




SCALE: 10 centimeters
between black lines



METHANE GAS (white)
rising from an Arctic lake
bottom is frozen into
ice that is forming
across the surface.

Methane: A MENACE SURFACES



Arctic permafrost is already thawing, creating lakes that emit methane. The heat-trapping gas could dramatically accelerate global warming. How big is the threat? What can be done?

BY KATEY WALTER ANTHONY

Touchdown on the gravel runway at Cherskii in remote northeastern Siberia sent the steel toe of a rubber boot into my buttocks. The shoe had sprung free from gear stuffed between me and my three colleagues packed into a tiny prop plane. This was the last leg of my research team's five-day journey from the University of Alaska Fairbanks across Russia to the Northeast Science Station in the land of a million lakes, which we were revisiting as part of our ongoing efforts to monitor a stirring giant that could greatly speed up global warming.

These expeditions help us to understand how much of the perennially frozen ground, known as permafrost, in Siberia and across the Arctic is thawing, or close to thawing, and how much methane the process could generate. The question grips us—and many scientists and policy makers—because methane is a potent greenhouse gas, packing 25 times more heating power, molecule for molecule, than carbon dioxide. If the permafrost thaws rapidly because of global warming worldwide, the planet could get hot-

KEY CONCEPTS

- Methane bubbling up into the atmosphere from thawing permafrost that underlies numerous Arctic lakes appears to be hastening global warming.
- New estimates indicate that by 2100 thawing permafrost could boost emissions of the potent greenhouse gas 20 to 40 percent beyond what would be produced by all natural and man-made sources.
- The only realistic way to slow the thaw is for humankind to limit climate warming by reducing our carbon dioxide emissions. —The Editors

COURTESY OF KATEY WALTER ANTHONY

ter more quickly than most models now predict. Our data, combined with complementary analyses by others, are revealing troubling trends.

Leaving the Freezer Door Open

Changes in permafrost are so worrisome because the frozen ground, which covers 20 percent of the earth's land surface, stores roughly 950 billion tons of carbon in the top several tens of meters. (More permafrost can extend downward hundreds of meters.) This carbon, in the form of dead plant and animal remains, has accumulated over tens of thousands of years. As long as it stays frozen beneath and between the many lakes, it is safely sequestered from the air.

But when permafrost thaws, the carbon previously locked away is made available to microbes, which rapidly degrade it, producing gases. The same process happens if a freezer door is left open; given long enough, food thaws and begins to rot. Oxygen stimulates bacteria and fungi to aerobically decompose organic matter, producing carbon dioxide. But oxygen is depleted in soil that is waterlogged, such as in lake-bottom sediments; in these conditions, anaerobic decomposition occurs, which releases methane (in addition to some carbon dioxide). Under lakes, the methane gas molecules form bubbles that escape up through the water column, burst at the surface and enter the atmosphere.

Anaerobic decomposition is the primary source of methane in the Arctic. Melting ice in per-

THREATENED BY THE NUMBERS

Permafrost covers **20%** of the earth's land surface.

One third to one half of permafrost, a rich source of methane, is now within **1.0° C to 1.5° C** of thawing.

At predicted rates of thaw, by 2100 permafrost will boost methane released into the atmosphere **20% to 40%** beyond what would be produced by all other natural and man-made sources.

Methane in the atmosphere has **25 times** the heating power of carbon dioxide.

As a result, the earth's mean annual temperature could rise by an additional **0.32° C**, further upsetting weather patterns and sea level.

