SCIENTISTS drill out a meter-long core of permafrost soil at the Eight Mile Lake research site near Healy, Alaska, in September. The dark color and texture (*opposite page*) indicate the soil is packed with organic matter that can decompose and give off greenhouse gases.

CLIMATE CHANGE

THE PERMAFROST PREDICTION

Thawing Arctic tundra will likely speed up climate change for a century or more. The question is: How drastically?

By Ted Schuur

IN BRIEF

Permafrost—soil frozen year-round—is thawing widely across the Arctic. Microbes are breaking down plant and animal remains in the warming soil, releasing carbon dioxide and methane to the atmosphere.

The Northern Hemisphere permafrost region is vast and contains about 1,450 billion metric tons of organic carbon, almost twice as much carbon as exists in Earth's atmosphere.

Data from numerous sensors suggest that 5 to 15 percent of that carbon could escape this century. At 10 percent, 130 billion to 160 billion metric tons of carbon would enter the atmosphere, accelerating global warming. Slowing overall warming is the best way to prevent permafrost from heating up.

Photographs by Brian Adams

Ted Schuur is a professor of ecosystem ecology at Northern Arizona University. He has conducted almost two decades of field research across the Arctic. He is also the lead investigator for the Permafrost Carbon Network, an international consortium of researchers that synthesizes new findings about permafrost carbon and climate.

THE SOLID, 20-KILOGRAM BLOCK OF HARDENED snow and ice somehow slides free from my rubber-gloved grasp and drops back down into the long ditch I am excavating in deep snow, landing with a crunch. On my knees at the edge of the trench, I straighten up to catch my breath and arch my sore lower back, protected with a weight-lifting belt. On this bright, cold day in interior Alaska, five scientists and I are digging out tons of snow along the fourth of six snow fences positioned on a gradual hill on the tundra, hauling it away on sleds. Our labor is part of an experiment designed to warm the ground, simulating what future climate may do in this remote location just outside of Denali National Park.

It is early April, and my team is spending more than a week removing compressed snowdrifts that have accumulated along the fences we install every fall at the site. Each fence is about one and a half meters high and eight meters long. The extra snow insulates the ground from the frigid winter air like a blanket, keeping the surface of permafrost—soil that usually remains frozen year-round—warmer than it otherwise would be. We remove the excess snow so that spring's impact penetrates our experimental plots at the same time as the surrounding tundra region and so that no extra meltwater percolates down into the ground, altering the soil in comparison with that in the larger area.

Keeping the frozen soil warmer during winter causes it to thaw sooner and more extensively in the summer. This reaction is exactly what is projected to occur as temperatures rise across the Arctic and boreal ecosystems just south of the Arctic, which is happening twice as fast as the increasing global average. Permafrost contains rock, frozen soil and ice, so it thaws, rather than melts, when it warms. Like hamburger pulled from your freezer, it softens but does not become liquid. As permafrost thaws, previously frozen microbes reactivate and decompose the remnants of plants and animals accumulated into the frozen soil over hundreds to thousands of years, giving off carbon dioxide and methane.

The permafrost zone that circles the northern part of Earth holds so much organic material in soils that releasing just a fraction of it as greenhouse gases into the atmosphere would dramatically raise the rate of global warming. Our experiment in Alaska is one important part of integrated research around the world to figure out how big this effect is likely to be over the coming decades. We are now starting to know enough to make solid predictions.

VAST QUANTITIES COULD THAW

HOW CAN WE POSSIBLY put a number on how much permafrost will thaw, and how fast, and how much the carbon release will affect global warming? A quantification would have to assess a massive area of the planet. The permafrost zone extends across 16.7 million square kilometers of the Northern Hemisphere, almost one quarter of the ice-free land area. And the frozen ground can be tens to hundreds of meters deep. (Much of the Southern Hemisphere's high latitudes is covered by ocean or ice sheets on land, so permafrost extent there is limited.)

Although satellites and remote-sensing equipment can accurately record changes in ice sheets such as those on Greenland, there is no comprehensive remote-sensing system for permafrost regions. For years scientists monitored ground sensors installed in certain permafrost spots, but we just did not have enough data points worldwide. We have steadily added more sensors, however. The Global Terrestrial Network for Permafrost now tracks more than 1,000 boreholes lined with instruments that monitor temperatures in the top few meters of soil as well as deeper underground.

