Sculpted by melting ice: thermokarst lakes, like the ones shown here on the Kolyma River in Siberia, can form when the permafrost thaws. Global warming is intensifying this process.

PHOTO: MARTIN HEIMANN/MPI FOR BIOGEOCHEMISTRY

THAWING PERMAFROST

TEXT: KLAUS JACOB

Over a trillion tons of carbon are sequestered in permanently frozen soils (permafrost), especially in the Arctic Circle. But this frozen ground is steadily thawing as a result of climate change. Whether or not this will lead to the release of large quantities of greenhouse gases is one of the vital unresolved questions in climate research. Mathias Göckede, who heads a research group at the Max Planck Institute for Biogeochemistry in Jena, is among those looking into this question and he has already come up with some surprising answers.

The terrain doesn't exactly look as if it could be helping to fuel global warming – there are no open-pit mines from which bucket-wheel excavators are scooping out coal, no oil industry drilling rigs, and no forests threatened by drought or slash-and-burn agriculture. Instead, the vegetation is rather sparse, only broken now and then by small groups of trees, and a scattering of smaller and larger lakes, partly connected by natural channels. Many permafrost areas display a peculiar charm all their own. Yet, as idyllic as they may seem, the lakes bear witness to a profound change, because many of them have only been created since global warming has been causing once permanently frozen soils to thaw, which could also dissolve the carbon reservoir stored within the permafrost. According to one theory espoused by climate researchers, as temperatures rise, large quantities of this element – which had previously been bound by year-round frost – could escape into the atmosphere in the form of the greenhouse gases methane and carbon dioxide, which would accelerate global warming and thus climate change. Mathias Göckede, who heads a research group at the Max Planck Institute for Biogeochemistry in Jena, is currently investigating the extent to which this fear is justified.

About a quarter of the landmass in the northern hemisphere, including almost the whole of Greenland, large parts of Siberia, northern Canada, and Alaska, is considered a permafrost zone. Experts estimate the organic carbon content of these regions at around 1,500 billion tons, which is theoretically enough to triple the concentration of greenhouse gases in the atmosphere, which means that there is a huge potential for the far north to intensify global warming. The latest report by the Intergovernmental Panel on Climate Change also confirms this. They warn that thawing permafrost is extremely likely to play a role in changing the climate over the next few centuries. Moreover, if the warming exceeds a critical value, this zone could thaw even further, and the process would become irreversible. Because of the self-reinforcing mechanism involved, the system could go beyond a tipping point.

However, it has not yet been clarified how rapidly this process would unfold and what quantities of greenhouse gases would be emitted in the process. We simply don't have the data. While weather data has been recorded for more than a century, researchers have not been concerned with permafrost soils until recently. Thus far, the available measurement series are not long enough to be able to show a reliable trend against the background of natural weather fluctuations. Winter snowfall can be heavy at times but less extreme in other years; some summers can be extremely dry and some are extremely warm, and then again others are very cold. The COVID-19 pandemic has made research even more difficult: all research trips were canceled during a period of almost two years resulting in gaps in some data series. However, Göckede and his team were fortunate: their Russian colleagues downloaded the data from their devices for them. They were also

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able to resume travel as early as September. “Many of my international colleagues were envious because most of them were not yet able to access their survey sites,” says Göckede.

Even without measurements, it is evident that something is changing in the far north. Building foundations are subsiding because the thawing ground no longer supports them. Following a warm, dry summer in 2019, a house collapsed in Chersky where Göckede’s research base is located, leaving the elongated building without its central section. And the fuel storage tanks of a combined heat and power plant in the industrial city of Norilsk ruptured in May 2020, resulting in an environmental disaster when more than 20,000 tons of diesel spilled out. Landslides are affecting slopes, and deep craters and lakes are forming as well. Fires ignited by lightning during the increasingly frequent thunderstorms are also rising. “Fires had been extremely rare around Chersky until a few years ago,” Göckede explains. A number of wildfires have ravaged areas close to his team’s study sites during the past two years, even in floodplains that were assumed to be wet. It is of little consolation that the carcasses of Ice Age animals, such as mammoths or cave bears, will emerge from the eternal ice and can then be studied as a result of climate change.

