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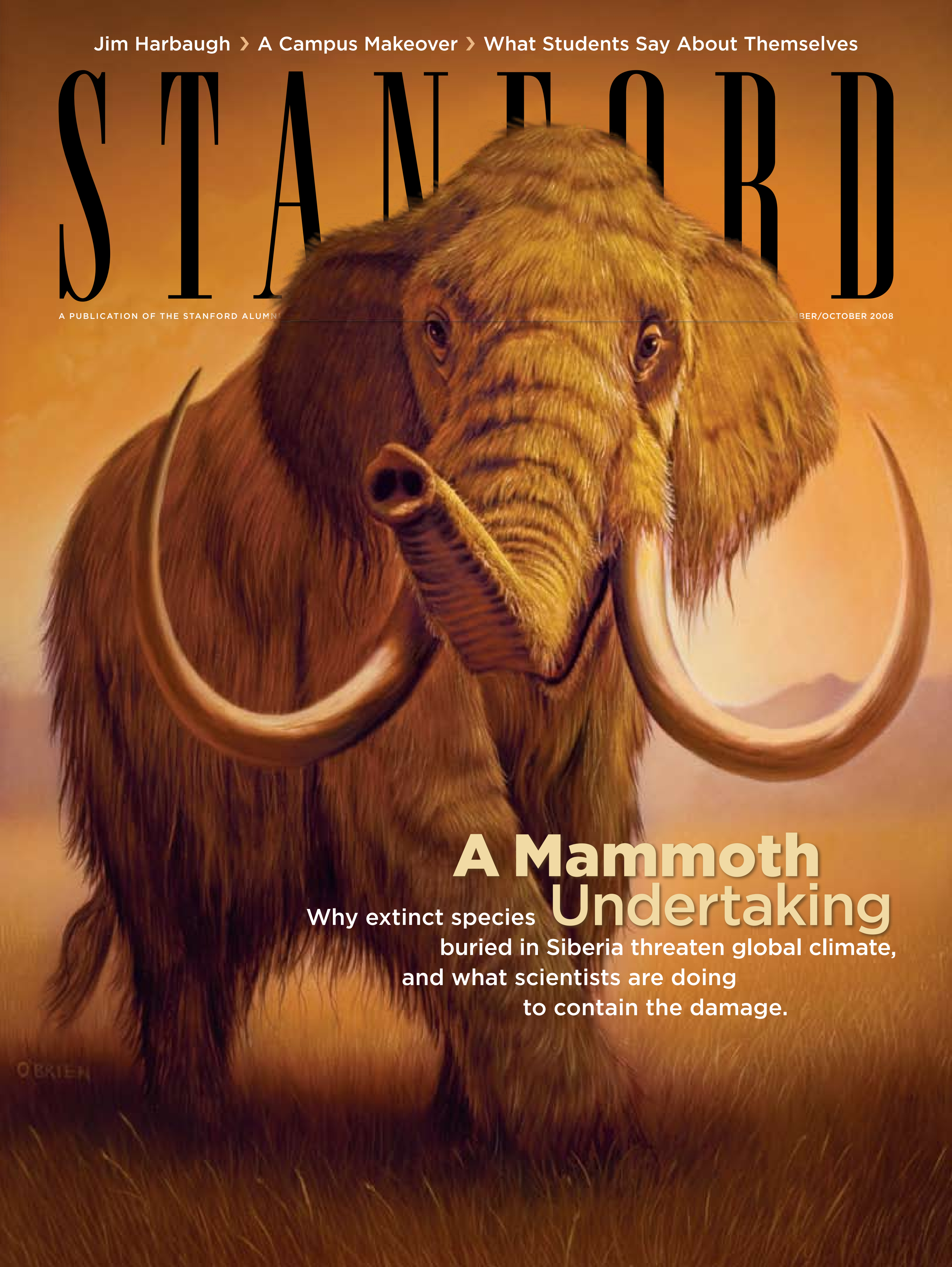
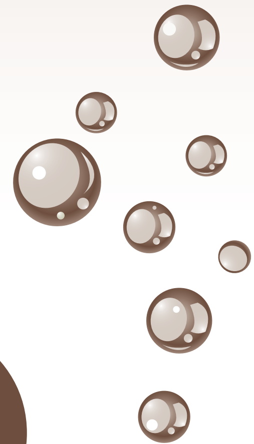


A Mammoth Undertaking

Why extinct species buried in Siberia threaten global climate, and what scientists are doing to contain the damage.



