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Unfrozen North

Vast stores of carbon are locked in the world's permafrost. What happens when it thaws?

By J. Madeleine Nash

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Wolverine Lake, near the Toolik Lake Research Natural Area, underlain by permafrost, on the North Slope of Alaska. THOMAS NASH

On the cover

A storm clears in the late evening during the summer solstice in the valley between Shublik and Sadlerochit mountains of the Brooks Range, in the Arctic National Wildlife Refuge.
THOMAS NASH

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Editor's note

Science matters

In Idaho, a political battle over climate change education is afoot. Lawmakers there want to scrub information about the subject from statewide science guidelines, veering away from national standards and leaving public-school students in ignorance. After all, the facts are in: Humans add greenhouse gases to the atmosphere, thereby trapping the sun's energy and heating up the planet. That's not a value judgment; it's just science. But denying it is akin to denying the existence of gravity.

For now, Idaho's more sensible teachers and students are pushing back, and it looks like some vestige of reason will be restored to classrooms. However, it is unlikely we've heard the last of this sort of thing, as a full-on ideological war on science is underway in our country. Ideas once confined to shock jocks and Twitter trolls have entered national politics, and now the White House.

As the venerable *Scientific American* recently reported, under President Donald Trump critical science positions in federal agencies have not been filled, science advisory panels are being disbanded, and science-based policies are being undermined. These, too, are facts, verifiable and indisputable, and yet I get letters these days asking me to stop disparaging the president. Believe me, I wish I could. But Trump's policies are endangering the long-term effectiveness of the Environmental Protection Agency, the Centers for Disease Control and Prevention, the Occupational Safety and Health Administration, the National Oceanic and Atmospheric Administration, and the National Aeronautics and Space Administration, to name just a few. In other words, this administration is undermining the American institutions that make our water and workplaces safe, cure diseases, and explore and study land, sea and space.

Why? I have no idea. But I do know this: The Earth's massive systems don't care a whit about you, me or Donald Trump. They will keep churning, turning, spinning and grinding according to universal laws, no matter what we say or believe. Here on this tiny rock in an infinite cosmos, we are free to extinguish ourselves or not, according to the rational (or irrational) choices we make.

This issue's cover story helps explain why these choices matter, why science matters. In it, writer J. Madeleine Nash takes us to the Alaskan Arctic, where researchers are trying to understand what will happen when vast stretches of permafrost thaw. Right now, no one knows for sure. What we do know is that, as temperatures rise, ice thaws. (Try denying that.) And when you defrost thousands of miles of muck, thousands of feet thick, something on our planet will change. If only it were the president's view of what actually makes America great: our power to reason, desire to discover and curiosity about the wonderful world we live in — at least while it lasts.

—Brian Calvert, editor-in-chief

Unfrozen North

The world's permafrost holds vast stores of carbon. What happens when it thaws?

By J. Madeleine Nash | Photographs by Thomas Nash

Like a giant dragonfly,

the chopper skims over undulating swaths of tussocky tundra, then touches down at Wolverine Lake, one of a swarm of kettle lakes near the Toolik Field Station on Alaska's North Slope. Even before the blades stop spinning, Rose Cory, an aquatic geochemist from the University of Michigan in Ann Arbor, gracefully swings to the ground and beelines to the spot where, four years ago, a subterranean block of ice began to melt, causing the steep, sloping bank to slump into the water. The lake throws back a somber reflection of the clouds swirling above, its surface riffled by the wind.

Cory has brought me here because the slump provides a vivid example of the ordinarily inaccessible stuff she studies. Slick with meltwater, the chocolaty goop brims with microscopic bits of once-living things that have not touched sunlight or air or flowing water for centuries, perhaps millennia. Deeper still lie plant and animal remains that could be tens of thousands of years old, dating back to the Pleistocene, when steppe bison and woolly mammoths wandered a treeless region that extended from here across the Bering Land Bridge, all the way to Siberia.

