The permafrost carbon feedback

The impact of global warming on Arctic ecosystems

Philip Wookey

The Arctic is warming faster than the rest of the planet, and this is affecting processes at all scales, from the molecular to the ecosystem. This article looks at the melting of permafrost, which not only impacts on landscapes, habitats and human activity, but could lead to massive increases in greenhouse-gas emissions

Despite extremes of cold and months of darkness, the Arctic supports complex food chains, from algae and cyanobacteria to large mammals. When these organisms die, their remains become part of the 'detritus' system. Organic detritus which does not fully decompose plays an important role as organic matter in soil in all environments. But in cold environments such as the Arctic, incomplete decomposition can lead to massive accumulations of organic matter, and thus carbon, in soils and sediments.

A similar process in UK uplands following the retreat of the British-Irish ice sheet between 27,000 and 11,500 years ago produced our peatlands and blanket bogs, where cold and wet conditions have restricted decomposition processes.

These areas of preserved organic matter act as huge carbon stores.

Permafrost

Much of the Arctic land surface, and adjoining land to the south, is underlain by **permafrost**. This is defined by the International Permafrost Association as 'ground (soil or rock and included ice or organic material) that remains at or below 0°C for at least two consecutive years'. Much of this permafrost formed during colder glacial periods, but persists in locations where the mean annual temperatures are too low, and the thaw season too short, for thaw to penetrate much more than a metre or so below the ground surface. Permafrost now occurs beneath 24% (23 million km^2) of the exposed land area in the northern hemisphere (Figure 1). This is an area 95 times the size of the UK and it extends well beyond the Arctic land surface (which covers around 14 million km^2). See Box 1.

Permafrost in the Mackenzie Uplands, Northwest Territories of Canada. Note the 'polygons', which form over many years due to the frozen ground shrinking in extreme low temperatures. For scale, the long axis of the image is about 300 metres

