A. COOPER/ALAMY

A world melting from the top down

Despite years of speculation, little can be said for sure about the future of the Arctic's permafrost. But that's no grounds for complacency, reports **Gabrielle Walker**.

Some of Phil Camill's trees are drunk. Once, the black spruce trees on the plots of woodland that he monitors in northern Manitoba stood as straight and honest as pilgrims. Now an ever-increasing number of them loll about leaning like lager louts. The decline is not in the moral standards of Canadian vegetation, but in the shifting ground beneath their roots. Once it was all hard, solid permafrost. Now much of it has thawed into a soggy sponge that no longer provides a steady footing for the trees. Some contrive to grow at screwball angles; others have drowned and been replaced by floating mats of mosses or sedges. "It is really easy to tell when the permafrost has gone," says Camill. "The vegetation changes right before your eyes."

Camill, an ecologist from Carleton College in Northfield, Minnesota, has used those changes to trace the rate at which the permafrost is disappearing. In their desperate attempts to buttress themselves upright, his leaning spruces put on extra wood on the downslope side of their trunks. Counting the asymmetrical tree rings that result and measuring the distance of each tree from the current boundary of the permafrost gives a measure of the pace of change. The results are shocking. An average warming across his sites of 1.3 °C since 1970 has brought with it a trebling of the thaw rate. In some places the permafrost's perimeter is retreating by 30 centimetres a year[1]. If this trend continues, Camill estimates that no permafrost will be left in any of his five sites by the end of the century.

Thawed-out permafrost has already undermined buildings, highways and other infrastructure from Alaska to Siberia. The damage is one of the most visible effects of warming temperatures on human activities. But the effects on natural systems are to some extent more worrying. Buildings can be rebuilt, asphalt relaid and agricultural practices changed through adaptation, given the right policies and priorities (see page 716). But changes in the vegetation and, crucially, in the soils of the frozen northern landscapes might not be so easy to cope with. The soils of the Arctic are crammed with organic matter — a frozen reservoir of beautifully preserved roots, leaves and other raw material that may contain as much carbon as the whole atmosphere. They are quite unlike soils from more temperate regions, which are mostly made up of the parts that the bacteria cannot digest. "We are unplugging the refrigerator in the far north," says Camill. "Everything that is preserved there is going to start to rot."

For decades environmentalists have worried about the possibility of this great putrefaction. It has become perhaps the most cited example of the biogeochemical feedback that could drastically worsen the effects of anthropogenic climate change. The idea is that humans increase levels of carbon dioxide in the atmosphere, warming the permafrost, which in turn releases yet more carbon, warming the world — and the permafrost — further still in an ever-escalating positive-feedback loop.

However, although such feedback has been discussed for almost as long as the threat of global warming has been taken seriously by scientists, the lack of firm data on the subject is striking. "There is a lot that we don't know at this point," says Walter Oechel from San Diego State University in California. "People haven't quite pulled the whole picture together yet — but what we do know is that the potential amounts are huge and very, very scary."

The big picture

There is no doubt that the Arctic is heating up. Vladimir Romanovsky from the University of Alaska Fairbanks has collated borehole- and air-temperature data from throughout the Arctic[2]. He found that only one region in the Arctic had not warmed over the past 30 years — and in the 1990s even that region joined the trend. Some places are warming at more than twice the global average rate. Romanovsky recently received a US$1 million grant to take this monitoring work further with a network of stations in North America and Russia.

The effect that this warming will have on the permafrost and its stored carbon will vary from region to region. Not surprisingly, the most dramatic signs of thaw have come from the fringing, southerly regions of discontinuous permafrost — such as Camill's research sites — where the frozen layer is only a few metres thick and average temperatures are already within a whisker of the melting point. In the colder Arctic the permafrost can be hundreds of metres thick and it is harder to know what to expect. In principle, the thawing might be quite slow, with the warmth at the surface being transmitted gradually into the colder depths. In practice, things are probably more complex, and in places more precipitous.

Patchy progress

Permafrost is defined as ground in which the temperature is less than 0 °C for at least two successive years. But the ground in question does not have to be at the surface. In most places the top part of the soil thaws during the summer, providing plants and microbes with an 'active layer' above the permafrost in which they can flourish and decompose the defrosted organic matter. The probability that the active layer will deepen — putting a larger stash of carbon up for grabs — or that the permafrost will thaw completely depends on the type of vegetation and soil. Thus, thawing can accelerate rapidly if a fire passes through a dried-out forest in the uplands, or if the soil contains enough ice that thawing causes it to collapse, creating a crater-scarred 'thermokarst' landscape.

Researchers expect to see the first signs of thaw in a deepening of the active layer. But complications from terrain, vegetation and other local conditions mean that data need to be collected continuously over several decades to pick up such a trend. Unfortunately, the relevant measurements so far have been patchy and sporadic. In 1998, various organizations involved in permafrost research banded together to receive funding as the Circumpolar Active Layer Monitoring (CALM) programme, hosted at the University of Delaware in Newark, to tackle the problem. The network now includes 125 active sites and has participants from 15 countries. Still, it is unlikely to bear fruit in the form of spotting unequivocal trends for some time.