The network has shown that permafrost has been warming

SENSORS in white chambers near the snow-capped Alaska Range measure the soil's uptake and release of carbon dioxide (*1*). Researcher Meghan Taylor of Northern Arizona University records the data (*2*).

steadily over the past several decades, setting new records in 2014 and 2015 at many locations. The most dramatic increases have occurred where soil temperatures have historically been very cold, from –10 to –5 degrees Celsius. We have also seen increases in temperature in permafrost that is closer to the freezing point, from –2 to zero degrees C, where a one-degree change can have a big impact. In some locations where permafrost is just below the freezing point, the active layer—soil at the surface that thaws during summer and refreezes in winter—is becoming thicker. When we stitch together all these measurements worldwide, we get a good sense of soil-temperature change across the Arctic.

How much permafrost could thaw is only part of the calculation we want to make. We also need to know how much organic matter the softening soil contains. This past spring at the Eight Mile Lake research site, my team drilled down into the ground and pulled out cores of soil 1.5 meters deep, as we have done in various years since the project began more than a decade ago. Measurements by us and others across the tundra show that the top cubic meter of soil contains about 50 kilograms of organic carbon—carbon bound up in those partially decayed but frozen organisms (as opposed to inorganic carbon that is part of rock, unlikely to change regardless of temperature). That amount is about five times as much carbon as in nonpermafrost soils within the same region and about 100 times as much as is stored in shrubs and other plants that eke out a living in the Arctic.

Carbon can exist tens of meters down into the ground, too. Overall, researchers estimate that 1,330 billion to 1,580 billion metric tons of organic carbon is stored in Northern Hemisphere permafrost, almost twice as much carbon as exists in Earth's atmosphere. The top three meters of soil in the northern permafrost zone alone hold 50 percent as much carbon as the top three meters of soil everywhere else on the planet, even though the zone represents only 15 percent of the global soil area.

Scientists are also measuring organic carbon in places where we never have, such as permafrost that is submerged at the bottom of very shallow seafloors along parts of the Arctic coast. This permafrost is slowly degrading as seawater seeps into it, and we are not yet clear on how much organic carbon may be there. Carbon is also plentiful in thick sediments in vast Arctic river deltas, but we simply have not measured many sites. The best we can suggest at this point is that about 400 billion metric tons of additional carbon may be preserved in these disparate places.

HOW MUCH, HOW FAST?

GIVEN THE VAST STORES of organic carbon in permafrost, it seems plausible that thawing could release massive quantities of greenhouse gases. Pinning a number on that release depends on three key questions.

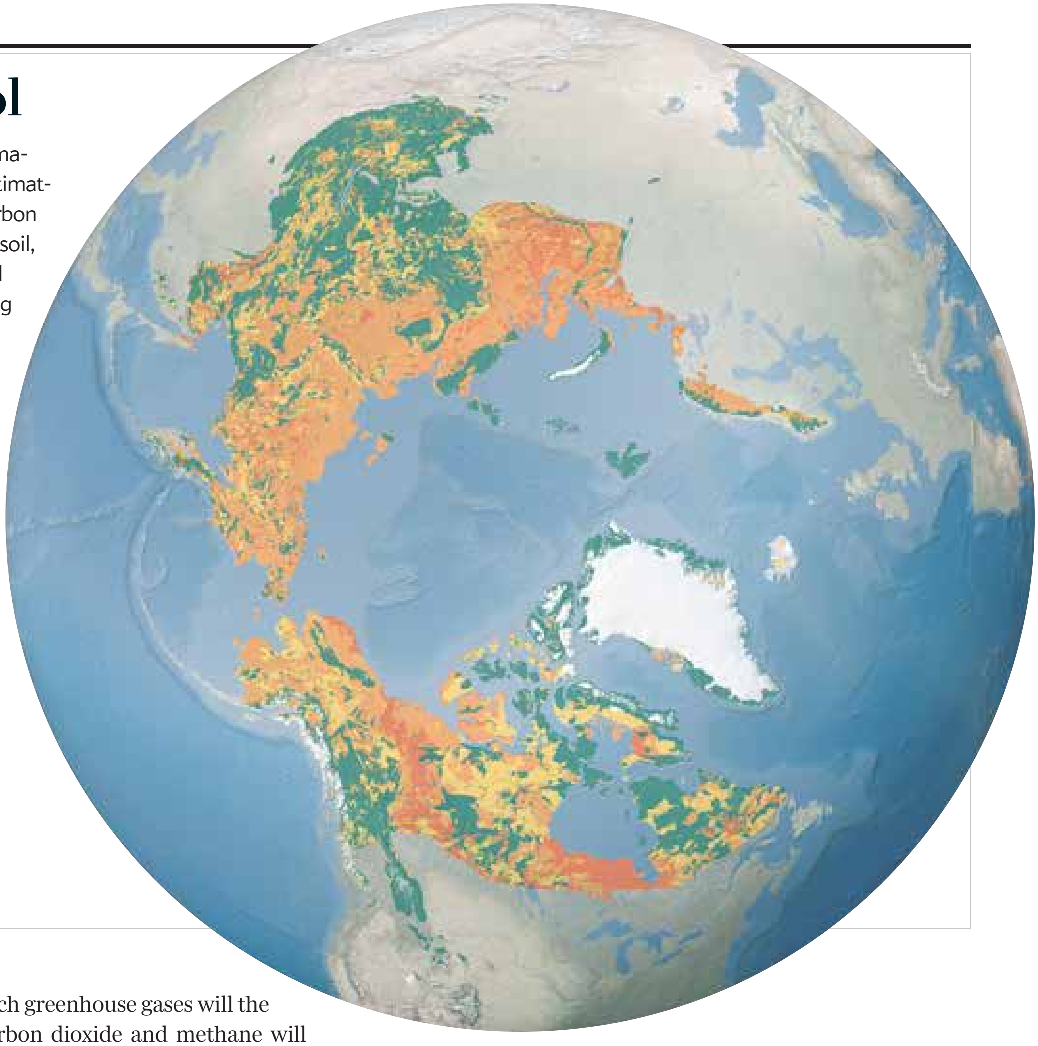
First, how much of the carbon might be converted into greenhouse gases? Microorganisms can easily metabolize and release some of the carbon but not all. As a result, some fraction of the carbon will simply remain in the ground because it is so inaccessible or inedible by microbes.