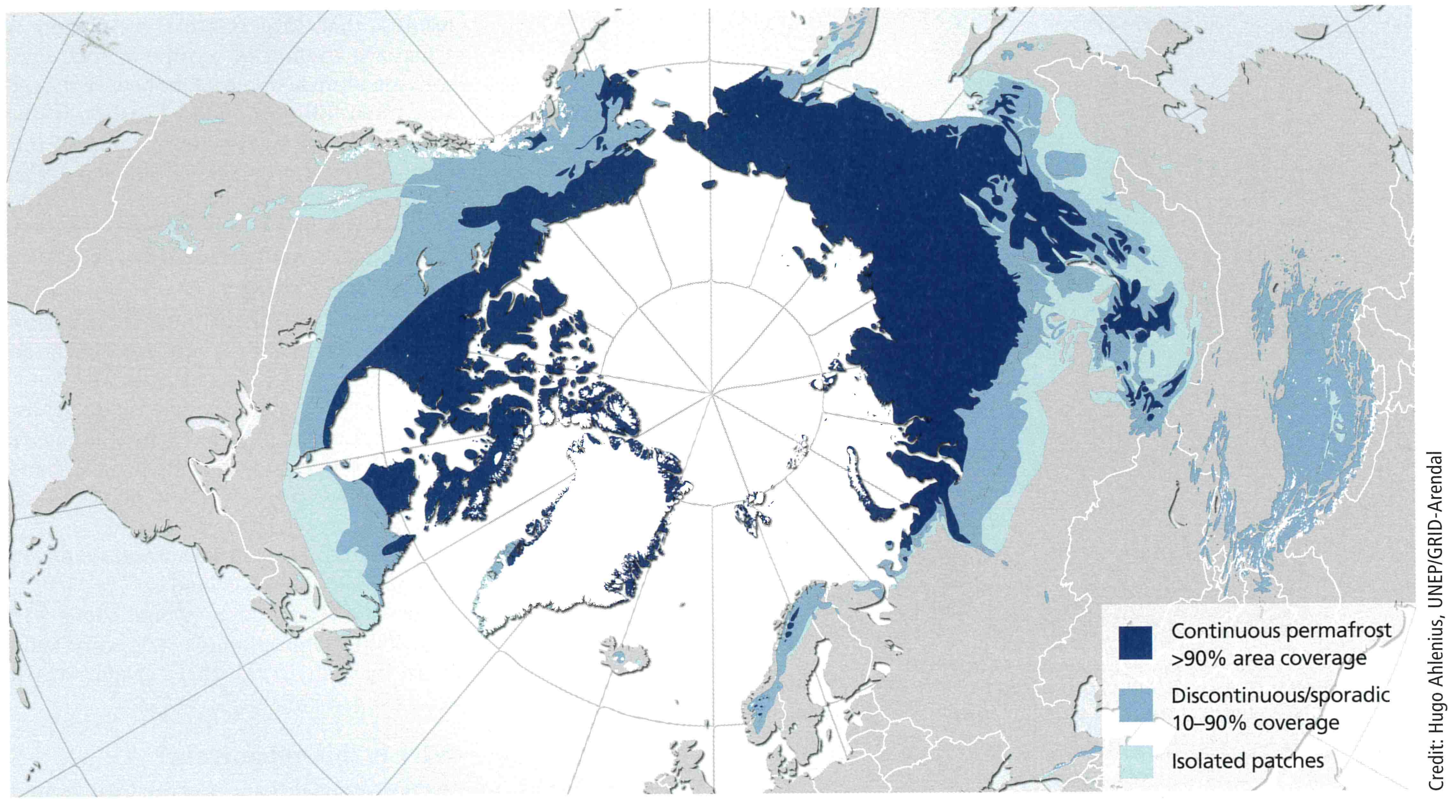


Figure 1 Permafrost extent in the northern hemisphere

Box 1 What is the Arctic?

In planetary terms, the Arctic comprises the area within the Arctic circle, an imaginary line that circles the globe at approximately 66.5°N. The Earth's axis is tilted 23.5° from the plane of its orbit around the sun (90° minus 66.5°). So, at the (northern hemisphere) winter solstice, areas north of 66.5°N receive no direct sunlight. This varies in duration from just 1 day of the year at the Arctic circle, to 6 months of the year at the north pole. Conversely, at the summer solstice, areas to the north of 66.5°N receive direct sunlight 24 hours a day.

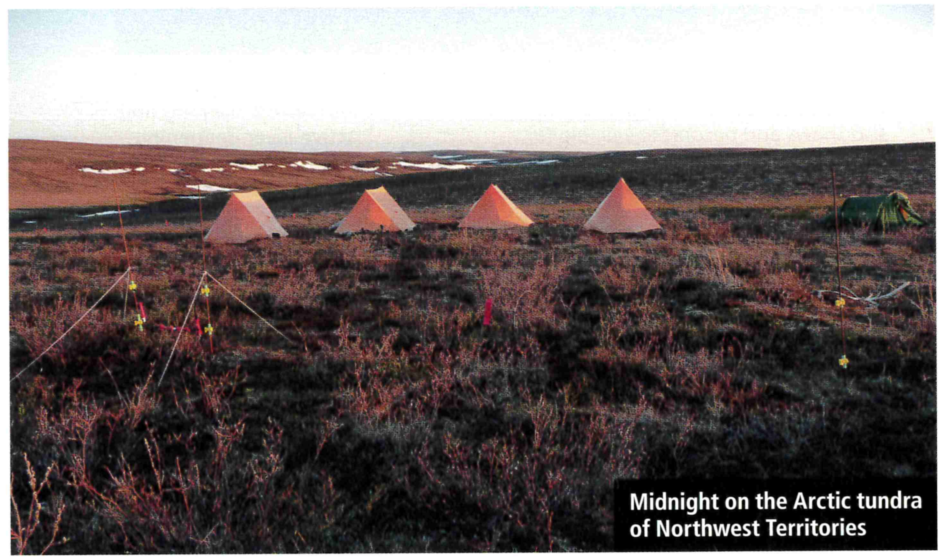
There are several other ways in which Arctic regions are defined (see **www.tinyurl.com/y9s6aq4x**), depending on context: environmental, biological, economic, legal or social. Biologists often consider the Arctic treeline (to the north of which boreal forest gives way to treeless tundra) as delimiting the Arctic, but this excludes large areas of forest, and also permafrost regions, both north and south of the Arctic circle.