If measuring the damage done so far is hard, predicting its future course is even harder. In 2005, two researchers from Boulder, Colorado — David Lawrence from the National Center for Atmospheric Research and Andrew Slater from the Cooperative Institute for Research in Environmental Sciences — published the results of the first attempt to project the fate of the permafrost through the twenty-first century using the climate predictions of a general circulation model (GCM). Their results made dramatic headlines. Using figures from one of the 'high emissions' scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) in the model resulted in 90% of the northern permafrost disappearing by 2100. Of 10.5 million square kilometres of permafrost around today, only about 1 million made it through the century. Even more worryingly, running the model with a 'low emissions' scenario still wiped out 60% of the permafrost, suggesting that severe losses are inevitable no matter which policies are followed. And the model did not take into account any further warming from carbon given off in the thaw[3].

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Thick and thin

The model has since attracted some criticism, most notably because its permafrost is a mere 3.4 metres thick throughout the Arctic, which is far from the hundreds of metres present in some regions. However, Lawrence says that he has since re-run the model for a mid-way emission scenario and dealt with some of the other criticisms at the same time, and the results remained more or less the same. He says that the model captures many important aspects of the Arctic system — including the hydrology and physical properties of the soil — and that the point is not so much the actual percentage of loss but the overall principle that a frighteningly large amount of permafrost could be vulnerable to quite small changes in climate. "In this field you have to accept that we won't have a perfect knowledge of what's happening up there," he says. "But we should be able to capture the fundamental properties. And so far the model shows that a major change is going to happen to the Arctic."

Perhaps the most intriguing of the complications that Lawrence's original work did not address is the suspicion in the minds of some researchers that the permafrost itself is putting up a defence against the thaw — a set of negative feedbacks. For instance, Oechel points out that warmer temperatures lead to a thicker layer of moss on the surface of his research sites in the Alaskan tundra. Because

P. REKACEWICZ, UNEP/GRID-ARENDAL; INT. PERMAFROST ASSOC., 1998. CIRCUMPOLAR ACTIVE-LAYER PERMAFROST SYST. (CAPS), V. 1.0.

M. HOSHINO/MINDEN PICTURES/FLPA

Mosses act as insulators for underlying permafrost.

moss is a superb insulator, especially when dried out by surface warming, the thickened vegetation helps to shield the frozen soil beneath from the warmth above. In one of the north–south transects he studies on Alaska's North Slope, the warmest, southernmost section has both the thickest layer of moss on the surface and the shallowest active layer.

Frederick Nelson at the University of Delaware points to another self-preserving feature of permafrost. The base of the active layer, he says, can become especially icy because water draining down there will pool above the impermeable layers below. The richer this layer is in ice, the more difficult it is to thaw, preventing the active layer from deepening further[4]. Even snow cover does its part. Like moss, snow is an effective insulator. But because it falls in the winter, it works in the opposite direction, shielding the soil from cooling further in air temperatures that can be as low as –40 °C. Camill noticed that the snow at some of his sites has thinned in the past few decades, which may cause the soil to grow colder in winter than it used to and thus store up protection against the heat of the following summer. Increased forest cover can have a similar effect, causing snow to be thinner beneath the trees than it would have been on open ground. "At face value you would expect the permafrost to start thawing really rapidly as temperature rises, but these feedbacks can keep it around longer than you would expect," says Camill.

Pushing the boundaries

But these effects can't last forever — and although they might forestall thawing, the sudden change in conditions when one or more of them fails might lead to quicker thawing thereafter. A few really hot summers could break through the ice barrier. And Oechel is already worried about his mosses. He has noticed that they are highly sensitive to direct sunlight, and now that the Arctic has fewer cloudy days the mosses could well begin to suffer. Loss of any or all of these protections would allow any thaw to accelerate. "It is difficult to push permafrost over the threshold of thawing," says Romanovsky. "But after tipping it will go by itself".

Uncertainties about thawing obviously complicate the question of how much greenhouse gas the permafrost will emit — but they are not the only complications. Oechel has been tracking the carbon balance of his Alaskan tundra for several decades. After a serious bout of warming in the late 1970s, he saw the region emit a mighty pulse of carbon dioxide — a pulse that is now showing signs of tailing off. He suggests that one possible reason for the decline is that the initial orgy of decomposition spurred by the warming released nitrogen-containing nutrients into the soil. The plants have now responded to the additional nutrients by growing more and taking up carbon dioxide in the process. Oechel thinks that in the summer some of his sites now take up more carbon than they emit, although when winter emissions are added in they are still sources, not sinks, overall[5]. Another factor is the northern march of the treeline. As the region warms, the growth of new forests over what was once tundra could also help to reduce the net release of carbon.