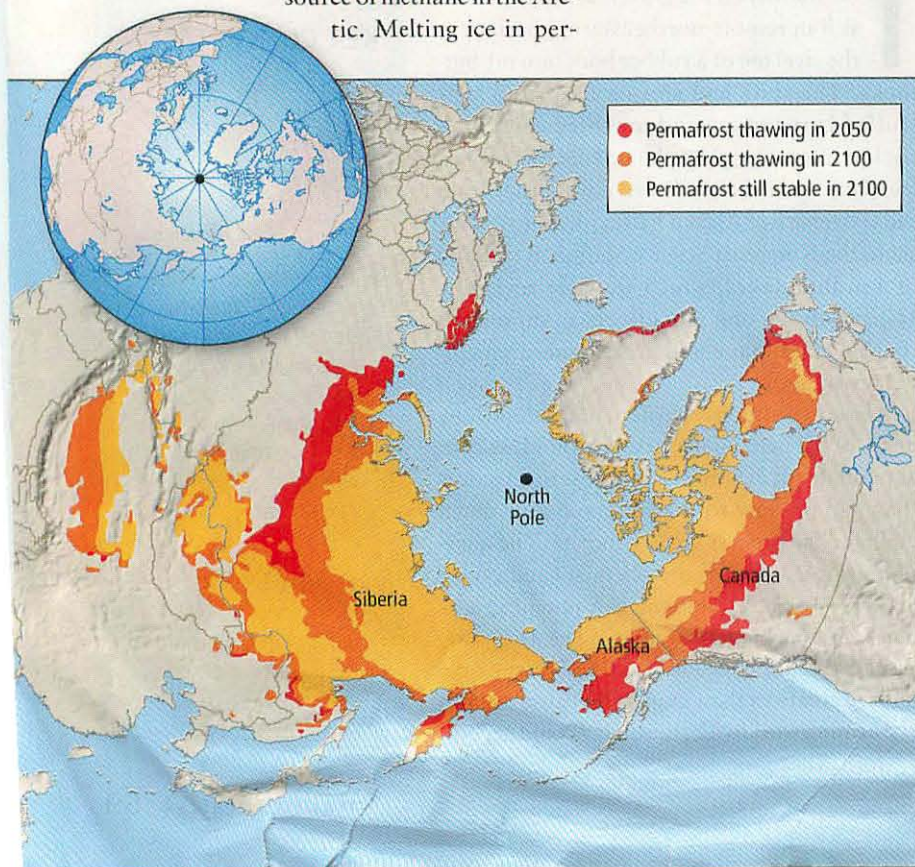
mafrost causes the ground surface to subside. Runoff water readily fills the depressions, creating many small, newly formed lakes, which begin to spew vast quantities of methane as the permafrost that now lines their bottom thaws much more extensively. Scars left behind reveal that this process has been going on for the past 10,000 years, since the earth entered the most recent interglacial warm period. Satellite recordings made during recent decades suggest, however, that permafrost thaw may be accelerating.

Those recordings are consistent with observations made at numerous field-monitoring sites across Alaska and Siberia maintained by my Fairbanks colleague Vladimir E. Romanovsky and others. Romanovsky notes that permafrost temperature at the sites has been rising since the early 1970s. Based on those measurements, he calculates that one third to one half of permafrost in Alaska is now within one degree to one and a half degrees Celsius of thawing; in some places worldwide, it is already crossing that critical zero degrees C threshold.

Ongoing observations, made by my research team during trips to Cherskii and numerous other sites and by our colleagues, reinforce the sense that thawing is accelerating and indicate that the emissions could be much greater than anticipated. My group's latest estimates are that under current warming rates, by 2100 permafrost thawing could boost methane emissions far beyond what would be produced by all other natural and man-made sources. The added greenhouse gas, along with the extra carbon dioxide that exposed, thawing ground would release, together could raise the mean annual temperature of the earth by an additional 0.32 degree C, according to Vladimir Alexeev, also at Fairbanks.

That increase may sound minor, but it is not; it would contribute significantly to global-warming-induced upset of weather patterns, sea level, agriculture and disease dispersal. If deeper sources of methane were to escape—such as that stored in material known as methane hydrates [see box on page 74]—the temperature rise could be as high as several degrees. Therefore, humankind has more reason than ever to aggressively slow the current rate of warming so that we do not push large regions of the Arctic over the threshold.

◀ **NORTHERN EXPOSURE:** Vast swaths of permafrost will thaw by 2050 and 2100 if global warming continues unabated, releasing large quantities of methane that will worsen warming.