A 'detritus deep-freeze'

The decomposition of plant and animal remains in soils is mainly carried out by microorganisms and soil invertebrates. This releases carbon and other nutrients from organic remains and drives the growth of the soil organisms (the 'decomposers') themselves. Decomposition releases carbon dioxide (CO_2) back to the atmosphere and nutrients such as nitrogen and phosphorus into the soil.

GeographyReviewExtras

For a quiz on the Arctic and Antarctic, go to: www.hoddereducation.co.uk/geographyreviewextras



Midnight on the Arctic tundra of Northwest Territories

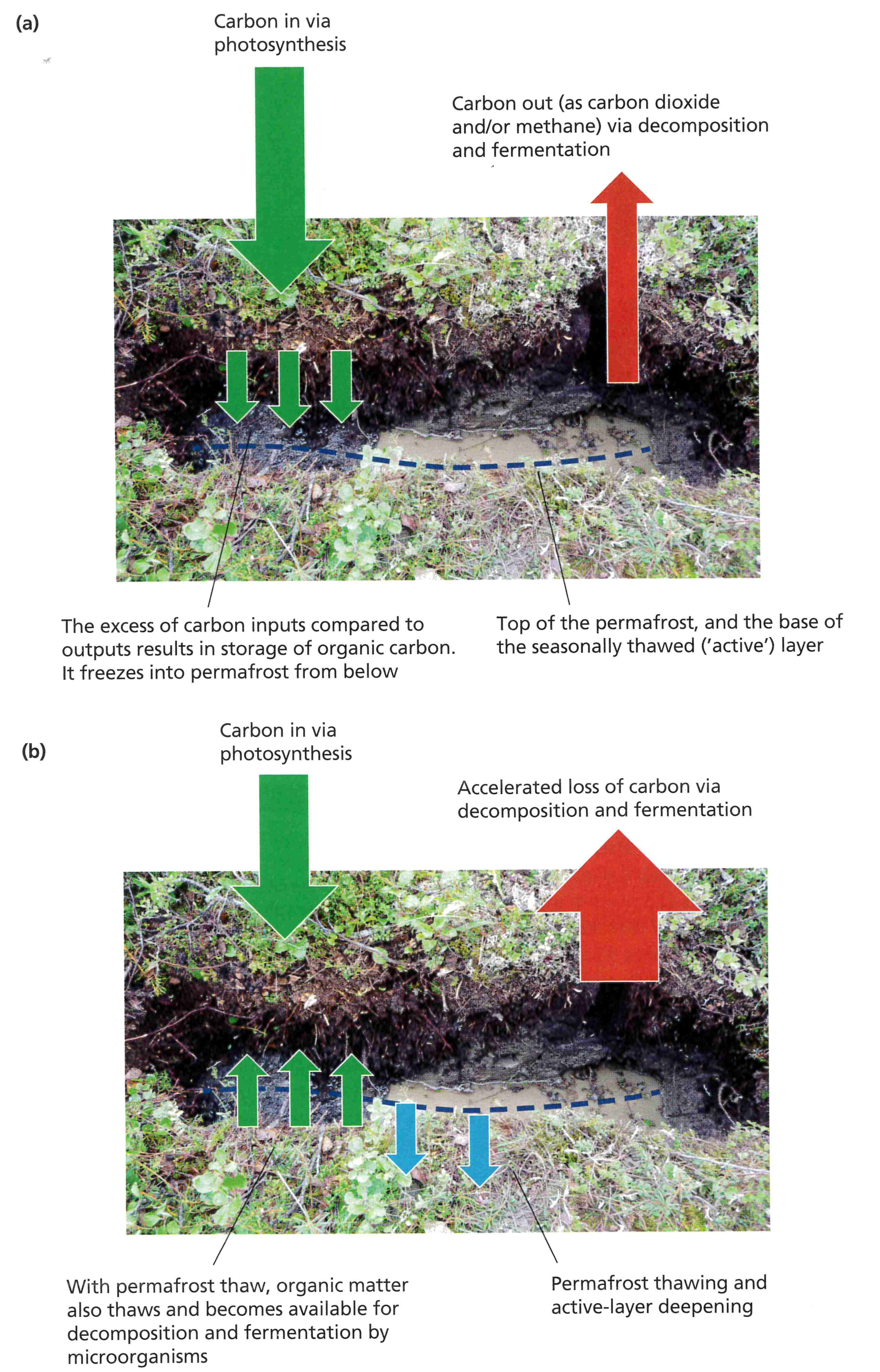


Figure 2 **(a)** For thousands of years organic carbon has been incorporated into permafrost. **(b)** As permafrost thaws, decomposition could strengthen carbon losses to the atmosphere. The background photo is a soil pit in the Northwest Territories, Canada

In cold regions, organic matter tends to be produced faster than it decomposes, partly because soil organisms are more sensitive to temperature than photosynthesising plants. This leads to a build-up of organic matter so that over centuries and millennia, an increasing amount of organic matter is stored in soils and sediments. As this organic matter accumulates, it restricts the depth to which the seasonal thaw can penetrate (Figure 2), and the deeper thaw layer starts to freeze, upwards, from the permanently frozen ground below.

Imagine this process continuing, little-by-little, over thousands of years. The net result is that, in permafrost soils, there is a massive amount of organic matter. Such soils are estimated to contain between 1,400 and 1,850 billion tonnes of carbon in the top 3 metres alone (Figure 3). Much of this currently remains frozen year-round, but that seems to be changing.

The Arctic amplification of global warming