For a moment we just stand there, staring down at the raw gash. Occasionally, Cory lifts her head to scan the shoreline for furry visitors. Despite our proximity to the field station, we are in a wild place, without roads or trails or protective shelter. For years, in fact, the lake was known to researchers only by a number. It earned its moniker in 2013, when a hardy trio of young researchers hauled their instruments nearly five miles cross-country to measure the just-discovered slump and spotted a wolverine circling a wounded caribou.

Cradled by cloudberry, dwarf birch and willow, Wolverine Lake crouches in the shadow of the snow-streaked Brooks Range. A bit over a third of a mile across, it formed during the retreat of a giant lobe of ice that, 60,000 years ago, advanced from its stronghold in those looming mountains to fill the valley of the Sagavanirktok River — commonly called "the Sag" — into which the lake's outlet stream now drains. The irregular shoreline still traces out the shape of the marooned ice fragment that molded the bowl-like basin. The buried ice that triggered the slump is yet another relict of this long-vanished world, as are the glacier-ground rock and organic debris now streaming into the water.

To those like Cory who know how to parse it, this slump is a source of wonder. It offers a tantalizing portal into the hidden world of permafrost, the broad band of perpetually frozen soils that undergirds a circumpolar region more than twice the size of the continental U.S. This region is now warming at twice the rate of the global average, with grave implications for the stability of permafrost and all it holds. Both small and large things are poised to emerge from this gelid domain, from common soil-dwelling bacteria, to the nearly intact carcasses of Ice Age megafauna. The most important, however, is the carbon stored in the frozen layers of leaves, stems and roots that lie beneath our feet.

"Think of a cup of tea," Cory suggests. The carbon-rich organic materials the slump is carrying into the lake are too small to be removed with a filter, but substantial enough to impart a tinge of color and even flavor. The water samples collected from the lakes, streams and rivers here indicate that the brew percolating out of freshly exposed permafrost differs sharply from the steep that comes from shallow layers of soil that thaw and refreeze in accordance with the natural cycle of seasons.

At first, this might seem little more than a bit of esoterica to tuck away for a trivia exchange in the Toolik dining hall. Yet discerning permafrost's protean signature is one of the keys to understanding what this vast landscape's transformation might mean — not just for the Arctic, but for the whole planet. The research Cory conducts on a meticulous, molecular scale is just part of a larger body of work aimed at answering an increasingly critical question. Globally, the frigid soils of the Far North store almost double the amount of carbon already circulating in the atmosphere in the form of heat-trapping carbon dioxide — enough to drive the climate system into territory Earth has not experienced for millions of years.

But carbon travels an invisible highway with multiple on- and off-ramps, some of which lead into the atmosphere, some away from it. Figuring out all of this entails an excruciatingly complicated set of calculations. In order to plug in the numbers, scientists like Cory must first understand the biological and chemical processes that control the routes carbon takes through soils and surface waters. As the preserved past thaws and begins to decay, Cory wonders, just how much of that carbon will end up in the atmosphere? And how fast?

Previous page: Caribou dot the landscape in the Tamayariak River drainage on Alaska's North Slope, near the base of the Sadlerochit Mountains in the Arctic National Wildlife Refuge.

The Toolik Field Station on Alaska's North Slope, as seen from an approaching Robinson R44 Raven II helicopter.

A gleaming ice wedge in the permafrost within the Permafrost Research Tunnel north of Fairbanks illustrates permafrost's geophysical Achilles' heel. Once subsurface temperatures creep above freezing, the ice will melt and flow away. Visible surface of the wedge is about 8 feet wide. Holes near bottom are where ice samples were taken for scientific measurements.

Rose Cory in front of the thermokarst of Wolverine Lake, near the Toolik Lake Research Natural Area on the North Slope of Alaska. Cory, an aquatic geochemist from the University of Michigan in Ann Arbor, is studying how much carbon will end up in the atmosphere as the permafrost thaws.

If the warming trend continues, permafrost close to the surface could reach the thawing point by 2050.