Göckede is taking detailed measurements to determine whether additional greenhouse gases are being released through the warming of the permafrost regions and, if so, how much, whereby it is obvious that both methane and carbon dioxide could be released into the atmosphere in the process. To understand this, one first has to consider the forests of the warm south: trees in temperate latitudes and the tropics absorb carbon dioxide from the air, which they then incorporate into their leaves, branches and trunks. When the leaves fall or a tree topples over, microbes decompose the organic matter thus releasing the carbon, so the overall balance in mature forests and a stable climate should be equalized. Different rules apply in permafrost zones, where the upper layer of the soil thaws in the summer and refreezes in the winter. This so-called active layer, which is not part of the permafrost, is between 40 centimeters and several meters thick. Although sparse vegetation often thrives on it, not all of its detritus decomposes, not only because of the low temperatures, but also due to waterlogging, which is common in Arctic ecosystems. Carbon has therefore accumulated over thousands of years – frozen within the soil, sometimes to a depth of several hundred meters.

If the average temperatures in the Arctic zones rise, which has been observed in recent decades, the soil can thaw to greater depths. This destabilizes the underlying permafrost layers and microbes break down the carbon contained within them, producing greenhouse gases, such as CO_2 and CH_4, in the process. The microbial community in dry ecosystems with well-oxygenated soil primarily produces carbon dioxide. In waterlogged ecosystems, by contrast, anaerobic microorganisms produce methane, which has a particularly strong greenhouse effect. The extent to which thawing permafrost will exacerbate climate change will be significantly affected by the quantity of methane released into the atmosphere.

The journey there is arduous enough

But accurately measuring the gas exchange between air and soil is truly a challenge. Göckede and his team first have to travel to their study area, which is arduous enough: after flying to Moscow, they then fly another six hours to Yakutsk, the largest city in

Climate catastrophe: in 2020, the thawing ground caused the tank farm of a combined heat and power plant in the industrial city of Norilsk to subside and rupture. Over 20,000 tons of diesel spilled out and polluted the environment.

the Siberian permafrost zone. Then they take another four-hour flight on a smaller plane to Chersky, which has a population of just 2,500 and lies about 100 kilometers from where the Kolyma River flows into the Arctic Ocean. Once they reach the "Northeast Science Station", a Russian research base, they then set off for their research sites. Their instruments are installed on two towers in an undisturbed area of the tundra in the Kolyma River's floodplain. These devices measure the concentrations of methane, carbon dioxide, and water vapor 20 times per second. Airflows are also recorded. This high frequency is necessary in order to capture the turbulent exchange processes that take place in the near-surface atmosphere. It is a powerful approach to determine the quantity of carbon being absorbed or released by the soil and vegetation. The inhomogeneity of permafrost zones presents another research problem: no two areas are alike – here a recently formed lake, there a patchy group of scraggly trees, here a floodplain, there a scarp. One would actually have to run numerous test series to get a proper understanding of this localized fragmentation. However, there is one type of terrain that is common, which is characterized by numerous wedge-shaped ice patches that crisscross the ground like a network. When heated, these ice wedges thaw out more and the ground can subside in the affected areas, transforming a previously flat, largely homogeneous tundra surface into a landscape of hollows in which water collects, interspersed with relatively dry islands. It is expected that this process of ice wedge degradation will occur frequently in the far north over the coming decades. The Max Planck researchers artificially replicated this effect by draining an area of about 200 meters in diameter with the aid of a drainage ditch to see how it changes carbon flows.