The Arctic is warming at double the rate of the global mean, and for large areas the mean annual temperature has increased by 2–3°C in the last 30 years. This so-called 'Arctic amplification' of global warming is caused by various aspects of the global climate and ocean circulation system. The implications are:

- reduced extent of Arctic sea-ice
- reduced depth, duration and extent of seasonal snow cover on land
- increases in productivity and changes in vegetation composition of Arctic ecosystems
- an increase in the thaw of permafrost across large areas

Why is this important?

Deeper seasonal thaw of permafrost ground produces some spectacular geomorphological features such as 'permafrost thaw slump', in which whole hillslopes, river banks or coastal areas literally slide over a thawing, and often waterlogged, layer beneath. Permafrost thaw can also expose organic matter that has been frozen for hundreds or thousands of years to temperatures above freezing.

This melting is important because, in the presence of liquid water and organic matter, microorganisms can start to become metabolically active. Add oxygen to the mix and this metabolism is **aerobic** (using free oxygen). A by-product is the release of carbon dioxide. If oxygen availability is limited (for example, **anaerobic** conditions where the ground is waterlogged and oxygen is slow to diffuse) some bacteria, known as 'methanogens' (methane producers) can metabolise using fermentation reactions which produce methane (CH_4) as a by-product.

In other words, permafrost thawing effectively releases ancient stores of organic matter which have been safe in the 'deep-freeze' for thousands of years. It could lead to substantial emissions of both carbon dioxide and methane, in addition to those considered part of the natural global carbon cycle. Methane is an even more potent greenhouse gas than carbon dioxide.