TO PEEK AT PERMAFROST from below, I toured the "permafrost tunnel" bored into a hillside outside Fairbanks, Alaska, by the Cold Regions Research and Engineering Laboratory of the U.S. Army Corps of Engineers. Kept at a chilly 25 degrees Fahrenheit, it exudes a smell reminiscent of garden dirt. There, embedded in a matrix of frozen silt, I could see the bones of mammoths, the horns of bison and the roots and leaves of sedges that grew here more than 30,000 years ago. I could also see rocks and gravels and dark wedges of ice glistening in the artificial light.

This hard, heterogeneous composite has long been a barrier to economic development in both the Arctic and sub-Arctic. The gold miners who flocked to the Alaskan and Canadian Yukon hoping to make their fortune around the turn of the 20th century had to use wood fires, hot water and steam to thaw the gold-bearing gravels. "As resistant to excavation as a mass of reinforced concrete," the general manager of one mining company complained, though the difficulty didn't stop it from buying up and working a number of placer claims.

Yet as the slump at Wolverine Lake illustrates, permafrost has a geophysical Achilles' heel. Once subsurface temperatures creep above freezing, the ice it contains melts and flows away. In the uplands, as around Wolverine Lake, this ice is often a glacial legacy. Elsewhere it comes from rain and snowmelt that have gradually worked their way down through a network of surface cracks and refrozen. Some sections of permafrost contain the merest flecks of ice, barely enough to moisten thawing soils; others are larded with massive wedges that can measure 10 or more feet across.

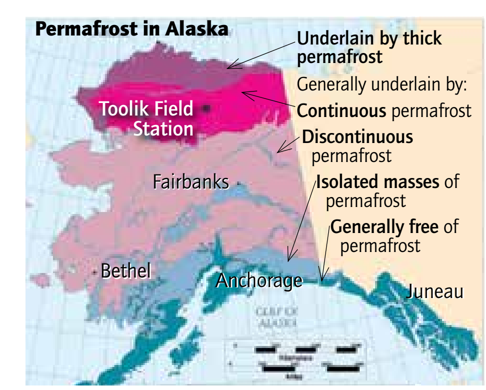
Until recently, worries about the stability of permafrost focused on the more southerly boreal zone. But geophysicist Vladimir Romanovsky, head of the Permafrost Laboratory at the University of Alaska Fairbanks Geophysical Institute, has grown increasingly concerned about the permafrost on Alaska's cold North Slope. For four decades now, the lab has tracked permafrost temperatures in a network of deep holes that field crews have drilled across the region. Beginning in 1988, Romanovsky notes, temperatures in the northernmost holes started to rise, echoing the rise in air temperatures. Readings taken near Prudhoe Bay show that the permafrost there has now warmed by more than 5 degrees Fahrenheit at a depth of 65 feet and by 9 degrees Fahrenheit at a depth of 3 feet, where temperatures are now in the 20s. If the trend continues, Romanovsky says, the permafrost close to the surface could reach the thawing point by 2050.

Even today, ice-rich permafrost can grow warm enough to lose its structural integrity. Almost anything that insulates the ground and blocks the flow of cold winter air can do it: a road, a building, a big pile of snow. So can the destruction of vegetation, which shades soils from the summer sun. In 2007, an intense North Slope tundra fire stripped the landscape bare, creating a new landmark, the Valley of Thermokarsts. ("Thermokarst" is the technical term for thaw slumps and related phenomena. Typically, karst topography, riddled with sinkholes and caves, comes from rain and snowmelt that trickles into the ground, dissolving underlying layers of limestone. In the case of thermokarst, water from ice melted by heat provides the erosive force.)

Areas adjacent to sun-warmed bodies of water — coastal bluffs, the banks of rivers and lakes — are prone to thermokarst, especially when undermined by floods or the persistent action of waves. In Alaska, the first recorded sighting of a thermokarst event in progress comes from a 19th century voyage along the Alaskan coast made by Otto von Kotzebue, a lieutenant in the Russian Imperial Navy. At one landing site, he and his party came across "masses of … ice, of the height of a hundred feet, which are under a cover of moss and grass. … The place which, by some accident, had fallen in … melts away, and a good deal of water flows into the sea."

