Permafrost

What will happen to the Arctic if it warms up?

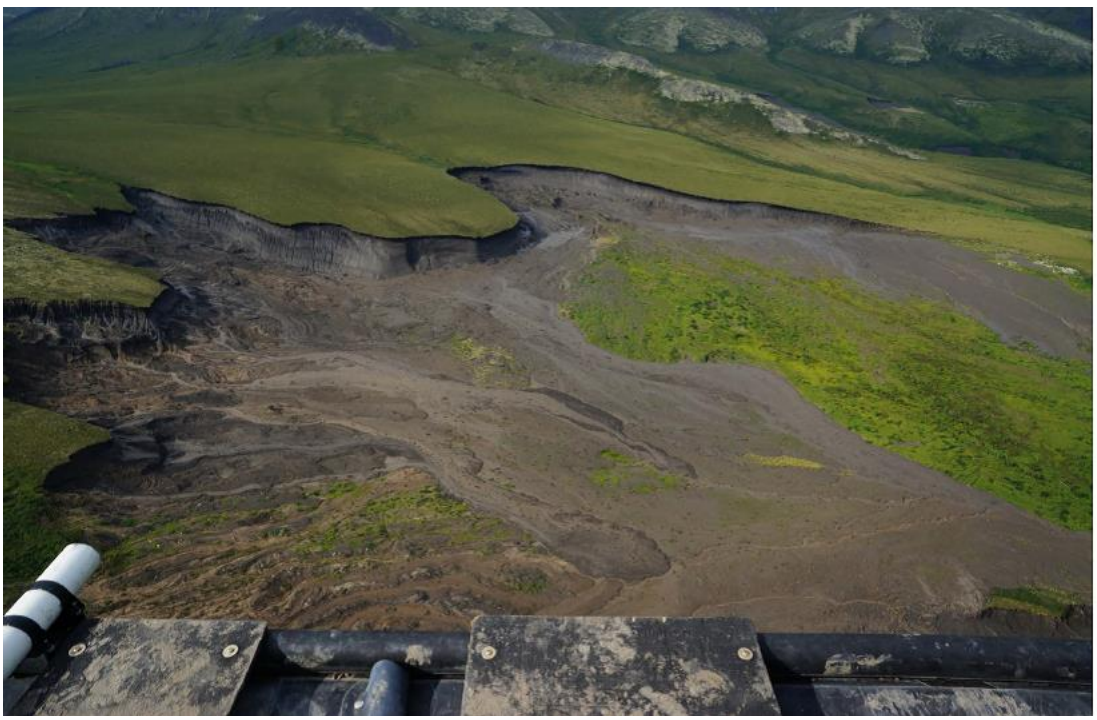

Figure 1: Permafrost thaw causing slumping at the foothills of the Richardson Mountains in Northern Canada. Photo credit: Rob Fraser, Canada Centre for Remote Sensing. Accessed from www.nwtgeoscience.ca/services/permafrost-thaw-slumps on 05 September 2021.

Margaret A. Cramm[1] and James A. Bradley[1,2]

[1]Aix Marseille Univ, Université de Toulon, CNRS, IRD, MIO, Marseille, France
[2]School of Biological and Behavioural Sciences, Queen Mary University of London, London, UK