The Mother Lode in Siberia

Probing regions such as Cherskii is key to verifying—or revising—our estimations. Walking along a Siberian riverbank with my colleague from the Northeast Science Station, Sergei A. Zimov, I am careful where I stop. The skin of the earth is only a half meter thick, made up largely of muddy, mossy peat that sits loosely atop ice that is 40 to 80 meters deep. The stunted trees are slanted at various angles in this “drunken forest” because they cannot send roots into the frozen ground, and cycles of summer thaws generate large heaves. Behind me, one drunken tree crashes to the ground; through the torn blanket of forest floor we see the shiny black surface of solid ice and catch the musty scent of decomposing organic matter. It is also hard not to stub one’s toe on the plethora of scattered bones: woolly rhinoceros, mammoth, Pleistocene lion, bear and horse.

To Zimov, this region is a goldmine—and not because of the tusks and skulls of extinct fauna. In 1989, spurred by an interest in the amount of carbon locked in the ground, he led a group of young scientists that set up the isolated Northeast Science Station to monitor permafrost in tundra and taiga year-round. The researchers traveled the great Russian rivers in small skiffs and scaled cliffs of permafrost without ropes to measure carbon content, the harbinger of methane release. With army tanks and bulldozers, they simulated disturbances that remove surface soil in the way that severe wildfires do. Their experiments proved the size and importance of the permafrost carbon pool to the world.

But why did Zimov—and my group later—

concentrate studies here, in a region known previously only for its Soviet gulags? Because not all permafrost is the same. Any ground where the mean annual temperature is below zero degrees C for at least two consecutive years is classified as permafrost, whether ice is present or not. This vast part of Siberia contains a distinct type of permafrost called yedoma, rich in ice and carbon—both central to the methane story. Massive wedges of ice 10 to 80 meters high and smaller lenses constitute up to 90 percent of the ground volume; the remainder is columns of organic-rich soil, a cornucopia of the remains of Pleistocene mammals and the grasses they once ate.

Yedoma formed over roughly 1.8 million square kilometers in Siberia and in a few pockets of North America during the end of the last Ice Age. The organic matter froze in place before microbes could decompose it. A huge storehouse of food was being locked away until conditions would change, leaving the freezer door open.

A warmer climate recently has helped melt the yedoma ice, creating lakes. Vegetation collapses into the edges as the ground thaws and subsides, a process known as thermokarst. Today lakes cover up to 30 percent of Siberia. Further melting makes them larger and deeper, coalescing into broad methane-producing water bodies.

Blown Away by Bubbles

During the 1990s researchers at the Northeast Science Station observed that methane was bubbling out of the bottoms of lakes year-round but they did not know how important the lakes might be globally. Hence, my rough landing by

▲ **HOT ON THE TRAIL:** Leading an effort to measure how much methane is escaping into the atmosphere worldwide, the author (in blue jacket) and graduate student Dragos Vas collect gas bubbling up to the ice covering a lake in Alaska’s interior. Like natural gas, methane is highly flammable.

[THE AUTHOR]

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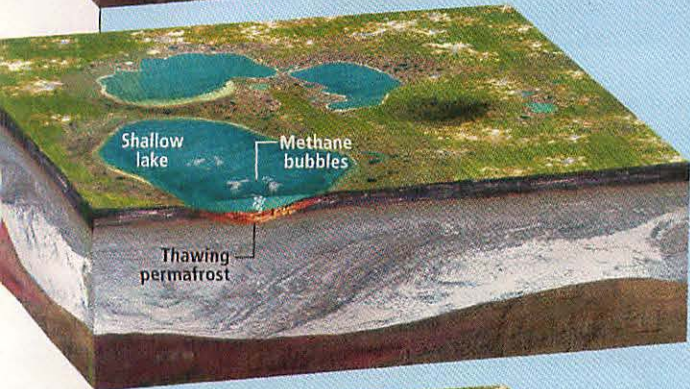
[HOW METHANE IS PRODUCED]

BURSTING BUBBLES

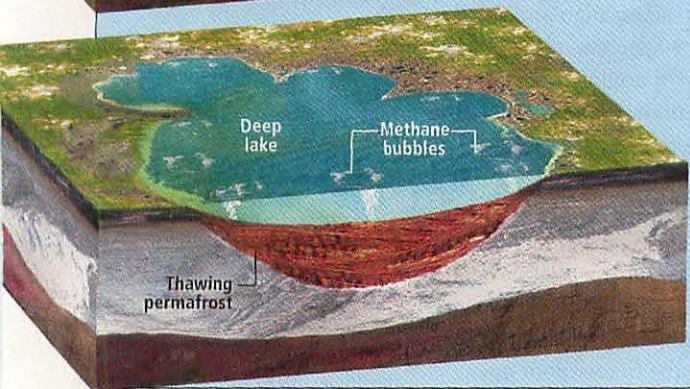
In the cold Arctic environment, dead plant and animal matter lies frozen in ancient permafrost below a thin layer of modern soil. But as the atmosphere warms, the ground thaws. That is when methane production begins.