Thaw slumps can occur in colder times — Kotzebue's voyage took place towards the end of the centuries-long cold snap known as the Little Ice Age — but they are more likely to occur in balmy interludes. In 2005, a thaw-triggered landslide near Toolik hit another lake known to scientists only as N14. It charged the water with so much glacier-ground rock that the color "went from clear to milky blue," recalls Feng Sheng Hu, a paleoecologist at the University of Illinois at Urbana-Champaign. The same rock flour showed up as distinct deposits in the 6 feet of cored sediments Hu and his colleagues obtained from the deepest part of the lake. The sediments yielded a thermokarst record that covers the past 6,000 years. Of 10 large slumps that occurred over that time span, seven coincided with climatic intervals marked by warmer summers.

Thermokarst events are the "high-speed trains of permafrost thaw," observes Cory's colleague, University of Michigan ecologist George Kling, and there are suggestions they may be increasing. In 2008, an aerial census around Toolik counted nearly three dozen within a 230-square-mile area. Two-thirds did not exist prior to 1980. How many of these might have occurred without the profligate burning of fossil fuels is hard to gauge, but in the future, according to an international team of scientists, an estimated 20 percent of the area underlain by permafrost may become vulnerable to thaw-driven collapse as gears in the climate system continue to shift, ratcheting Arctic temperatures ever higher.



SOURCE: U.S. GEOLOGICAL SURVEY

FOR A SENSE of how permafrost shapes Alaska's northern reaches, you might drive to Toolik from Fairbanks, heading out on the Elliott Highway to Livengood, then turning north onto the Dalton Highway. This is the legendary Haul Road, the rough two-lane trucking corridor that parallels the flow of crude oil from the North Slope through the Trans-Alaska Pipeline to the tanker terminal at Port Valdez. The route roller-coasters through some of the state's most scenic country. It is treacherous, with steep curves, virtually no guardrails, and, in places, a slalom course of thaw-triggered potholes.

For the first part of the journey, the Haul Road slices through the boreal forest of the cold, dry Alaskan interior. Here, the permafrost is disconnected, creating a subtle mosaic in the form of alternating stands of black and white spruce. White spruce mark the warmer, better-drained slopes that are often permafrost free, while black spruce — funny little trees that look like dark green bottle brushes — sink their roots into the cold, soggy soils above an impermeable layer of frozen ground. After you cross the Arctic Circle and head into the Brooks Range, the trees become sparser and scragglier, then disappear.

Beneath the tundra of the North Slope, permafrost forms a continuous underlayment, extending from the Brooks Range to the edge of the Arctic Ocean. At Toolik, this icy substrate is 600 feet thick from top to bottom, compared to 150 feet in the boreal zone. Farther north, beneath the Arctic Coastal Plain, it extends to depths of 2,000 feet.

Throughout this vast realm of frozen soil, thermokarst serves as a source of ecological disturbance and renewal. On steep terrain it causes landslides, bulldozing new clearings and replenishing the nutrients in waterways. (Along with carbon, permafrost also contains nitrogen, phosphorus and calcium.) On the flat, it creates depressions that evolve into ponds, lakes and wetlands. In the boreal zone, along the Tanana River, successive episodes of thermokarst are now converting a birch forest into bogland. Thermokarst is impacting the built landscape as well. In Alaska, one of the most serious impacts of climate change will be the billions of dollars in damage, already extensive, that thermal erosion deals to infrastructure.

But until warmth awakens it, permafrost remains inert. The biological and chemical action takes place in the layer of seasonally thawed soil above it, the "active layer," as it's called. This is where the root zone is, where microorganisms live, where rain and snow melt circulate, blocked from following pathways that would lead to deeper drainage. Along with the chilly air, which stymies evaporation, the impermeability of permafrost is the reason the Far North can be so dry — Prudhoe Bay gets less precipitation than Phoenix, Arizona — and yet so water-logged.

