Abrupt thaw, as seen here in Alaska's Noatak National Preserve, causes the land to collapse, accelerating permafrost degradation and carbon release.

High risk of permafrost thaw

Northern soils will release huge amounts of carbon in a warmer world, say **Edward A. G. Schuur**, **Benjamin Abbott** and the Permafrost Carbon Network.

Arctic temperatures are rising fast, and permafrost is thawing. Carbon released into the atmosphere from permafrost soils will accelerate climate change, but the magnitude of this effect remains highly uncertain. Our collective estimate is that carbon will be released more quickly than models suggest, and at levels that are cause for serious concern.

We calculate that permafrost thaw will release the same order of magnitude of carbon as deforestation if current rates of deforestation continue. But because these emissions include significant quantities of methane, the overall effect on climate could be 2.5 times larger.

Recent years have brought reports from the far north of tundra fires[1], the release of ancient carbon[2], CH_4 bubbling out of lakes[3] and gigantic stores of frozen soil carbon[4]. The latest estimate is that some 18.8 million square kilometres of northern soils hold about 1,700 billion tonnes of organic carbon[4] — the remains of plants and animals that have been accumulating in the soil over thousands of years. That is about four times more than all the carbon emitted by human activity in modern times and twice as much as is present in the atmosphere now.

This soil carbon amount is more than three times higher than previous estimates, largely because of the realization that organic carbon is stored much deeper in frozen soils than was thought. Inventories typically measure carbon in the top metre of soil. But the physical mixing during freeze–thaw cycles, in combination with sediment deposition over hundreds and thousands of years, has buried permafrost carbon many metres deep.

The answers to three key questions will determine the extent to which the emission of this carbon will affect climate change: How much is vulnerable to release into the atmosphere? In what form it will be released? And how fast will it be released? These questions are easily framed, but challenging to answer.

KNOWN UNKNOWNS

As soils defrost, microbes decompose the ancient carbon and release CH_4 and carbon dioxide. Not all carbon is equally vulnerable to release: some soil carbon is easily metabolized and transformed to gas, but more complex molecules are harder to break down. The bulk of permafrost carbon will be released slowly over decades after thaw, but a smaller fraction could remain within the soil for centuries or longer. The type of gas released also affects the heat-trapping potential of the emissions. Waterlogged, low-oxygen environments are likely to contain microbes that produce CH_4 — a potent greenhouse gas with about 25 times more warming potential than CO_2 over a 100-year period. However, waterlogged environments also tend to retain more carbon within the soil. It is not yet understood how these factors will act together to affect future climate.

The ability to project how much carbon will be released is hampered both by the fact that models do not account for some important processes, and by a lack of data to inform the models. For example, most large-scale models project that permafrost warming depends on how much the air is warming above them. This warming then boosts microbial activity and carbon release. But this is a simplification. Abrupt thaw processes can cause ice wedges to melt and the ground surface to collapse, accelerating the thaw of frozen ground[5]. Evidence of rapid thaw is widespread: you can see it in the 'drunken' trees that tip dangerously as a result of ground subsidence, and in collapsed hill slopes marked by scars from landslides. These are just some of the complex processes that models don't include.

At the same time, few data are available to support these models because of the difficulties of gathering data in extreme environments. Only a handful of remote field stations around the world are collecting data to support this research, even though the permafrost zone covers about almost one-quarter of the Northern Hemisphere's land area. The field studies that do exist confirm that permafrost thaw is tightly linked to ground subsidence and soil moisture as well as temperature. So modelling carbon emissions from permafrost thaw is much more complex than a simple response to temperature alone.

Models have flaws, but experts intimately familiar with these landscapes and processes have accumulated knowledge about what they expect to happen, based on quantitative data and qualitative understanding of these systems. We have attempted to quantify this expertise through a survey developed over several years.

SURVEY SAYS

Our survey asks what percentage of the surface permafrost is likely to thaw, how much carbon will be released, and how much of that carbon will be CH_4, for three time periods and under four warming scenarios that will be part of the Intergovernmental Panel on Climate Change Fifth Assessment Report. The lowest warming scenario projects 1.5 °C Arctic warming over the 1985–2004 average by the year 2040, ramping up to 2 °C by 2100; the highest warming scenario considers 2.5 °C by 2040, and 7.5 °C by 2100. In all cases, we posited that the temperature would remain steady from 2100 to 2300 so that we could assess opinions about the time lag in the response of permafrost carbon to temperature change.