1 Ice in the frozen soil melts, and the ground subsides, forming sinkholes that fill with water, becoming ponds.



2 Ponds merge into lakes. The water thaws the soil below, and microbes decompose the organic matter anaerobically, producing methane.



3 Deepening lakes thaw permafrost, frozen earth that is far richer in organic matter. It decomposes as well, generating numerous methane bubbles that rise to the lake surface and burst into the atmosphere.

plane in Cherskii this past August, for my ninth expedition of wading into voraciously expanding thermokarst lakes, to measure changes in permafrost and the release of methane.

My quest had begun as a Ph.D. research project in 2000. At the time, scientists knew that levels of methane—the third most abundant greenhouse gas in the atmosphere after carbon dioxide and water vapor—were rising. The amount and the rate of increased emissions were unprecedented during the previous 650,000 years. Evidence indicated that in bygone eras the methane concentration in the atmosphere fluctuated by

50 percent in association with natural climate variations over thousands of years. But that change was slim by comparison with the nearly 160 percent increase that had occurred since the mid-1700s, rising from 700 parts per billion (ppb) before the industrial revolution to almost 1,800 ppb when I started my project.

Scientists also knew that agriculture, industry, landfills and other human activities were clearly involved in the recent rise, yet roughly half of the methane entering the atmosphere every year was coming from natural sources. No one, however, had determined what the bulk of those sources were.

From 2001 to 2004 I split my time between my cabin in Fairbanks and working with Zimov and others in Cherskii, living with the few local Russian families. In the attic library above our little, yellow wooden research station I spent long nights cobbling together plastic floats that I could place on the lakes to capture bubbles of methane. I dropped the traps by leaning over the side of abandoned boats that I claimed, and I checked them daily to record the volume of gas collected under their large jellyfishlike skirts. In the beginning I did not capture much methane.

Winter comes early, and one October morning when the black ice was barely thick enough to support my weight I walked out onto the shiny surface and exclaimed, "Aha!" It was as if I was looking at the night sky. Brilliant clusters of white bubbles were trapped in the thin black ice, scattered across the surface, in effect showing me a map of the bubbling point sources, or seeps, in the lake bed below. I stabbed an iron spear into one big white pocket and a wind rushed upward. I struck a match, which ignited a flame that shot up five meters high, knocking me backward, burning my face and singeing my eyebrows. Methane!

All winter I ventured across frozen lakes to set more traps above these seeps. More than once I stepped unknowingly on a bubbling hotspot and plunged into ice-cold water. Methane hotspots in lake beds can emit so much gas that the convection caused by bubbling can prevent all but a thin skin of ice from forming above, leaving brittle openings the size of manhole covers even when the air temperature reaches -50 degrees C in the dark Siberian winter. I caught as much as 25 liters (eight gallons) of methane each day from individual seeps, much more than scientists usually find. I kept maps of the hotspots and tallies of their emissions across numerous

KEVIN HAND (Illustration), COURTESY OF GUIDO GROSSI, Geophysical Institute, University of Alaska Fairbanks (opposite page)

lakes. The strongest bubbling occurred near the margins of lakes where permafrost was most actively thawing. The radiocarbon age of the gas, up to 43,000 years old in some places, pointed to yedoma carbon as the culprit.

From 2002 to 2009 I conducted methane-seep surveys on 60 lakes of different types and sizes in Siberia and Alaska. What scientists were not expecting was that the increase in methane emissions across the study region was disproportional to the increase in lake area over that same region. It was nearly 45 percent greater. It was accelerating.