A stunning example can be glimpsed from a bush plane flying northwest of Toolik, along the coastal plain. Everywhere, it seems, water puddles on the surface in geometric arrays. It twists and turns in sinuous ribbons. It collects in lakes that look like daubs of sky brushed across the tundra. These are the famous "thaw lakes," scooped out of the permafrost by thermokarst. Many are too shallow to sustain fish, but nonetheless help support hundreds of thousands of migratory waterfowl and shorebirds, including Brant geese, king eiders and buff-breasted sandpipers.

This is a dynamic landscape, one highly responsive to climate change. Already the loss of ice along the coast is exposing the outer fringe of lakes and wetlands to seawater intrusion. In response, plants adapted to wet tundra are giving way to salt-tolerant species. Eventually, rising temperatures may combine with higher precipitation to cause a more rapid cycle of lake formation and decay. In 2014, one thaw lake swollen with rain and snowmelt breached its permafrost-armored banks and drained in the space of just 36 hours.

As permafrost thaws, its carbon will also enter the hydrologic system, becoming an increasingly important part of the emissions stream.

The aquatic environments of the Arctic are not just ecologically important; they are climatologically significant as well. Over 40 percent of the carbon dioxide currently entering the atmosphere from the Arctic comes from its surface waters. The reason is simple: In addition to the carbon-rich detritus thrown off by algae and other aquatic organisms, Arctic lakes, rivers and streams also receive generous infusions of soil carbon that seeps into their waters from the active layer above the permafrost. As permafrost thaws, its carbon will also enter the hydrologic system, becoming an increasingly important part of the emissions stream.

But a carbon molecule drifting through water doesn't magically throw off carbon dioxide (or methane, a less common but even more potent greenhouse gas.) First, it must be broken down, most often by microbes that remain metabolically active year round. One of the curiosities around Toolik is the sudden release of CO_2 that occurs each spring when the ice covering its lakes breaks up. This short-lived event is a bit like uncapping a soda bottle, without the audible fizz. It's due to the fact that, under the ice, microbes have been busy consuming carbon-rich molecules, exhaling carbon dioxide as a byproduct.

The addition of permafrost carbon to soils and surface waters adds a new layer of complexity. Not long ago, much of this carbon — dissolved organic carbon or "dead old carbon," as Rose Cory calls it — was thought to be structurally so complex that it would take a long time for microbes to process it. Instead, Cory and her colleagues are finding, these tiny organisms lustily respond to fresh infusions of permafrost carbon, attacking tasty morsels with enzymes like nanoscale ninjas hurling dagger-sharp stars.

Thaw lakes and patterned ground surrounding the Colville River at the edge of the National Petroleum Reserve on Alaska's North Slope. More than 40 percent of the carbon dioxide entering the atmosphere from the Arctic comes from its surface waters.

THE TOOLIK FIELD STATION, a compact jumble of pre-fab structures, straddles a site that once housed construction crews for the Trans-Alaska Pipeline. Operated by the University of Alaska Fairbanks and funded by the National Science Foundation, along with other government agencies, it has become a magnet for scientists involved in Arctic research. To avoid perturbing the permafrost, many of the buildings here are elevated above ground, as are long sections of the pipeline.

Climbing the steep staircase to Cory's trailer lab, I find her huddled with her graduate students in front of a computer. She says it feels a bit serendipitous to find herself in a doublewide again. The shape and feel of the workspace evoke warm memories of the trailer in rural Montana that was her childhood home. "I loved it," she says. "You know the old expression, 'You can take the girl out of the trailer, but. …' " Everyone has just arrived, so the lab is a study in controlled clutter. This is where the team will spend hours doing tedious and painstaking analysis. Still unpacked are boxes of plastic bottles, which, over the summer, will be filled in the field with samples of water aswirl with carbon and brought here for study.