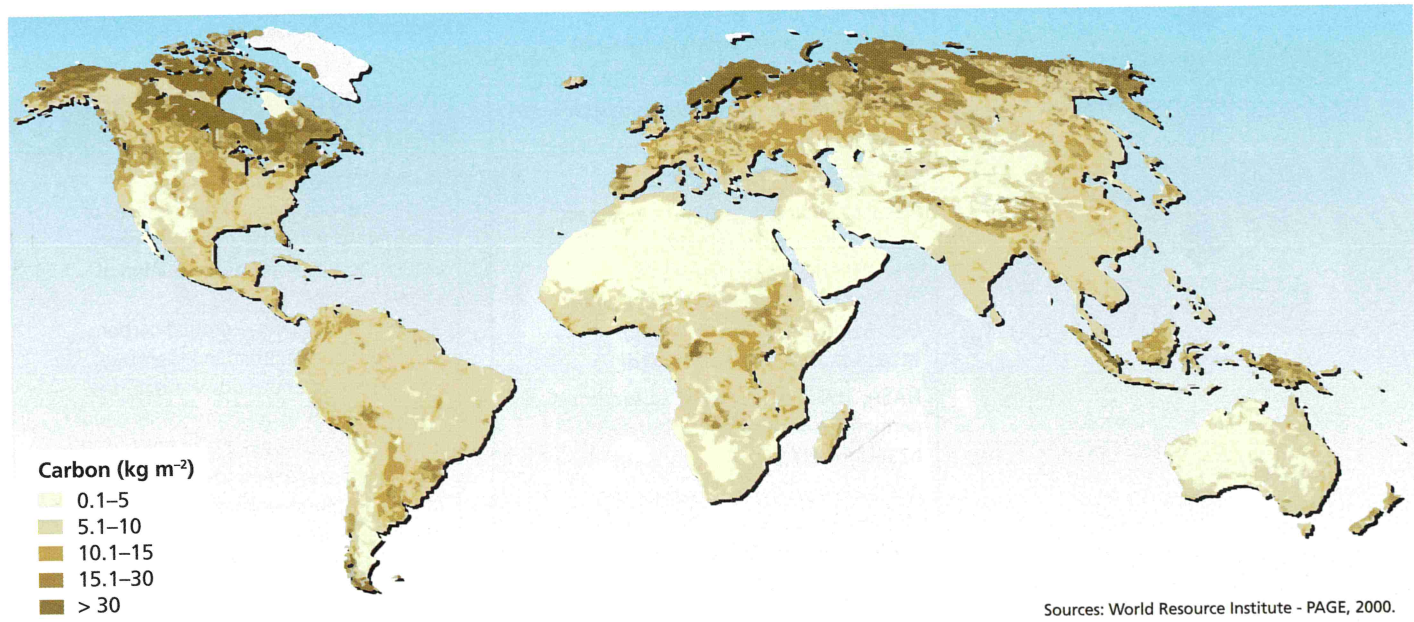
Such emissions can be seen most dramatically where thawed soil organic matter finds its way into lakes and ponds, settles to the bottom, and is fermented by methanogenic bacteria beneath the seasonal ice cover. Bubbles of methane make their way through the sediment and water above, and are trapped beneath the ice. So much methane can accumulate that if the ice surface is broken the gas can escape violently, and can even be ignited if caught at the right moment (see Further reading for a video). Although less dramatic, the same process of methanogenesis can occur in waterlogged soils and sediments over very large areas.

A large permafrost thaw slump in the Peel Plateau, Northwest Territories. This one is estimated to have displaced about 5 million m³ of materials in the past two decades. There are hundreds of features like this in the western Canadian Arctic and they can rapidly thaw thick layers of ice-rich permafrost

A greenhouse-gas store

To put this risk in context, all fossil-fuel combustion and other human activities since 1850 have released around 350 billion tonnes of carbon to the atmosphere (mainly as carbon dioxide). This is equivalent to just 21.5% of the carbon currently found stored in permafrost soils. Researchers estimate that, between now and the year 2100, around 120 billion tonnes of carbon may be emitted to the atmosphere as a direct consequence of permafrost thaw.

The effects of this on global climate will depend on the relative amounts of the two gases emitted. Methane, although present at much lower concentrations in the atmosphere than carbon dioxide, is a much more powerful greenhouse gas on a molecule-for-molecule basis. Best estimates at present suggest that



Credit: Riccardo Pravettoni, UNEP/GRID-Arendal

Figure 3 Global soil carbon stocks. Note the highest values in the far north, much of which is underlain by permafrost this 'permafrost carbon feedback' could be equivalent to around 5.7% of global anthropogenic (human-related) carbon emissions to the atmosphere until the end of this century. This may not seem much, but it could increase global warming by around a third of a degree Celsius. For context, it is similar to the current contribution that China makes to total anthropogenic greenhouse-gas emissions.