V. ROMANOVSKY, UNIV. ALASKA FAIRBANKS

Thawing ice under the surface can cause the landscape to collapse.

However, even if the surface ecosystem starts to take up more carbon, the old, dead material frozen in the soil still needs to be considered. What's more, the overall amount of carbon emitted is not necessarily the whole story. Torben Christensen at Lund University in Sweden also has data on the carbon balance that span several decades, in his case from a low-lying mire in the patchy permafrost of northern Sweden[6]. As the permafrost has steadily thawed, the ground has grown soggier; the previous hummock vegetation has been replaced by sedges, which are better at tolerating wet roots. The water seals the underlying soil from the air, which means that decomposition has to proceed without the benefit of oxygen. This slows things down, and has reduced the region's carbon emissions by 13% since 1970. However, the carbon that is released by this oxygen-free decomposition comes out in the form of methane, rather than carbon dioxide, and methane packs a far greater warming punch than its oxidized sibling. So the overall greenhouse effect of the mire has actually gone up by a disturbing 47%.

Back to biology

These are the sorts of issues that future attempts to model the process will need to take into account. Lawrence says that the next phase of this work will be to treat the biology more carefully, incorporating carbon and nitrogen cycles into the models, allowing the vegetation to respond to the changes in climate, and modelling sources of methane. According to Nelson at least half a dozen groups around the world are planning to develop their GCMs to address at least some of these aspects of the permafrost thaw, and the plan is to have a much more extensive set of predictions in the next IPCC report, in five years time.

Knowing more about the thaw, though, will allow useful predictions of carbon emissions only if researchers can also quantify the amount of organic matter in the soils. A series of workshops under the auspices of the Global Carbon Project and the International Polar Year is aiming to answer those questions. Current estimates of the amount of carbon that might be in play range from 350 gigatonnes to more than 900 Gt;

S. ZIMOV

Fire and ice: decomposition under thaw lakes is releasing large amounts of methane, which bubbles to the surface and adds to carbon emissions.

by way of comparison, the atmosphere contains 750 Gt or so. The estimates at the high end of the scale are based on the discovery of a new, vast pool of buried carbon — a type of wind-blown soil called yedoma, which was laid down over large tracts of northern Siberia in the ice ages.

Rich sources

Stuart Chapin, also from the University of Alaska Fairbanks, says that the yedoma soil is extraordinarily rich in carbon. Last year, he and his colleagues estimated the range and possible thickness of this layer and calculated that it alone could contain 450 Gt of carbon, compared to the estimated 350–450 Gt in the rest of the Arctic[7]. This number, says Chapin, is probably "only good to within a factor of two"; but even half of such a huge amount would be significant, whereas twice as much hardly bears thinking about. Camill points out that humans release around 9 Gt of carbon per year from fossil fuels and deforestation. "If just 1% of [the possible 900 Gt in the yedoma] is decomposed in a warmer world it would be as if we doubled our current rate of emissions. That's what is alarming."

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— Vladimir Romanovsky

Ominously, the first signs that parts of the continuous permafrost might now be thawing have come from lakes that overlie this carbon-rich yedoma. Katey Walter from the University of Alaska Fairbanks and colleagues have been tracking the methane that bubbles out of thaw lakes in northern Siberia. These lakes don't necessarily arise from global warming. Any local disturbance can trigger a temporary thaw in the permafrost. As the ice melts, the ground sinks and fills with water. The lakes then tend to migrate across the landscape, eroding away their margins, and can last as long as a thousand years; their sideways motion allows them to eat through permafrost much more quickly than would a steady heating pulse heading down from the surface. And decomposition in their oxygen-free depths and the thawed sediment beneath will produce methane, not carbon dioxide.

How much methane nobody realized until recently — mainly because it bubbles out from random parts of the lake and disappears unnoticed into the air. Walter and her colleagues managed to catch this methane in the act, by noting where the bubbles emerged when the lake froze over in the winter, and then leaving instruments to catch the emissions throughout the following year[8]. They calculate that bubbling lakes from northern Siberia are already responsible for nearly four million tonnes of methane a year, and that the amount is on the rise. Warmer temperatures mean that the lake area in Walter's study region has increased greatly in the past few decades, leading to a rise in methane emissions of nearly 60%. And that methane seems to be coming from the depths of the permafrost: its lack of carbon-14, an isotope continually made in the atmosphere that takes thousands of years to decay, suggests that the organic matter beneath the lakes has been stored away for a very long time.

This and the Arctic's other warning signs make it increasingly urgent that researchers resolve their remaining questions about the fate of the permafrost. And those answers won't come a moment too soon. "We have been asleep at the switch," says Oechel. "If you look at the things that were said in the 1970s about the Arctic's response to increasing CO_2, the place we were off is not that we overstated or were overly pessimistic, but that we were not aggressive enough about the predictions. To me, the precariousness of the situation is now clear. We are in a world of hurt." ■

Gabrielle Walker is the author of *An Ocean of Air*.

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