Now 42, Cory first set foot in Toolik 15 years ago when she herself was a student. Ever since, the arc of her career has tracked rising concern about the fate of permafrost and the carbon it contains. Trained in photochemistry, Cory often sees things others do not. Previously, for example, scientists thought mostly about the carbon dioxide released by microbes that, in soils, operate totally in the dark. But from the moment she arrived at Toolik, Cory saw a landscape awash in light. For a few months of the year, 24 hours a day, Arctic waters are quite literally sun-struck, which turns out to be relevant to the release of carbon from permafrost.

Starting in 2010, Cory linked up with Michigan's George Kling and Byron Crump, a microbiologist from Oregon State University, to explore the biochemical and geochemical impacts of light. One set of experiments involved collecting water samples from seven active thermokarst sites. After removing impurities with a filter, the team put the samples into plastic pouches and left them outside to bask in the sun. This "sun tea" was then presented to bacteria sieved from the same thermokarst-infused water.

This sunlight treatment, the scientists found, substantially boosted the microbes' ability to convert the dissolved carbon compounds in the samples into carbon dioxide. The mechanism? Light, ultraviolet light in particular, is a breaker of chemical bonds. Like a kitchen knife, it slices and dices organic molecules into smaller, more palatable bits. A second series of experiments focused on the microbial communities cultured from Arctic soils. Most effective at decomposing light-treated organic carbon were those that emerged from thawed chunks of permafrost where they'd remained dormant, or even — as some believe — sluggishly active for centuries.

But microbes are just part of the story. In a study of more than 70 lakes, streams and rivers, including the Sag, Cory and her colleagues have established that exposure to sunlight alone can turn carbon into CO_2 without any microbial involvement. The rate at which this happens varies with the cloudiness of the sky, the thickness of the ice cover and the depth and clarity of the water. But on average, they found, this abiotic conversion may account for about a third of all the carbon dioxide currently released by Arctic surface waters. It's a photochemical pathway that will increase in importance as rising temperatures accelerate the thawing of permafrost and the melting of sunlight-occluding ice.

Climate is only one factor that affects the rate at which carbon is wrested from organic material and released into the atmosphere. Another is molecular structure. Soil samples that Cory and a graduate student cored from the watershed of a major creek contained more than 2,500 different organic compounds. Twenty percent were found only in permafrost; 30 percent, only in the active layer, with the remainder common to both. The masses of these compounds are known, as are the identities of the atoms that compose them, but not the Tinkertoy-like configurations in which the atoms are arranged.

It's a knowledge gap that bears directly on the question of how much additional carbon will end up in the atmosphere, and Cory and others are racing to fill it. Not all the carbon in permafrost will end up being converted to carbon dioxide. Some of it will be captured by sediments and swept by the Sag and other rivers into the carbon graveyard in the Arctic Ocean. Some of it will prove difficult for microbes and sunlight to break down. "Without knowing the structures of these compounds,

Peering into carbon's future

An open-air experiment in the permafrost zone near Denali simulates a warmer North

STRUGGLING TO KEEP MY BALANCE, I teeter along a narrow plankway that wends through the rolling foothills near Denali National Park and Preserve. Just ahead, Northern Arizona University ecologist Ted Schuur, a lanky 6-footer, leads the way to Eight Mile Lake, his research field site since 2003. Occasionally I slip off the planks onto the squishy vegetative carpet below. The feathery mosses, sedges and diminutive shrubs that grow here — Labrador tea, low bush cranberry, bog rosemary — are well-adapted to wet, acidic soils.

Ted Schuur with his permafrost research monitoring equipment at Eight Mile Lake study area, near Healey, Alaska. Schuur mimics conditions expected in the future to monitor how much carbon will be released in a warmer future Alaska.

Rounding the top of a knoll, we look down on an expanse of tundra that bristles with so many sensors and cables that it resembles an outdoor ICU ward. At the center of the site stands a gas-sensing tower that sniffs out the carbon dioxide drifting through the air from as far away as a quarter of a mile. At ground level, polycarbonate chambers placed atop the tundra *whoosh* as their tops periodically shut, then open, then shut again. Their job, I learn, is to trap the carbon dioxide rising from the surface and shunt it to an instrument that measures the amount.

