the world's peatlands. Increased awareness of their importance as a carbon store has led to many governments and political organisations such as the European Union to invest in large-scale restoration of peatlands. This typically involves blocking drainage ditches to re-establish waterlogging, as well as the planting of native peatland plant species. The hope is that this will not only save the last remnants of pristine peatland on our planet, but that these peatlands will recover their ability to trap carbon and again become an important strategy for solving the stored carbon crisis.




**How is carbon cycled in healthy vs. drying peatlands.** Peatlands accumulate carbon as vegetation growing on the surface takes up carbon dioxide from the atmosphere to build plant matter. When plants die at the surface the high water table in a healthy peatland means that this matter is held in a low-oxygen environment. Anaerobic microbes living in the peat may be able to break down some organic matter if other electron acceptors are available (see Fig. How microbes make greenhouse gases). These processes can produce some methane which is a greenhouse gas, but on balance the peatland is taking up more carbon than it emits. In drained or drying peatlands, the water level is lower and so oxygen is available in the peat. Microbes can use this oxygen to respire (see Fig. How microbes make greenhouse gases) and break down the organic matter. Methane produced below the water table can be oxidised in the upper peat now that oxygen is available. The peatland carbon balance is uneven, and dry peatlands emit more carbon than they take up.

## Relevance for Sustainable Development Goals and Grand Challenges

This topic is of relevance to UN sustainable development goal 13 "climate action" and goal 15 "life on land".

## Potential Implications for Decisions

The release of carbon from terrestrial carbon stores into the atmosphere by microorganisms has important implications for the way our planet responds to climate change. Some terrestrial ecosystems such as peatlands have an extremely large role in storing carbon, thus awareness of their importance is essential for their preservation in the future.

1. ***Individual***
    a. Should I use peat-containing compost/soil for my garden or house plants?
    b. Should I buy pot-plants and herbs grown in peat-containing compost?
    c. Should I use peat as a fuel for heating and cooking?

2. ***Community policies***
    a. Should peat-containing products be used in community-owned/serviced facilities, like parks, green areas and plant-decorated areas?
    b. What impact can local information campaigns have on the use of peat and its global consequences?
    c. Should the sale and use of peat products in the community be actively disincentivized?
    d. What could some incentives be for creating and maintaining wetlands?

3. ***National policies***
    a. What impact could national information campaigns have on the use of peat and its global consequences?
    b. Should we have national programmes of restoration of previous wetlands/creation of new wetlands?
    c. What policies would lead to reduction of trading peat products?
    d. What international policies exist in your region to reduce trading peat products?
    e. What international efforts are being made to protect the world's peatlands, wetlands and permafrost lands?

## Pupil Participation

1. ***Class discussion of the issues associated with stored carbon***

2. ***Pupil stakeholder awareness***
    a. Peat is often used to improve water retention in the soils our plants grow in. What are the alternatives??
    b. Peat is often used to improve soil texture for our plants. What could we use instead?
    c. Wetlands are vital for the planet: would it help to create a mini-wetland in our garden/school plot (think not only about its effect on global warming, but also about its educational value for family and friends, its contribution to biodiversity, its ability to bring new wildlife into our lives, etc.)
    d. Can you think of anything that might be done to reduce the loss of wetlands and its negative consequences?

## The Evidence Base, Further Reading and Teaching Aids

1. **For more information on carbon cycling, peatlands and climate change:**
    a. **A review by NASA on the Carbon Cycle:** https://www.earthobservatory.nasa.gov/features/CarbonCycle
    b. **UN issues of emerging concern (permafrost and peatlands):** https://wedocs.unep.org/bitstream/handle/20.500.11822/27542/Frontiers1819_ch3.pdf?sequence=1&isAllowed=y
    c. **Website of the UN Environment Program (UNEP) on protecting peatlands for people and planet:** https://www.unep.org/explore-topics/ecosystems-and-biodiversity/what-we-do/protecting-peatlands-people-and-planet
    d. **The International Peatland Society website:**

https://peatlands.org/peatlands/peatlands-and-climate/

e. **Website of the Global Peatlands Initiative:** https://www.globalpeatlands.org/
f. **IUCN Peatland Programme website:** https://www.iucn-uk-peatlandprogramme.org/about-peatlands

2. **Interactive resources and videos:**
   a. **Video resources from the IUCN Peatland Programme:** https://www.iucn-uk-peatlandprogramme.org/resources/videos-vr-images
   b. **Animated videos on peatlands:** https://www.re-peat.earth/educational-videos
   c. **Virtually explore peatland pavilion at COP26** https://storage.net-fs.com/hosting/6147066/7/
   d. **UNEP interactive journey to visit different peatlands around the world:** https://www.unep.org/interactive/explore-ecosystems/peatlands/en/index.php
   e. **Interactive journey through the peatlands of Canada:** https://storymaps.arcgis.com/stories/19d24f59487b46f6a011dba140eddbe7

## Glossary

**Aerobic respiration:** a metabolic process by which living things turn carbon (i.e. as fats or sugars) into energy using oxygen
**Anaerobic respiration:** a metabolic process whereby cells break down carbon to produce energy without the use of oxygen
**Carbon dioxide:** a carbon containing greenhouse gas with the formula $CO_2$
**Carbon sink:** a part of the Earth system which acts to remove carbon from the atmosphere i.e. soils or the oceans.
**Carbon source:** a process that acts to release carbon into the atmosphere e.g. forest fires or burning fossil fuels.
**Climate feedback:** Occurs when one climatic process triggers changes in another process, that in turn influences the initial process. Positive feedbacks will amplify the effect. Negative feedbacks will dampen the effect.
**Greenhouse gas:** a gas that contributes to the greenhouse effect (i.e. causing global temperatures to rise) by absorbing infrared radiation.
**Methane:** a carbon-containing greenhouse gas with the formula $CH_4$
**Peatland:** a generic term for carbon-rich wetlands. Includes bogs, mires, quagmires, and fens
**Permafrost:** a thick subsurface layer of soil that remains below freezing point throughout the year, occurring chiefly in polar regions.