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The Storyline

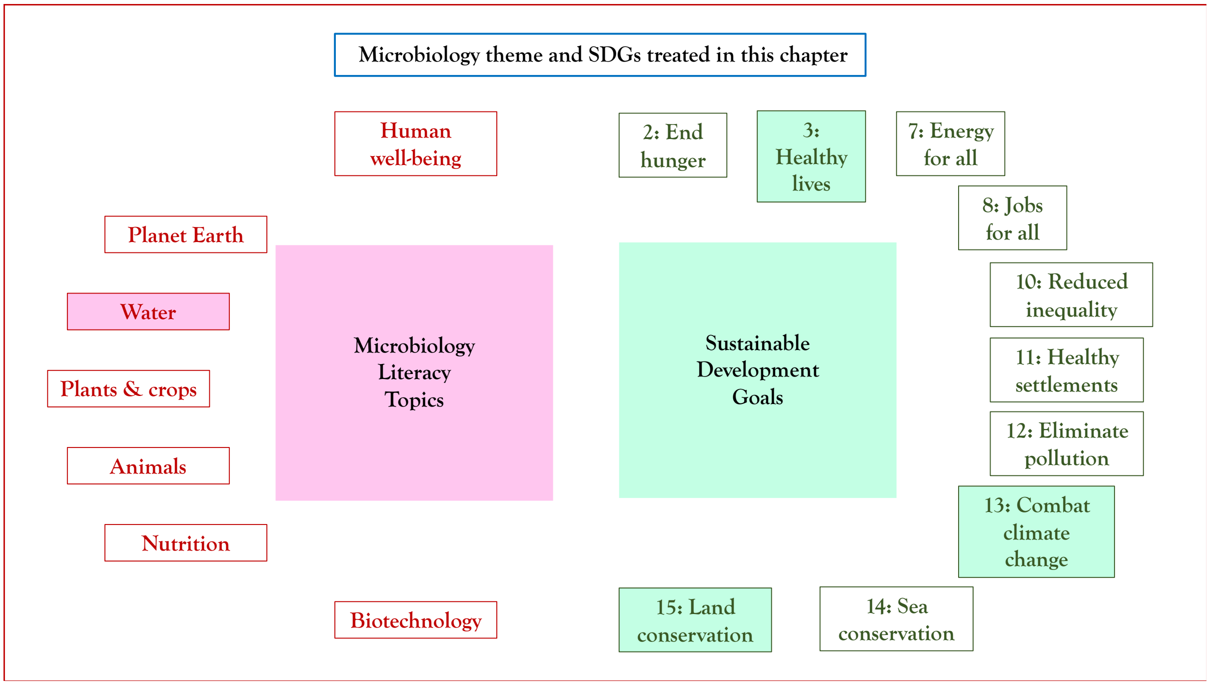
There are parts of the Earth which are so cold that all the soil and water is permanently frozen. This permanently frozen ground, known as permafrost, is most common at high latitudes – such as in regions near the North and South Pole, and at high elevations – such as mountain ranges and plateaus. Soils are important habitats for sustaining life – including microbial life (single-celled organisms such as bacteria and archaea) – and even frozen soils contain billions of microbial cells in each spoonful.

In typical soils, these microorganisms work together in a community to decompose dead biomass, and produce and consume gases in our atmosphere. However, biological reactions in soil, such as those that produce gases, are affected by temperature. In fact, many biological reactions are slowed down by cold temperatures. The temperature of permafrost is below 0°C (the temperature at which water freezes), and therefore any water contained within these soils turns to ice. When soil-water becomes soil-ice, many biological reactions either cannot occur, or occur very slowly, because of the cold temperatures and the lack of liquid water available to help microorganisms carry out these reactions. Permafrost is a unique environment that preserves entire biomes that are frozen in place, and also frozen in time. In these frozen soils, microorganisms are either dormant (inactive), or have unique adaptations for remaining active in sub-zero temperatures.

As increases in greenhouse gases warm the Earth's atmosphere, the ice in permafrost begins to melt, and permafrost thaws. Anthropogenic warming of the Earth's climate therefore causes a decrease in the extent of permafrost covering high-latitude and high-elevation regions. The microorganisms that have been frozen in place within this ground for thousands of years begin to 'wake up' (i.e. re-animate) as they gain access to liquid water for the first time, perhaps in thousands of years. As warming continues, the microorganisms contained in thawing soils become increasingly active, producing gases, including greenhouse gases that contribute to further global temperature rise. The revival of ancient microorganisms in thawing permafrost will present challenges and opportunities for humans inhabiting areas of the world affected by permafrost.