The objective is to keep a running tally of CO_2 as it's inhaled and exhaled by plants and soil microbes, but not merely in the here and now. By artificially warming selected patches of tundra, Schuur's open-air experiment aims to mimic the future, when air temperatures in Alaska are expected to be significantly higher. By 2100, the state is projected to see an additional warming of at least 4 to 5 degrees Fahrenheit over what's already occurred, and that's under the most optimistic scenario. Already, the tundra here is leaking carbon dioxide to the atmosphere, according to recent satellite-based measurements. The question Schuur is hoping to answer: As the region continues to warm, just how much more carbon dioxide will it contribute to the global pool?

Along with terrestrial and aquatic plants, the soil microbes that decompose organic matter are major players in the global carbon cycle. In the lingo of climate science, plants are "sinks" for carbon. Through the sunlight-driven process of photosynthesis, they lock up more carbon dioxide than they release, thus keeping it out of the atmosphere. By contrast, soil microbes that decompose organic matter are "sources" that burp out micro-bubbles of CO_2 night and day, winter and summer.

Schuur draws my attention to the stack of drift-catching snow fences that, come October, researchers will array around half a dozen experimental plots, then laboriously remove again in April. Snow is an excellent insulator, he explains: "It's like a giant blanket." Beneath the drifts, Schuur and his colleagues have found, the ground can stay a good 3 to 4 degrees Fahrenheit warmer than it does in the unfenced control plots, thereby accelerating the warming that occurs in spring.

The impacts of this manipulation are many. Triggered by the extra warmth, subsidence caused by slumping permafrost has lowered the surface of the experimental plots by several feet. The depth to which the soil thaws at the end of summer has likewise increased, indicating that the top layer of what used to be permafrost has added more organic matter to the microbial dining table.

Most dramatic of all is the speed-up in the carbon cycle that Schuur and his colleagues have observed. Plants in the experimental plots grow faster, and sop up more carbon dioxide, than do plants in the cooler control plots. Soil microbes in the experimental plots have likewise increased their metabolic rate. But plants lock up carbon only during the growing season, whereas microbial activity continues year round. On an annual basis, the CO_2 microbes release more than offsets the amount removed by plants.

Given the present rate of temperature rise, the imbalance between plant uptake and microbial release of CO_2 may well grow. By the end of the century, Schuur says, the amount of carbon the world's permafrost zone transfers to the atmosphere each year could be in the range of 1 billion tons, comparable to the present-day emissions of Germany or Japan.

Still unaccounted for, though, is the significant amount of carbon that appears to have vanished from underlying soils — about 20 times the amount Schuur and his colleagues have detected in the air. "Wow," Schuur remembers saying to himself when he realized the size of the discrepancy. "This is a surprise." Perhaps water seeping downslope is ferrying the missing carbon into streams, rivers and lakes, including Eight Mile Lake, or shunting it to swampy, oxygen-poor pockets of soil ruled by microbes that convert carbon to methane.

How much of the carbon coming out of permafrost will be transformed into methane? That's another question Schuur is starting to tackle, for while methane is less abundant than CO_2, it has 30 times the heat-trapping power over the course of a century. On the way back to the car, Schuur points out a clump of cotton grass whose partly hollow stems pipe methane into the atmosphere. "What matters is not that carbon goes in and out," he says. "The important question is, what's the net effect?" J. MADELEINE NASH

The Trans-Alaska Pipeline crosses the Toolik Lake Research Natural Area on the North Slope. In Alaska, one of the most serious impacts of climate change will be the billions of dollars in damage, already extensive, that thermal erosion deals to infrastructure.

it's impossible to predict how many will get converted to carbon dioxide, and over what time scale," Cory observes. "Is it five seconds or a thousand years?"

LEAVING CORY'S LAB, I head out on the network of boardwalks that lead from the field station to study sites scattered across miles of tundra. In one way or another, most of the scientists who work here are involved in tracking the changes rippling through this region. On either side of the boardwalk, fields of cotton grass prepare to carpet the landscape with silvery seed heads. What will this high-latitude ecosystem look like a century from now? Will cotton grass, Toolik's signature plant, still grow here in such profusion?