The survey was filled out this year by 41 international scientists, listed as authors here, who publish on various aspects of permafrost. The results are striking. Collectively, we hypothesize that the high warming scenario will degrade 9–15% of the top 3 metres of permafrost by 2040, increasing to 47–61% by 2100 and 67–79% by 2300 (these ranges are the 95% confidence intervals around the group's mean estimate). The estimated carbon release from this degradation is 30 billion to 63 billion tonnes of carbon by 2040, reaching 232 billion to 380 billion tonnes by 2100 and 549 billion to 865 billion tonnes by 2300. These values, expressed in CO_2 equivalents, combine the effect of carbon released as both CO_2 and as CH_4.

Our estimate for the amount of carbon released by 2100 is 1.7–5.2 times larger than those reported in several recent modelling studies[6–8], all of which used a similar warming scenario. This reflects, in part, our perceived importance of the abrupt thaw processes, as well as our heightened awareness of deep carbon pools. Active research is aimed at incorporating these main issues, along with others, into models.

Are our projected rapid changes to the permafrost soil carbon pool plausible? The survey predicts a 7–11% drop in the size of the permafrost carbon pool by 2100 under the high-warming scenario. That scale of carbon loss has happened before: a 7–14% decrease has been measured in soil carbon inventories across thousands of sites in the temperate-zone United Kingdom as a result of climate change[9]. Also, data scaled up from a single permafrost field site point to a potential 5% loss over a century as a result of widespread permafrost thaw[2]. These field results generally agree with the collective carbon-loss projection made by this survey, so it should indeed be plausible.

Across all the warming scenarios, we project that most of the released carbon will be in the form of CO_2, with only about 2.7% in the form of CH_4. However, because CH_4 has a higher global-warming potential, almost half the effect of future permafrost-zone carbon emissions on climate forcing is likely to be from CH_4. That is roughly consistent with the tens of billions of tonnes of CH_4 thought to have come from oxygen-limited environments in northern ecosystems after the end of the last glacial period[10].

All this points towards significant carbon releases from permafrost-zone soils over policy-relevant timescales. It also highlights important lags whereby permafrost degradation and carbon emissions are expected to continue for decades or centuries after global temperatures stabilize at new, higher levels. Of course, temperatures might not reach such high levels. Our group's estimate for carbon release under the lowest warming scenario, although still quite sizeable, is about one-third of that predicted under the strongest warming scenario.

Knowing how much carbon will be released from the permafrost zone in this century and beyond is crucial for determining the appropriate response. But despite the massive amount of carbon in permafrost soils, emissions from these soils are unlikely to overshadow those from the burning of fossil fuels, which will continue to be the main source of climate forcing. Permafrost carbon release will still be an important amplifier of climate change, however, and is in some ways more problematic: it occurs in remote places, far from human influence, and is dispersed across the landscape. Trapping carbon emissions at the source — as one might do at power plants — is not an option. And once the soils thaw, emissions are likely to continue for decades, or even centuries.

The scientific community needs to collect more data and develop more-sophisticated models to test the hypotheses presented by this survey. Fortunately, awareness of the problem is increasing and these are starting to happen. The US Department of Energy, for example, has initiated a project called Next-Generation Ecosystem Experiments — Arctic, which aims to improve the representation of these processes in large-scale models. NASA is pursuing an Arctic–Boreal Vulnerability Experiment, which aims to improve satellite observations of this region. The Vulnerability of Permafrost Carbon Research Coordination Network funded by the US National Science Foundation, of which we are part, is bringing together people and observations to synthesize results and validate models. These are just some of the many international initiatives aimed at filling these research gaps.

In the meantime, our survey outlines the additional risk to society caused by thawing of the frozen north, and underscores the urgent need to reduce atmospheric emissions from fossil-fuel use and deforestation. This will help to keep permafrost carbon frozen in the ground. ■

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'Drunken' trees reveal areas of subsidence.

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