Currently almost no additional greenhouse effect

This experimental area has now been in existence for around seventeen years. Following an initial four-year experiment and a subsequent break of several years, Göckede's team has been continuously measuring and observing how the landscape on the artificial island has been changing for the past eight years. The change is clearly visible: vegetation is thriving and growing taller and, instead of just grass, bushes now grow there as well.

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PHOTO: IMAGO / ITAR-TASS

Of course, the greenhouse gas emissions are of particular interest. “We were surprised by the results,” says Göckede. Because the largely dry artificial island is no longer a suitable habitat for anaerobic microbes, methane emissions decreased by roughly fifty percent compared to an undisturbed reference area, as the measurements showed. In contrast, the situation regarding carbon dioxide is rather different: the ecosystem should actually have absorbed more CO_2 as the vegetation increased. Yet, the opposite proved true overall: the vegetation actually did suck more carbon dioxide out of the air, but the ecosystem as a whole was now close to neutral regarding CO_2 exchange. This effect was due to increasing emissions from the thawing permafrost, for which the additional uptake capacity of the vegetation was unable to compensate.

Because methane is a more efficient greenhouse gas than carbon dioxide, there is currently almost no net additional greenhouse effect. Less methane, more carbon dioxide – “the net effect is amazingly balanced,” Göckede explains. Nobody had expected that. So, despite the significantly altered properties of the ecosystem, the greenhouse gas balance in disturbed permafrost areas could be similar to that of undisturbed areas in the immediate surroundings on the long-term. But, whether these results can be applied to other Arctic regions remains unclear and only experiments at other sites will be able to shed light on this question.

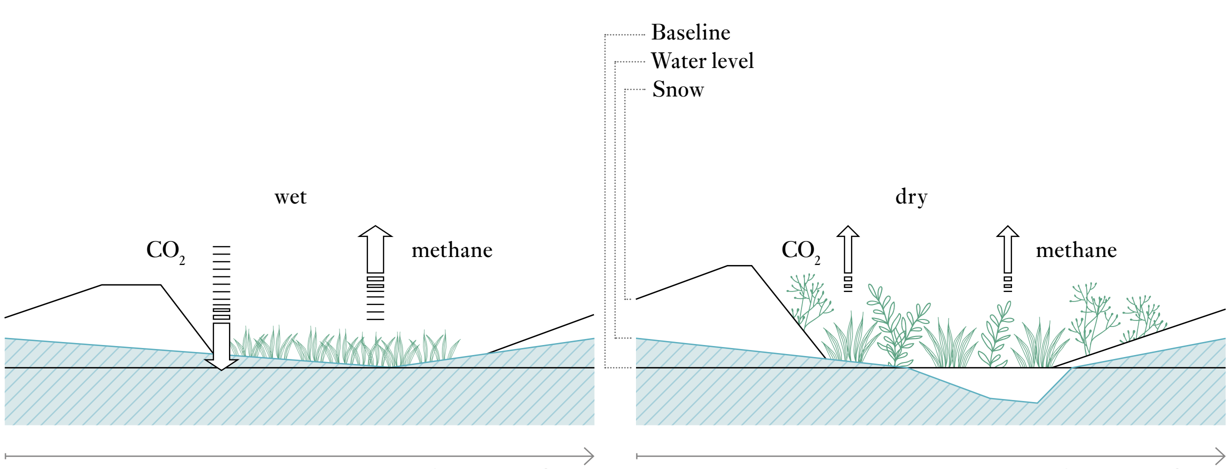
Probably more greenhouse gases in the future

Göckede is rather pessimistic about the long-term development because, as he explains, even if it continues for a few years or decades, the positive effect of enhanced vegetation growth on the carbon budget of permafrost ecosystems will not be permanent, because a point will eventually be reached after which no further growth will be possible – bushes and trees cannot grow infinitely into the sky. It is therefore likely that carbon dioxide and methane emissions will increase as a result of thawing soils.