Extrapolated to lakes across the Arctic, my preliminary estimate indicated that 14 million to 35 million metric tons of methane a year were being released. Evidence from polar ice-core records and radiocarbon dating of ancient drained lake basins has revealed that 10,000 to 11,000 years ago thermokarst lakes contributed substantially to abrupt climate warming—up to 87 percent of the Northern Hemisphere methane that helped to end the Ice Age. This outpouring tells us that under the right conditions, permafrost thaw and methane release can pick up speed, creating a positive feedback loop: Pleisto-

cene-age carbon is released as methane, contributing to atmospheric warming, which triggers more thawing and more methane release. Now man-made warming threatens to once again trigger large feedbacks.

How fast might these feedbacks occur? In 2007 global climate models reported by the Intergovernmental Panel on Climate Change (IPCC) projected the strongest future warming in the high latitudes, with some models predicting a rise of seven to eight degrees C by the end of the 21st century. Based on numerous analyses, my colleagues and I predict that at least 50 billion tons of methane will escape from thermokarst lakes in Siberia as yedoma thaws during the next decades to centuries. This amount is 10 times all the methane currently in the atmosphere.

Fine-tuning the Models

Even with our best efforts, our current estimates beg more sophisticated modeling as well as consideration of potential negative feedbacks, which could serve as breaks on the system. For instance, in Alaska, a record number of thermokarst lakes are draining. Lakes formed in upland areas grow



▲ LAKES are forming across Siberia as warming air thaws formerly frozen ground (above). Below, the author (in red jacket) and graduate student Louise Farquharson sample exposed permafrost (gray earth), which often extends tens of meters below a thin cap of unfrozen soil.



HYDRATES: DEEPER TROUBLE

Permafrost is not the world's only methane concern. Vast quantities of the gas lie trapped in ice cages hundreds of meters down in the ground and below ocean bottoms. If these "methane hydrates" were to somehow melt and release their gas to the atmosphere, they would almost certainly trigger abrupt climate change. Evidence in seafloor sediments suggests that this very event, spurred by rapidly rising ocean temperatures, may have occurred 55 million years ago.

Some Russian scientists claim that more than 1,000 billion tons of methane lie beneath the Siberian shelf—submerged land extending seaward from the coastline that eventually drops to the deep ocean. If even 10 percent escaped—100 billion tons—it would be twice the 50 billion tons we project could be released by permafrost thaw [see *main article*]. Warming of the deep ocean is unlikely in the near future. But high concentrations of methane in shallow waters along the shelf have recently been observed; continuing research there should determine whether the source is hydrates or (more likely) decomposing organic matter in permafrost thawing in the shallow seafloor.

On land, if lake-bed thawing extended like fingers deeper into the earth below, it could conceivably break into hydrate deposits and give them a channel to bubble upward to and through the water and into the atmosphere. My group is collaborating with U.S. Geological Survey scientists Carolyn Ruppel and John Pohlman to evaluate this possibility.

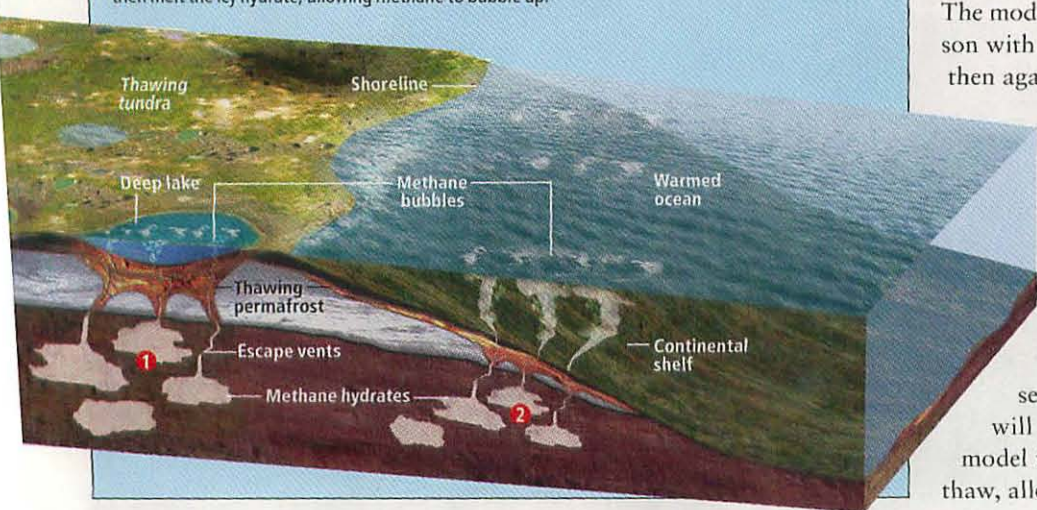
If hydrates prove to be a threat, the effect might be counteracted a bit by extracting the methane as a fuel before it is released. The methane in global hydrates would produce more energy than all the natural gas, oil and coal deposits on earth combined. Very little of it would ever be economically recoverable, however, because it is too dispersed in geologic strata, making exploration and extraction too expensive, even if oil was \$100 a barrel. In a few places, mining concentrated hydrates might prove more affordable, and countries such as Japan, South Korea and China, eager to reduce fossil-fuel imports, are investing in technology to possibly extract those deposits. ConocoPhillips and British Petroleum are assessing the commercial feasibility of certain hydrates in the U.S.