The last time our planet confronted such a consequential upheaval was around 12,000 years ago, when the last Ice Age ended in a rolling thunder of warmth. On a geological time scale, the changes that followed were fast — sea levels rose, weather patterns changed, species migrated pole-ward — but measured against the lifetime of an itinerant hunter-gatherer, they would have been all but imperceptible. This time around, the rate of transformation and its impacts on our densely settled planet are becoming obvious within a generation, especially in the Far North, where air temperatures have been rising at a clip of 1 degree Fahrenheit per decade.

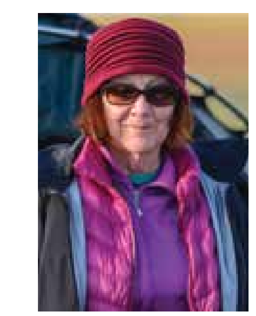
The natural world is now responding in ways that amplify that warming. Dwindling sea ice is changing the color of the Arctic Ocean, uncovering dark blue waters, which absorb solar heat rather than reflect it. The loss of ice is likewise exposing the permafrost-rich coastline, and the remote communities along it, to storms and frenzied waves. In the boreal zone, wildfires stimulated by record heat and drought have burned through millions of acres of trees and released the carbon once locked into wood; they have also turned thick layers of forest duff to ash, ripping away the summer insulation that once protected the permafrost.

The good news, says Northern Arizona University ecologist Ted Schuur, lead investigator for the Permafrost Carbon Network, is that a sudden, catastrophic release of CO_2 from permafrost seems unlikely. The bad news is that a steady, incremental leak is plenty problematic on its own. Under the current warming trajectory, Schuur and his colleagues estimate, between 5 and 15 percent of the carbon stored in the Far North's soils is likely to make it into the atmosphere by the start of the 22nd century.

This might not sound like much, but 15 percent is equal to the jump in atmospheric CO_2 — from 280 to more than 400 parts per million (ppm) — that has occurred since the Industrial Revolution. To avoid courting danger, any additional rise in global mean temperature would wisely be kept below 2 degrees Fahrenheit, according to the Intergovernmental Panel on Climate Change (IPCC). That, in turn, means stabilizing carbon dioxide levels at 450 ppm, leaving little time to dawdle. This is why permafrost carbon is such a wild card. Even a modest release will complicate efforts to step back from the brink. So new is this concern that the global climate models used by the IPCC have not yet factored in permafrost. Likewise, the permafrost models currently under development do not incorporate the potential for rapid, landscape-scale carbon release through thermokarst, which could cause projections to rise. But one thing is clear, says the Permafrost Carbon Network's Schuur: By easing up on the pressure we're placing on the climate system, we can reduce the potential for unpleasant surprises. "The more we push the system, the less control we have," he says.

AS I HEAD BACK DOWN THE HAUL ROAD, the questions that arose at Wolverine Lake seem more pressing than ever. Out the side window, I watch the pipeline track along its 800-mile journey. Late last year, in an attempt to keep the pipeline at full capacity, Alaskan Republican Sens. Lisa Murkowski and Dan Sullivan tacked onto the federal tax bill a provision that opens an ecological gem along the coast — the Arctic National Wildlife Refuge — to oil and natural gas exploitation. Signed into law by President Donald Trump, the bill revives a long-simmering controversy that pits economic interests against potentially enormous environmental costs.

Were it not for the pipeline, and the occasional 18-wheeler lumbering by, I would feel as though I were traveling through an exquisitely rendered scroll painting, marveling at timeless vistas of craggy peaks, rolling hills and jewel-like lakes. The sweep of the terrain invites a sense of permanence, as if things have always been this way, as if they will continue to be this way forever. And, yet beneath the surface, a geophysical dragon is stirring. A penumbra of clouds gathers above the pipeline, casting it into shadow. □



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