Second, how fast will microbial action release gases? Rapidly decomposing carbon can become airborne in less than a year after thaw, but more of the carbon will most likely be released gradually over decades after thaw, in part because it is already in a semidecomposed state that microbes only further degrade slowly.

DATA

Carbon Pool

The Northern Hemisphere's permafrost zone (*colors*) contains an estimated 1,035 billion metric tons of carbon in the top three meters of frozen soil, which could escape if the ground thaws, amplifying global warming significantly. Permafrost is nearly everywhere in the northernmost regions. It is more discontinuous further south, but many areas in both regions contain high carbon concentrations (*red* and *orange*).



Map by Mapping Specialists

SOURCE: "CLIMATE CHANGE AND THE PERMAFROST CARBON FEEDBACK," BY E.A.G. SCHUUR ET AL., IN *NATURE,* VOL. 520; APRIL 9, 2015

The third key question is: Which greenhouse gases will the microbes release? The mix of carbon dioxide and methane will determine the ultimate climate warming potential. Waterlogged, low-oxygen soils (known as anaerobic environments) such as peat bogs, for example, typically produce much more methane than carbon dioxide, and methane has about 33 times the global warming potential of carbon dioxide by weight over a century.

We track gas release at study sites such as Eight Mile Lake and the surrounding tundra with infrared gas analyzers that measure concentrations in the air across seconds, days, seasons and years. The tundra at Eight Mile Lake appears to be losing more carbon to the atmosphere than it is absorbing. Warming the ground with snow along the fences helps plants grow faster and larger, pulling and storing more carbon dioxide from the air. But it also helps microbes decompose more carbon in the soil. In the summertime, the extra plant growth completely offsets additional carbon release from the soil, but continued microbial activity throughout the long autumn and winter, when plants are dormant, shifts the annual balance to net carbon loss to the atmosphere.

When we combine our results with those from other types of experiments around the world, we conclude that thawing permafrost is spewing excess carbon into the atmosphere. Researchers bring data together through the Permafrost Carbon Network. Just like the parable of the blind men describing the elephant, field researchers across the Arctic each have important and unique information that when linked together creates knowledge about the true size and nature of this phenomenon. The Permafrost Carbon Network also synthesizes science results for reports, agency briefings and media interviews to inform decision makers and the wider public so these groups can decide how to respond to our changing Earth.

One recent synthesis project has helped answer the question about relative releases of carbon dioxide and methane. In aerobic conditions (dry soils), microbes mostly release carbon dioxide. But in anaerobic conditions in wetlands and peat soils, they release both carbon dioxide and methane. Christina Schädel, an assistant research professor at Northern Arizona University working with my group and a key player in the Permafrost Carbon Network, has been studying how this trade-off might ultimately affect climate.

