How much permafrost will melt this century, and where will its carbon go?

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This is thermokarst, ice-rich permafrost thaws. From Hudson Bay, Canada in 2008. Credit: Wikipedia via CC BY-SA 3.0

Among the many things global warming will be melting this century—sea ice, land glaciers and tourist businesses in seaside towns across the world—is permafrost. Lying underneath 15% of the northern hemisphere, permafrost consists of accumulating dead biomass that remains frozen, never having had a chance to release all its carbon.

As the surface and lower atmosphere warms from human enhancement of the greenhouse effect, crucial questions are how much permafrost will thaw and how much carbon will that release into the atmosphere?

It's a question complicated by the many processes that take place in the carbon cycle. Now a new study using a process-based biogeochemical model combining the science with observational data suggests the majority of thawed permafrost carbon will remain sequestered in layers that have been frozen, but this will create a significant challenge to future climate change mitigation efforts if the thawing accelerates.

The work, by four scientists in China and one at Purdue University in the US, is published in the journal *Earth's Future*.

Permafrost forms mostly where the annual average temperature is below the freezing point of water. If that average is below -5°C, the freezing can be permanent at today's climate level. (It was much more extensive during the Last Glacial Maximum.)

Making this problem worse is warming amplification at the Earth's poles—the fact that global warming isn't evenly distributed over the surface of the globe but increases with latitude. For example, the Arctic has warmed nearly four times faster than has the global average since 1979.

Thawing permafrost would act as a positive feedback to warming—adding to global warming via emissions of carbon dioxide—with the amount depending on how much anthropogenic forcing of climate takes place. With about 1 trillion tons of permafrost ultimately vulnerable to global climate change, modeling its future is a complex business.

Researchers have been working at reducing the uncertainties in the process, which include differences in regional amounts of thawing (which can also undermine buildings and communities), a dearth of observational data in remote regions, changes in vegetation coverage (which may absorb some of the emitted carbon), unpredictable weather extremes and wildfires, and what the paper's authors describe as "the complex and unique water, energy, carbon, and nutrient interactions among the atmosphere, plants, soils, frozen layers, and microbes."

Most of all, the amount of carbon thawing permafrost will emit into the atmosphere depends on what socioeconomic path humanity takes into the future. (Meaning any model result is necessarily a projection based on assumed parameters, not a prediction.)

The team considered two established scenarios of the future, the so-called Shared Socioeconomic Pathways (SSPs)—one, SSP126 (earlier: RCP2.6), an optimistic scenario of the future that limits global warming to 2.0°C, and the other, SSP585 (RCP8.5), being the most extreme scenarios where fossil fuel use remains business as usual and provides the vast majority of the future's energy.

This study, with lead author Lei Liu of Zhengzhou University in China, improved on past models by incorporating new physical processes, such as incorporating soil carbon exposure and decomposition due to permafrost thaw in deep soils up to 6 meters below the surface, twice as far as previous studies.

It also incorporated profiles of soil organic carbon using data sets based on observations. After validating their model, they applied it to permafrost thaw in the Northern Hemisphere for the rest of this century.

The new model estimated the permafrost area for the Northern Hemisphere for 2010 to 2015 to be 14.4 million square kilometers, containing 563 gigatons (Gt) of carbon in the latter year. For the SSP126 scenario that limits warming to 2.0°C, the model determined that permafrost degradation would make 119 Gt of carbon available for decomposition by 2100 from soil that was permanently frozen, reducing the carbon in permafrost ecosystems by 3.4 Gt. For the extreme SSP585 scenario, 252 Gt of carbon would become available, reducing the same carbon ecosystem by 15 Gt of carbon.

However, the model found that only about 4% to 8% of this newly thawed carbon is expected to be released into the atmosphere by 2100, a fraction that is within a range estimated by experts in 2015. This implies a maximum of 10 Gt of carbon for the least impactful scenario and 20 Gt of carbon for the most extreme scenario.

For comparison, in 2023, humans emitted 11.3 Gt of carbon from burning fossil fuels, land use changes, raising cattle and other activities, about half of which stays in the atmosphere for years. At present there is 880 Gt of carbon in the atmosphere, 300 Gt of which has been added by humans.

So thawing permafrost does not, in this model, appear to be a serious problem this century. However, degradation of permafrost increases nitrogen availability in soil, as decomposing previously frozen organic matter releases nitrogen in forms plants can use, and nitrogen stored in deeper soil layers is mobilized.

This can significantly increase plant growth and the dynamics of ecosystems. This is a negative, though small, feedback to global warming—in this model by Liu and his team, permafrost thaw increased the nitrogen stock in vegetation by 10 and 26 million tons in the two scenarios, and the carbon stock in vegetation by 0.4 and 1.6 Gt of carbon in the respective scenarios.

While this carbon increase does not compensate for the carbon loss from degrading permafrost, such permafrost thaw has already led to significant changes in plant species composition and growth. Other changes are more complicated.

For warming to cease, human emissions must drop to zero—it's not enough that they level off at a constant value. As long as warming continues, more and more permafrost will thaw, adding to mitigation challenges this century and larger feedback problems in the 2100s.

The largest uncertainties in warming are in high latitudes and high altitudes, and deeper complications like "abrupt thaw, root deepening and microbial colonization may accelerate the decomposition of this vast amount of thawed [soil organic carbon] in deep soils" the group writes, incorporating ever more nuances into the carbon and nitrogen cycles to better quantify carbon loss in permafrost soils.

As ever, the largest uncertainty will be the actions of man.

More information: L. Liu et al, The Fate of Deep Permafrost Carbon in Northern High Latitudes in the 21st Century: A Process-Based Modeling Analysis, *Earth's Future* (2024). DOI: 10.1029/2024EF004996