Tapping hydrates is controversial. If enough evidence suggested an imminent, uncontrolled release of methane from destabilized hydrates, then capturing the gas instead would help mitigate climate warming. No proof of large hydrate releases exists yet, however, so commercial extraction would simply exasperate fossil-fuel driven climate changes. From a global-warming point of view, we are better off leaving those hydrates deep underground.

—K.W.A.

THE GIANT BELOW ▼

Large, deep deposits of ice and gas known as hydrates could suddenly release vast quantities of methane if breached. Two theoretical pathways might exist. ① On land, thawing fingers of permafrost could extend downward and break into a deposit, allowing methane to vent upward. ② Under continental shelves, warming ocean water could thaw the thin permafrost cap, then melt the icy hydrate, allowing methane to bubble up.



until they hit a slope. Then the water flows downhill, causing erosion and further drainage, sending melted sediment into rivers and eventually the ocean. Drained basins fill in with new vegetation, often becoming wetlands. Although they produce methane when they are unfrozen in summer, their total annual emissions are often less than those of lakes.

It is hard to say whether such potential processes would lessen methane release by a sizable amount or just a few percentage points. Two projects of mine, with my Fairbanks colleague Guido Grosse, Lawrence Plug of Dalhousie University in Nova Scotia, Mary Edwards of the University of Southampton in England and others, began in 2008 to improve the first-order approximations of positive and negative feedbacks. A key step is to produce maps and a classification of thermokarst lakes and carbon cycling for regions of Siberia and Alaska, which we hope to draft by early 2010. The cross-disciplinary research links ecological and emissions measurements, geophysics, remote sensing, laboratory incubation of thawed permafrost soils and lake sediments, and other disciplines. The goal is to inform a quantitative model of methane and carbon dioxide emissions from thermokarst lakes from the Last Glacial Maximum (21,000 years ago) to the present and to forecast climate-warming feedbacks of methane from lakes for the upcoming decades to centuries.

To help predict how future warming could affect thermokarst lakes, Plug and a postdoctoral student working with us, Mark Kessler, are developing two computer models. The first, a single-lake model, will simulate the dynamics of a lake basin. The second, a landscape model, includes hill-slope processes, surface-water movement and landscape-scale permafrost changes. The models will first be validated by comparison with landscapes we are already studying, then against data from sediment cores going back 15,000 years in Siberia and Alaska, and then against other climate simulations from 21,000 years ago. The final step will be to couple the thermokarst-lake models with the vast Hadley Center Coupled Model that describes the circulation of oceans and atmosphere—one of the major models used in IPCC assessment reports. The result, we hope, will be a master program that can fully model the extent and effects of permafrost thaw, allowing us to calculate a future rate of

methane release and assess how that would drive global temperatures.

More fieldwork, of course, will continue to refine the data going into such models. In 2010, with the help of a hovercraft, we will investigate lakes along nearly 1,000 miles of Siberian rivers and Arctic coast. A huge expedition will also retrieve sediment cores from lakes dating back millennia. Field data, together with remote sensing, will ultimately be used in the Hadley Center program to model climate change drivers from the Last Glacial Maximum to 200 years into the future. Maps of predicted permafrost thaw and methane release should be complete by April 2011.