Perhaps more worrying, this process could become even more serious into the twenty-second century.

Measuring photosynthesis and decomposition in the Northwest Territories

Why is this called 'feedback'?

In simple terms, more global warming will lead to more permafrost thaw, which will release more greenhouse gases, meaning more warming, accelerating permafrost thaw even further — in other words positive feedback (Figure 4). It can be argued that anthropogenic climate warming has set this type of domino effect in motion. However it is important to note that there is great uncertainty in estimates of permafrost thaw, and in estimates of carbon storage in permafrost. We cannot measure either of these from satellites, and we are talking about very large remote areas (for the Arctic land surface alone, 14 million km^2, and for the total northern hemisphere permafrost region, 23 million km^2).

This is an area where further fieldwork and research is crucial, at all sorts of spatial and temporal scales, ranging from detailed ecological studies on the ground, to satellite remote sensing and global climate modelling. Permafrost carbon feedback has possible implications for us all. It connects processes in the Arctic, for which we may be responsible, with the global climate and thus our own futures.

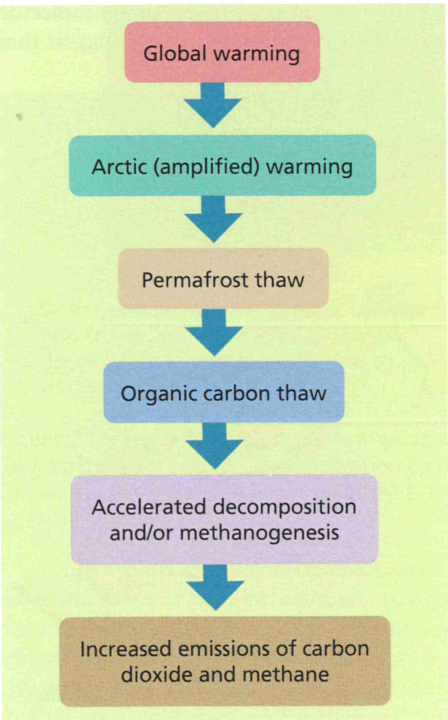


Figure 4 The permafrost carbon feedback

Further reading

Discovering the Arctic, an education resource for schools: **www.discoveringthearctic.org.uk**

NOAA, Arctic Report Card on recent environmental changes relative to historical records: **www.arctic.noaa.gov/Report-Card**

NASA, Global warming from 1880 to 2017 (graphic): **www.tinyurl.com/ydxlj3fc**

The International Permafrost Association: **https://ipa.arcticportal.org/**

Radio Canada article about the impact of permafrost thaw slumps: **www.tinyurl.com/yauzuc3c**

The Northern Circumpolar Soil Carbon Database (with interactive map): **https://bolin.su.se/data/ncscd/**

NASA, The 'sleeping giant' in Arctic permafrost: **https://youtu.be/hZSM8GcmJKg**

BBC article on thawing permafrost, 16 October 2017: **www.tinyurl.com/yatq7nyf**

Hunting for methane video, showing ignition of emerging pockets of gas: **https://youtu.be/YegdEOSQotE**

Questions for discussion

1 Thinking about cause and effect, discuss who is responsible for permafrost thaw and its consequences. Is it the people who live in the Arctic? How many such people are there, compared with the global human population?

2 What is the range of temporal and spatial scales considered in this article, and why is this important?

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Key points

- In Arctic ecosystems rates of photosynthesis have exceeded rates of decomposition for thousands of years, leading to a massive accumulation of organic matter.
- Much of this below-ground carbon is frozen in permafrost and therefore unavailable to decomposer organisms.
- The Arctic is warming twice as rapidly as the planet as a whole. Thawing of the permafrost could lead to decomposition of organic matter and release of greenhouse gases.
- This 'permafrost carbon feedback' could make measurable differences to levels of global warming, and has been referred to by NASA as 'waking a sleeping giant'.

The equality of water supply in Lilongwe

Noel Castree

A resource-security case study

This case study looks at recent research from Malawi showing that urban water security across its capital city depends on who you are and where you live

A stall selling drinking water