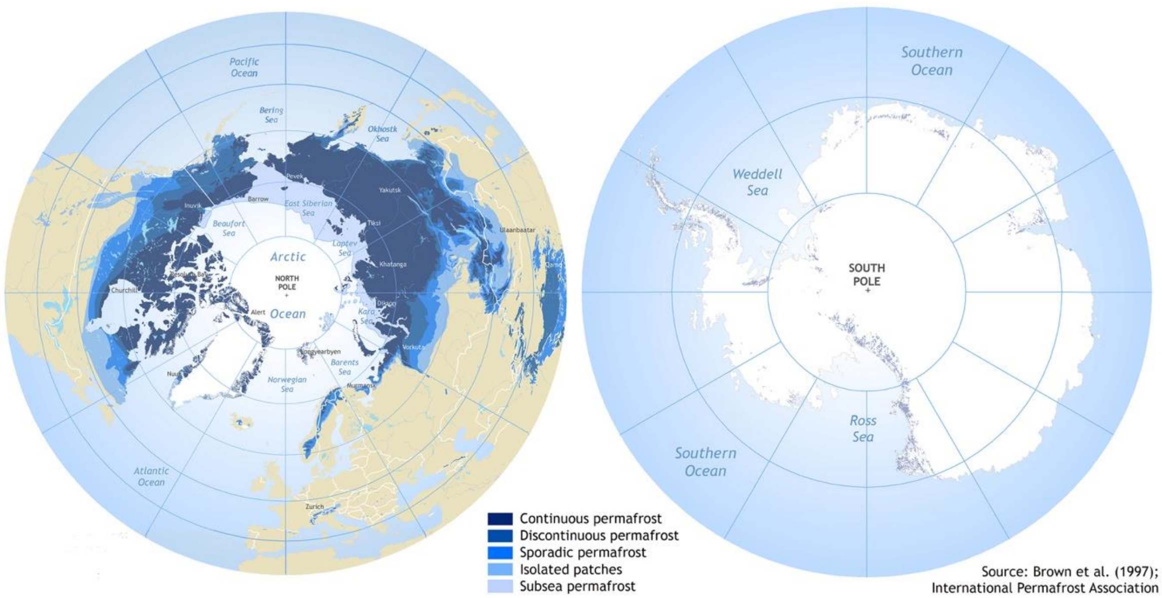
The Microbiology and Social Context

The microbiology: microbial greenhouse gas production; methane production; carbon dioxide production; microbial dormancy. *Sustainability issues*: global warming; health (preservation of human and animal pathogens in permafrost); protect terrestrial ecosystems.