Solutions

If, as all indicators suggest, Arctic methane emissions from permafrost are accelerating, a key question becomes: Can anything be done to prevent methane release? One response would be to extract the gas as a relatively clean fuel before it escapes. But harvesting methane from the millions of lakes scattered across vast regions is not economically viable, because the seeps are too diffuse. Small communities that are close to strong seeps might tap the methane as an energy source, however.

Zimov and his son, Nikita, have devised an intriguing plan to help keep the permafrost in Siberia frozen. They are creating a grassland ecosystem maintained by large northern herbivores similar to those that existed in Siberia more than 10,000 years ago. They have introduced horses, moose, bears and wolves to "Pleistocene Park," a 160-square-kilometer scientific reserve in northeastern Siberia. They intend to bring back musk ox and bison, depending on funding, which comes from independent sources,



▲ **SOLUTION?** A reindeer herder fixes a fence that surrounds a large area of Siberia known as Pleistocene Park. Grazing animals such as Yakutian horses are being introduced there to better establish grasslands that will help keep permafrost frozen.

es, the Russian government and U.S. agencies.

These grazing animals, along with mammoths, maintained a steppe-grassland ecosystem years ago. The bright grassland biome is much more efficient in reflecting incoming solar radiation than the dark boreal forest that has currently replaced it, helping to keep the underlying permafrost frozen. Furthermore, in winter the grazers trample and excavate the snowpack to forage, which allows the bitter cold to more readily chill the permafrost.

One man and his family have taken on a mammoth effort to save the world from climate change by building Pleistocene Park. Yet a global response is needed, in which every person, organization and nation takes responsibility to reduce their carbon footprint. Slowing emissions of carbon dioxide is the only way humankind can avoid amplifying the feedback loop of greater warming causing more permafrost thaw, which causes further warming. We predict that if carbon emissions increase at their current projected rate, northern lakes will release 100 million to 200 million tons of methane a year by 2100, much more than the 14 million to 35 million tons they emit annually today. Total emissions from all sources worldwide is about 550 million tons a year, so permafrost thaw, if it remains unchecked, would add another 20 to 40 percent, driving the additional 0.32 degree C rise in the earth's mean annual temperature noted earlier. The world can ill afford to make climate change that much worse. To reduce atmospheric carbon dioxide and thereby slow permafrost thaw, we all must confront the elephant in the room: people burning fossil fuels.

MORE TO EXPLORE

Methane Bubbling from Siberian Thaw Lakes as a Positive Feedback to Climate Warming. K. M. Walter et al. in *Nature*, Vol. 443, pages 71–75; September 7, 2006.

Thermokarst Lakes as a Source of Atmospheric CH₄ during the Last Deglaciation. K. M. Walter et al. in *Science*, Vol. 318, pages 633–636; October 26, 2007.

Assessing the Spatial and Temporal Dynamics of Thermokarst, Methane Emissions, and Related Carbon Cycling in Siberia and Alaska. G. Grosse, K. Walter and V. E. Romanovsky. NASA Carbon Cycle Sciences Project, April 2008–March 2011.

Understanding the Impacts of Icy Permafrost Degradation and Thermokarst-Lake Dynamics in the Arctic on Carbon Cycling, CO₂ and CH₄ Emissions, and Feedbacks to Climate Change. K. Walter, G. Grosse, M. Edwards, L. Plug and L. Slater. Project 0732735 for National Science Foundation/International Polar Year, July 2008–June 2011.

CITIZEN SCIENCE: METHANE IN LAKES NEAR YOU

Do you live near a lake? How much methane does it release? Methane rises from any lake bottom in which organic matter is decomposing, regardless of latitude. Beaver ponds are particularly productive. To find out how you can take part in mapping methane seeps in your own backyard, visit the Pan-Arctic Lake-Ice Methane Monitoring Network (www.alaska.edu/uaf/cem/ine/walter/ongoing_projects.xml). Educators can also get involved through a student program at the same Web site.