Another thing that Göckede’s team discovered is the strong influence of snowpack on permafrost. When three times as much snow fell in one winter as in an average year, the upper soil layer in some areas was more than ten degrees warmer than usual, despite the fact that the air temperature was virtually the same as in previous years. Snowy winters can significantly accelerate permafrost thaw because snow insulates the ground.

Russian researchers are taking an original approach to preserving permafrost and improving its greenhouse gas balance: they are relying on ruminants to do the work. They created the “Pleistocene Park” around 25 years ago and have since brought in entire herds of horses, musk oxen, bison, goats, sheep, and recently even camels at considerable expense. Their thinking is that the animals’ excrement will fertilize the soil, thus promoting plant growth and increasing carbon uptake. The animals also scrape the snow aside or compact it in winter, which reduces the insulating effect, which could keep the permafrost frozen despite rising temperatures.

Relatively dry islands form between the newly formed lakes in the thawing permafrost (right). Compared with the original wet ecosystem (left), the water table on the islands (shaded blue area) falls in summer, allowing taller vegetation to grow there. Because of climate change, snow also accumulates earlier in the fall and thaws a bit faster in the early summer. Unlike the wet ecosystem, the dry ecosystem emits CO_2 but releases less methane, so its net greenhouse gas balance is roughly the same.



GRAPHIC: GCO BASED ON MATHIAS GÖCKEDE/MPI FOR BIOGEOCHEMISTRY

PHOTO: MARTIN HEIMANN/MPI FOR BIOGEOCHEMISTRY

Eroding permafrost cliffs: the soil on the banks of the Kolyma River slides over the still-frozen layers, carrying organic material with it, which then gets washed away by the river. Much of it decomposes, releasing carbon dioxide.

SUMMARY

If the permafrost in the Arctic Circle were to thaw as a result of global warming, large amounts of carbon dioxide and methane could be released, which would intensify climate change.

Increased plant growth enables the ecosystem to absorb more carbon dioxide. For the time being, according to measurements by a team at the Max Planck Institute for Biogeochemistry, this process is able to compensate for the increased activity of microorganisms that release carbon dioxide or methane.

In the long run, however, vegetation will reach a growth limit and will not be able to store more carbon dioxide, so emissions from microorganisms will likely predominate.

Whether this approach will prove successful is still unclear. In fact, the landscape has since undergone a significant change, with continuous vegetation now thriving where there had been only isolated clumps of tall grass in the past. “In qualitative terms, the experiment has worked,” Göckede says. But as a scientist, he insists on reliable data: “What I want to see are measurement series, and they don’t yet exist.” He himself has been supporting the experiment for two years by taking sporadic measurements. But he points out that these have been only snapshots, which do not count as evidence. “We would need a large-scale monitoring system.” Göckede also doubts that the process would even be feasible on a larger scale, because the cost of bringing in and caring for the animals is enormous. Nevertheless, he thinks it is important to test such approaches. Every success, no matter how small, could make an important contribution towards preserving the permafrost.

Naturally, the best way to preserve permafrost is effective climate protection. Humans will ultimately decide how the climate changes over the coming decades and centuries – and with it the regions in the far north. Göckede, for one, is glad that he can still experience what he calls this “fascinating landscape” in its current form. “Who knows if it’ll still exist in twenty or thirty years?” He will continue to monitor the changes in the course of an EU-funded ERC project. In addition to the long-term experiments, he is planning to do more research into nonlinear processes that could fundamentally change the appearance of the Arctic. For example, he will be looking at what happens when lakes form – a process that is likely to become more common as warming increases. Because the insulating effect of an expanse of water is similar to that of a deep blanket of snow, one would expect the ground beneath it to thaw more rapidly. How exactly does this affect the greenhouse gas balance and what would happen if the lake were to drain away? Many such disruptive processes are taking place in the Arctic that remain largely unexplored, so there is still a lot for researchers to do in the far north.