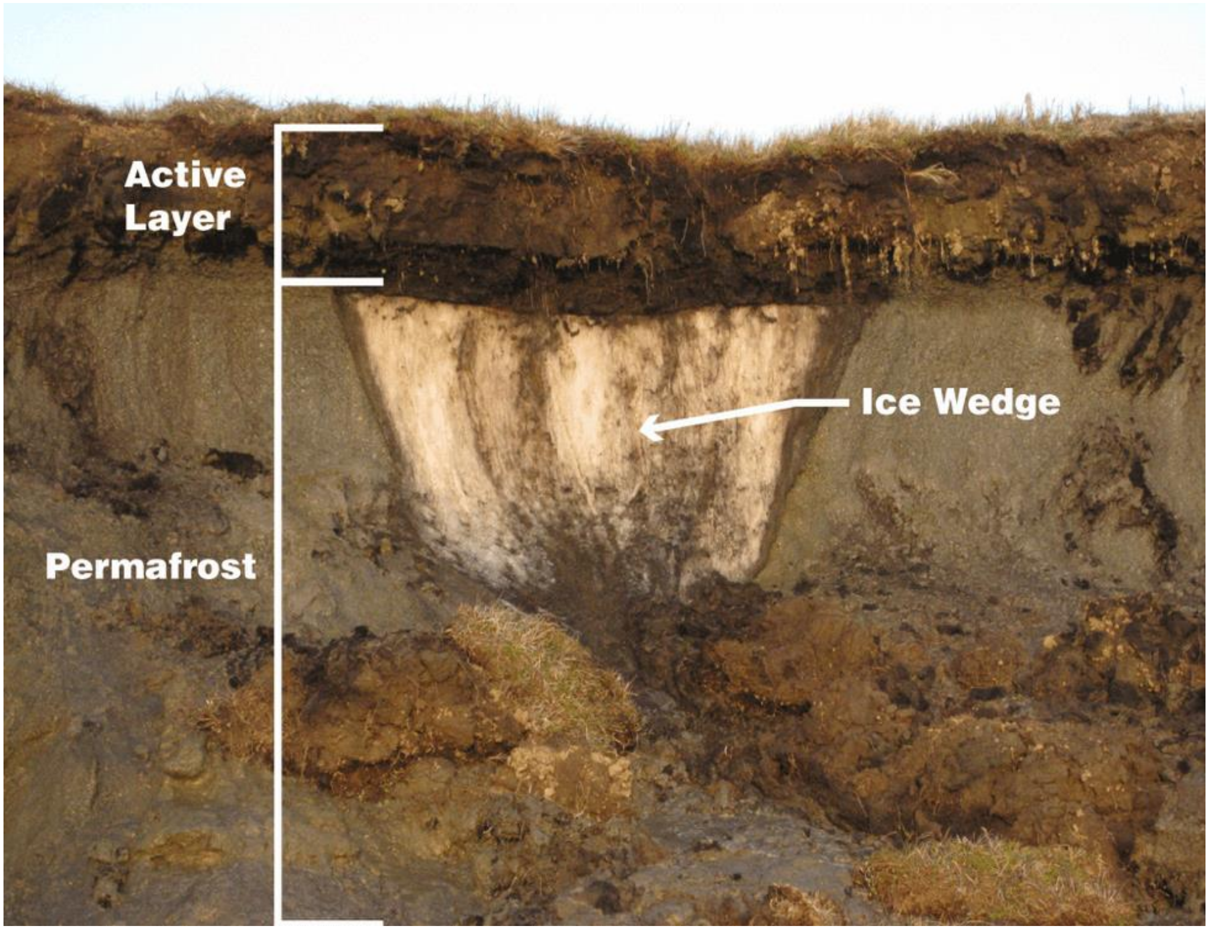
Permafrost: the Microbiology

1. ***What is permafrost and where is it found?*** Permafrost is soil that is frozen for at least two consecutive years. There is permafrost covering roughly one quarter of the total land area in the Northern Hemisphere – including large portions of Alaska, Northern Canada, Siberia, and the Tibetan Plateau. Just like in temperate parts of the Earth, permafrost soils are varied, and can have different water and mineral compositions depending on their location. The topography of the land in permafrost regions is affected by the presence of ice and liquid water. Ice in permafrost keeps the ground firm. Changing temperatures can dramatically affect the topography of permafrost regions: warming causes ice to melt which can lead to the slumping or collapse of previously firm ground (see image on title page).



Circum-Arctic map of permafrost and ground-ice conditions. Image credit: Brown, J., O.J. Ferrians, Jr., J.A. Heginbottom, and E.S. Melnikov, eds. 1997. Circum-Arctic map of permafrost and ground-ice conditions. Washington, DC: U.S. Geological Survey in Cooperation with the Circum-Pacific Council for Energy and Mineral Resources. Circum-Pacific Map Series CP-45, scale 1:10,000,000, 1 sheet.