In contrast to our field study, Schädel relied on experiments where frozen soil was taken into the laboratory and warmed in glass chambers so that the amount and rate of soil carbon converted into carbon dioxide or methane could be measured precisely. She used statistical techniques to bring data together from tests such as these around the world and has found that carbon dioxide is the predominant greenhouse gas by weight that is released by identical soil samples regardless of whether they were found in either aerobic or anaerobic conditions. Surprisingly, the climate impact of greenhouse gas release from aerobic decomposition is two times larger than for anaerobic decomposition, despite the additional potency of methane, which is released only from the latter.

The implication is that permafrost thaw in relatively well-drained, upland soils most likely will have a greater impact on climate than a similar amount of thaw in lowland, waterlogged soils. Although methane is still a key part of the equation, the overall distribution of upland and lowland environments across the Arctic landscape will significantly determine permafrost thaw's impact on climate.

ACCELERATING CLIMATE CHANGE

BY SYNTHESIZING DATA from field sites and lab tests and combining that information with computer simulations of future climate scenarios, the Permafrost Carbon Network has generated an answer to the overarching question of how permafrost thaw might affect climate. In the expert judgment of its members, between 5 and 15 percent of the permafrost carbon pool is likely to be released this century, most of it as carbon dioxide.

The midrange—10 percent—of the carbon pool, as best we know it, means that 130 billion to 160 billion metric tons of additional carbon would enter the atmosphere. That amount, if released primarily in the form of carbon dioxide at a constant rate over a century, would be similar to the amount of carbon released worldwide thus far by deforestation and other land-use changes but much less than that from fossil-fuel emissions. Permafrost thaw will make climate change happen even faster than scientists project based on emissions from human activities alone. And permafrost carbon emissions are likely to continue beyond this century. Each additional ton of carbon released from the thawing Arctic into the atmosphere will impose additional costs on society.

Reducing permafrost thaw with some kind of local fixes across the Arctic is not a realistic option. The only real solution is to limit emissions from fossil fuels and from deforestation to slow global warming overall. That in turn will reduce emissions from Arctic thaw, giving communities at all latitudes more time to adapt.

Scientists have generated the 5 to 15 percent number for the first time only in the past year. We still do not have a comprehensive observation system in permafrost regions to make a firmer prediction. More sensors would allow us to better detect both slow and rapid change, which could be cause for either lessened or heightened concern. And they would help us detect important surprises that might arise.

New initiatives, such as the U.S. Department of Energy's Next-Generation Ecosystem Experiments–Arctic project and NASA's Arctic-Boreal Vulnerability Experiment, are helping to fill in important gaps in modeling and in scaling up site-based measurements such as those from Eight Mile Lake to the surrounding region and, ultimately, to the global scale.

One intriguing and critical question is whether extensive plant growth could counterbalance permafrost carbon release. The latest simulations tend to show that longer growing seasons, warmer temperatures, more plant nutrients released by decomposing soils, and natural shifts to faster-growing plants and trees might offset carbon release from permafrost during this century. But that assessment contradicts measurements from Eight Mile Lake and elsewhere, which show net carbon loss across an entire year.

Better simulation of how thawing ground subsides would also be useful; it is currently missing from large-scale models that simulate the permafrost carbon and climate interactions. As ice in permafrost melts and drains away, the ground subsides, which then causes permafrost to thaw more abruptly. Could widespread subsidence boost emissions forecasts even more?

INSTRUMENT TOWER measures carbon dioxide and methane transfer between the air and soil year-round, indicating whether the ecosystem experiences a net gain or loss of gases annually.

My colleagues and I saw this very effect at Eight Mile Lake when we returned there this past spring. The boardwalks we had built almost a decade ago, along with the gas-flux monitors and other gear we had installed, had become twisted and angled from ongoing subsidence. The ground was undulating and pitted.

The spring 2016 thaw at Eight Mile Lake also went deeper than ever—more than a meter in some spots, an amount typically seen only at the end of summer in previous years. The unusual readings paralleled similar extremes elsewhere in the Arctic: record, early-season retreat of winter ice cover on the Arctic Ocean, early snowmelt across the Northern Hemisphere and early surface melt of the ice sheet in Greenland. Carbon emissions from permafrost are happening right now. The release of gases will not be a rapid burst that could alter climate abruptly, as some feared. But it will indeed be widespread and sustained over many decades, seriously compounding the daunting challenge that society already faces to slow global warming. SA

MORE TO EXPLORE

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