Permafrost is vertically layered. The surface layer of the permafrost is called the active layer. This layer is affected by changes in the air temperature, which causes the upper-ground to thaw and re-freeze seasonally. During summer months, when the air temperature is warm, the active layer thaws. Thawing will continue to creep downwards into deeper soil layers as long as temperatures remain above freezing – and therefore warming air (and longer periods of warm air) will cause a deepening of the active layer. When the air temperature cools, such as in the winter, the active layer refreezes. The permafrost layer is the layer directly beneath the active layer. This layer is not affected by changes in seasonal air temperature, and remains below freezing at a near-constant temperature all year-round.



Active layer and permafrost layer seen in a cross section of permafrost soil. Photo credit: Benjamin Jones, USGS. Accessed from climatekids.nasa.gov/permafrost/ 05 September 2021.

The active layer and the permafrost layer have different characteristics. More biological activity occurs in the active layer than the permafrost layer, because organisms are more active in non-frozen and warmer soils. Liquid water also contributes to the presence of more biological activity in the active layer, since liquid water enables biological reactions to occur. In the permafrost layer (i.e. the frozen layer), water exists as ice, so there is very little liquid water available for biological activity. The freezing point of water decreases with solutes – substances, like salt, dissolved in the water – so occasionally liquid water is available in the permafrost layer as a salty brine that prevents freezing at sub-zero temperatures. Some specialized microorganisms can use the salty liquid water in permafrost brine to stay active at sub-zero temperatures.

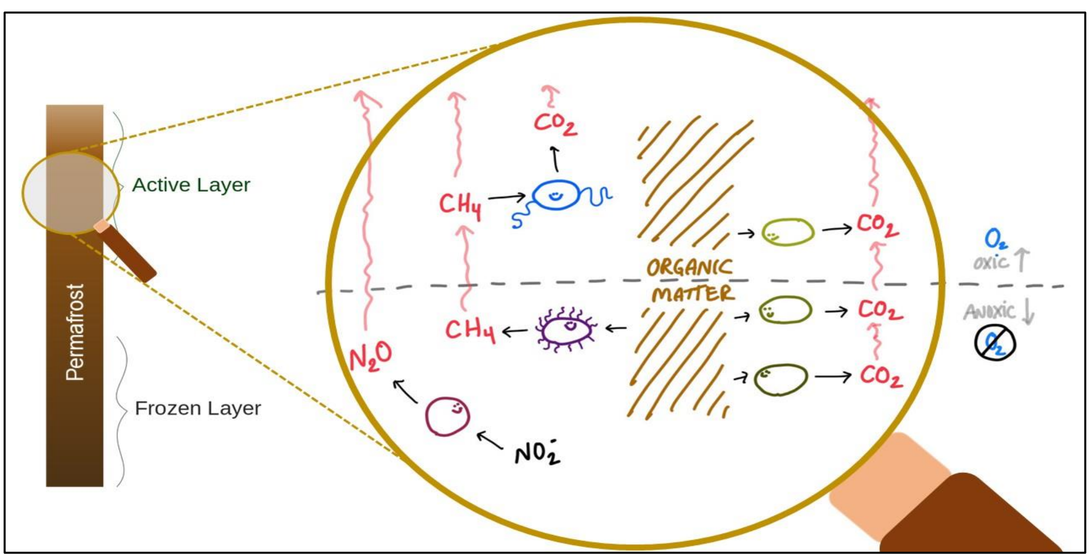
Ice is found in permafrost in pores in between soil particles, and also in large solid wedges - as shown by the image above. Ice wedges are solid pieces of ice that can vary in size from tens of centimeters to meters in width, and extend deep into the ground. When water percolates into pore spaces in soil and freezes, the water expands – enlarging the space it takes up and thus displacing some of the soil. This ice may crack or thaw during the following summer, and more meltwater is able to percolate inside, which freezes, and grows the ice wedge further.

2. ***How are microorganisms in permafrost connected to climate change?*** Soil contains organic matter which is the dead biomass or waste products of living organisms. Organic matter is

degraded and consumed by microorganisms such as bacteria, in order to gain energy and carbon, and in order to grow. Microorganisms that consume organic matter (known as heterotrophs) produce greenhouse gases such as carbon dioxide (CO_2), as a waste product. This is very similar to how humans consume food for energy and breathe out carbon dioxide (CO_2) as a waste product. In permafrost regions, the degradation of organic matter by microorganisms primarily happens in the active layer where warmer temperature and liquid water allow microorganisms to efficiently consume organic matter. In the active layer, microbial activities are primarily associated with growth, whereas in the permafrost layer, microorganisms are in survival-mode to cope with the stresses of low temperatures and low nutrient availability and so they are not growing or only growing very slowly.

The permanently frozen permafrost layer generally contains a lot of preserved organic matter. Organic matter is stored in this layer over very long timescales (sometimes upwards of hundreds of thousands of years), simply because freezing conditions prevent microorganisms from degrading it. At present, there is ~1,500 petagrams of organic carbon stored in permafrost (1,500 Pg, equivalent to about 1.5 million million - 10^{12} - small cars). This amount is twice the amount of carbon than is currently present in the Earth's atmosphere (750 Pg C).

As the temperature of the Earth's atmosphere increases due to human-caused climate change, permafrost will be lost due to its' thawing. Most of Earth's permafrost exists in the Arctic where temperature rise is occurring three times faster than in other parts of the planet. This is happening because environmental features that usually keep the Arctic regions cool, such as sea ice, are disappearing. Arctic temperature rise is accelerating permafrost loss. When regions of the permafrost layer thaw, the organic matter preserved within it becomes available for microorganisms to degrade. Decomposition of this newly available organic matter produces greenhouse gases, including carbon dioxide (CO_2) and methane (CH_4). The more permafrost that thaws, the more organic matter will be available for microorganisms to decompose into greenhouse gases. This in turn further contributes to global temperature rise as greenhouse gases released from thawed permafrost enter the atmosphere and cause further warming.



Microorganisms produce and consume greenhouse gases in thawed soil. Methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O) are greenhouse gases produced by microorganisms that enter the atmosphere after production. Artist credit: Margaret Cramm.

3. ***Microorganisms in permafrost produce and consume greenhouse gases.*** The main greenhouse gases produced by microorganisms are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The amount and type of greenhouse gas produced is largely controlled by the amount of oxygen that is present in the soil, as well as the physical and chemical properties of the soil itself. When oxygen is present in the soil, carbon dioxide is efficiently produced in association with aerobic decomposition of organic matter. This is done by a wide variety of bacteria called heterotrophs. When oxygen is not present, which often occurs in areas of the soil that are saturated with water, anaerobic decomposition occurs and carbon dioxide and methane are produced.

Methane is produced by methanogens, microorganisms belonging to the archaea. Methane has 32 times the warming potential of carbon dioxide in the first 100 years after its release from the soil. Given the larger warming potential of methane compared to carbon dioxide, methane is a gas of concern considering climate change. Interestingly, not all of the methane that is produced in permafrost escapes to the atmosphere: some microorganisms in soil can degrade methane and turn it into carbon dioxide. These organisms are called methanotrophs and they are active in layers of the soil with abundant oxygen. The process of turning methane into carbon dioxide is beneficial to reducing global warming because, despite also being a greenhouse gas, carbon dioxide is a less potent greenhouse gas than methane, with a lower warming potential.

The presence of oxygen in soil influences the release of greenhouse gases since most methane is produced in zones lacking oxygen, and microbial consumption of methane and most carbon dioxide production occurs in zones that contain oxygen. As permafrost thaws and ice melts, the hydrology of the soil changes and affects the diffusion of gases including oxygen (and therefore affects the soil oxygen content). Therefore, the changing hydrology of permafrost has a significant impact on the amounts and types of microbial activity, and therefore the abundance and type of greenhouse gases that are produced.

4. ***Permafrost preserves ancient microorganisms.*** Low temperatures and low water availability in frozen permafrost allow ancient organisms to be preserved over very long timescales (upwards of thousands of years). Microbiologists can study ancient biota by looking at organisms preserved in very old permafrost soils. In this way, permafrost provides a window into past microbial communities. Many microorganisms can form dormant or resting structures that allow them to survive the cold and low nutrient conditions in permafrost. When the permafrost thaws, these organisms wake up and become an active part of the microbial community of the soil.

5. ***Some microbes released from permafrost are pathogens.*** Bacteria that are human pathogens (e.g. *Bacilllus anthracis*, the bacterium that causes the disease anthrax) have become active after being released from thawed permafrost. This can have significant consequences for humans and animals living in permafrost regions. Thawing permafrost and the release of harmful microorganisms resulted in the death of a child in Siberia in 2016 who became sick after drinking water that was contaminated by anthrax bacteria released from the permafrost. Similarly, herds of reindeer in Siberia became sick and died due to pathogens being released from thawing permafrost.

Some dormant viruses isolated from permafrost remain infectious. So far, no known human-pathogenic virus has been revived from thawing permafrost, although human pathogens preserved in the bodies of humans previously buried in permafrost regions might find their way back into human populations if these viruses are released.

It is important to note that the majority of dormant microorganisms released from thawing permafrost are not pathogenic and do not pose a risk to humans and animals. Nevertheless, exploring these organisms may be useful for many different purposes. For example, organisms isolated from recently thawed permafrost have been shown to be rich in antibiotic compounds. Additionally, studying ancient microorganisms preserved in permafrost can help us understand how microorganisms lived hundreds of thousands of years ago.

Relevance to sustainable development goals and grand challenges

- **Goal 3. Ensure healthy lives and promote well-being for all at all ages.** The possibility of human pathogens moving from the permafrost to drinking water is a concern. Thawing permafrost destabilizes ground causing damage to infrastructure including buildings, roads, and drinking water.

- **Goal 13. Take urgent action to combat climate change and its impacts.** Permafrost stores carbon, in the form of organic matter, in the ground. Thawing permafrost gives microorganisms access to this organic matter, which is subsequently decomposed and transformed into greenhouse gases. These greenhouse gases enter the atmosphere where they contribute to global warming.

- **Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.** Permafrost contains ice that binds and stabilizes ground in high latitude and high elevation permafrost regions. When permafrost thaws and the ice melts, the land topography changes. Lakes may quickly form or drain, large regions of land may shift and slump, and the ground becomes unstable. These land changes affect terrestrial ecosystems and adjacent habitats. For example, land changes resulting from permafrost slumping affect the migration patterns of animals, and also cause trees that are adapted to grow in firm permafrost ground to fall and create 'drunken forests'.

'Drunken forest' in Fairbanks Alaska. Photo credit: Brandon Lucas, The Arctic Institute. Accessed from www.thearcticinstitute.org on 05 September 2021.

Potential Implications for Decisions

1. Individual

a. Make choices to reduce your carbon footprint and restrict global warming.

b. You could eat less meat, wash your clothes in cold water, and incorporate walking, biking, or public transportation into your regular commute.

c. You could contribute to dialogue and education on climate change to encourage corporations and governmental bodies to take climate action.

2. National

a. Meet the goals of the Paris Agreement to limit global warming to 1.5°C above pre-industrial levels and become climate neutral by 2050 by reducing greenhouse gas emissions.

b. Build economies based on the Sustainable Development Goals, such as those based on Doughnut Economics.

The Evidence base, further reading and teaching aids

https://www.thearcticinstitute.org/permafrost-thaw-warming-world-arctic-institute-permafrost-series-fall-winter-2020/This webpage hosts an article about how permafrost thaw affects those living in the North.

https://arctic.noaa.gov/Report-Card/Report-Card-2019/ArtMID/7916/ArticleID/844/Permafrost-and-the-Global-Carbon-Cycle
This webpage hosts a robust summary about global permafrost and its effect on climate change written by a leading permafrost scientist.

https://arctic.noaa.gov/Report-Card/Report-Card-2019/ArtMID/7916/ArticleID/844/Permafrost-and-the-Global-Carbon-Cycle
This is a site hosts teaching resources for climate related topics. It features a link to a downloadable video showing permafrost affected landscapes.

https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/climate-science/met-office-hadley-centre/risk-management-of-climate-thresholds-and-irreversible-change---6---permafrost---mar-2020.pdf
This is a summary from the UK Met Office focusing on expected changes to permafrost as it warms.

https://nsidc.org/cryosphere/icelights/subject/permafrost
A collection of articles relating to permafrost and climate change hosted by the National Snow & Ice Data Center.

Meredith, M., M. Sommerkorn, S. Cassotta, C. Derksen, A. Ekaykin, A. Hollowed, G. Kofinas, A. Mackintosh, J. Melbourne-Thomas, M.M.C. Muelbert, G. Ottersen, H. Pritchard, and E.A.G. Schuur, 2019: Polar Regions. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska,

K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. https://www.ipcc.ch/srocc/chapter/chapter-3-2/
An Intergovernmental Panel on Climate Change report about the effect of climate change on the polar regions. Section 3.4 focuses on permafrost.

Glossary

Aerobic	The term 'aerobic' describes biological activities that occur in the presence of oxygen.
Active layer	The surface layer of permafrost-affected soil that thaws and re-freezes seasonally.
Anaerobic	The term 'anaerobic' describes biological activities that occur in the absence of oxygen.
Biome	A biome is the living community in a particular habitat.
Dead biomass	Biomass is the organic matter living organisms and their waste products are made of. Dead biomass refers to the biomass that is left behind when an organism dies. This biomass is available for other living organisms to decompose.
Decomposition	Decomposition of organic matter occurs by chemical reactions that reduce the size and complexity of organic matter molecules. These chemical reactions are often facilitated by living organisms which gain energy or the building blocks for life from the organic matter decomposition.
Petagram (Pg)	1 Pg = 1 billion metric tons.
Greenhouse gases	Greenhouse gases are gases in the atmosphere that absorb and emit heat energy and contribute to global temperature rise. Water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are common greenhouse gases.
Heterotrophs	Heterotrophs are organisms that use organic matter for food to gain energy and the building blocks of life. They are different from autotrophs (such as plants and other photosynthetic organisms) that can produce their own food.
Methanogens	Methanogens are anaerobic microorganisms (specifically of the domain Archaea) that produce methane (CH_4). Methane is a product of their respiration which occurs in the absence of oxygen.

Methanotrophs	Methanotrophs are microorganisms that use methane (CH_4) as a carbon and energy source. Methanotrophic bacteria are aerobic and oxidize methane into carbon dioxide (CO_2). Methanotrophic archaea are anaerobic and must live in close proximity to a bacterial (syntrophic) partner in order to oxidize methane.
Organic matter	Organic matter is matter produced by living organisms that can be decomposed by microorganisms for their growth and activity. Organic carbon can be decomposed into the greenhouse gases methane (CH_4) and carbon dioxide (CO_2) by microorganisms. See also *Dead Biomass*.
Permafrost	Permafrost is ground or soil that has been frozen for at least two consecutive years.
Permafrost Layer	The permafrost layer of permafrost-affected soil is the layer that remains permanently frozen. The permafrost layer is below the active layer.
Salty brine	Brine is liquid water containing high salt content. The presence of salt in the water lowers the freezing temperature so that the water in brine can remain liquid even below 0°C, which is the temperature at which non-salty (fresh) water freezes.
Warming potential	Warming potential is the ability of a greenhouse gas to cause global temperature rise. The warming potential of a greenhouse gas is often described in comparison to the warming potential of carbon dioxide (CO_2). Greenhouse gas molecules decompose at different rates which affect their warming potential. This is why a time frame, e.g. 100 years, is often included in descriptions of greenhouse gas warming potential.