THE Big Thaw

BY ADAM WOLF
ILLUSTRATION BY TIM O'BRIEN

As Siberia's permafrost melts, billions of tons of carbon could escape and heat the planet. Do animals and plants hold a key to Earth's thermostat?


O'BRIEN

IN SOVIET TIMES, Siberia's Kolyma River basin was the destination of enemies of the state. Even today, the Kolyma highway is called the "Road of Bones," because the life expectancy of a prisoner there was just one winter and the bones of the fallen were buried in the road itself. Now, oddly enough, the Kolyma is earning its place in the annals of world history for a mass killing that happened here some 20,000 years earlier. When the prisoners scraped away moss to build the road, they were scraping away insulation keeping the permafrost frozen. In the past decade the underlying ice has vanished, leaving canyons as deep as the trucks that used to pace these roads. And in the canyon walls, mixed with ice and silt, are the bones of deer, horses, oxen, bison, rhinoceros, cave lions and mammoth. Mixed with the bones are hair and dung and skin. Hundreds of centuries since these animals were felled, bugs have found their flesh, and they are going to work. It stinks.

This vast supply of organic matter in the Texas-size Kolyma basin's unique soil, called yedoma, threatens to undermine the very foundations of civilization. Since the beginning of the industrial age, humans have released some 450 billion tons of carbon in fossil fuels, a lapse of judgment or understanding that already commits us to the greatest warming known in the past 55 million years—the last time atmospheric carbon dioxide levels were this high. That warming is catalyzing the collapse of the yedoma carbon bank, whose deposits total 500 billion tons. This carbon is pouring into the atmosphere as I write.

Like all roads in these parts, the Kolyma highway cuts through a larch forest, yellow conifers in fall colors above a thick carpet of moss, lichen and low bushes with berries. In the midst of this tranquil scene is a 20-year-old Toyota Land Cruiser buried in the moguls of mud left behind by the thawed ice, wheels spinning backward, car going nowhere. Sergei Zimov (his last name testifies to a man *of winter*) drove this vehicle from Vladivostok, some 2,000 roadless miles to the south, in the dead of winter. And now we are walking away from this scene, leaving the windows open and the keys in the ignition—Zimov is perhaps the only man in the history of Russian civilization to do that. He calls his son, Nikita, on the satellite phone to bring the other truck and rescue us. Nikita, 23, is the heir to an empire Sergei has built with his wife, Galina, whom he persuaded to settle at the mouth of the Kolyma about 30 years ago.

"From a spark, there ignites fire" is an aphorism attributed to V.I. Lenin, but it well describes life around what is officially the Northeast Science Station, a filial of the Vladivostok branch of the Russian Academy of Sciences. In practice the station is two families, the Zimovs and Sergei and Anya Davydov, who settled in this isolated hamlet of Cherskii more than two decades ago, slowly erecting a scientific powerhouse unmatched in its productivity of high-profile research in contemporary climate change, paleontology, soil science, hydrology, ecology and nearly every branch of the natural world.

In an era when the superabundance of scientific information has forced young scientists to delve into ever more peripheral investigations searching for some untouched territory, there is a place on Earth where two men and two women living in the wilderness have managed by virtue of their own skills at observation and analysis to make fundamental contributions to world science. And the most prominent among them has never touched a computer. Having walked every mile of this isolated landscape by the Arctic Ocean, picking up bones, throwing rocks in lakes, piecing together how this complex mosaic works, Sergei has at last settled on a plan to save civilization. He is building a preserve called Pleistocene Park, a menagerie devoted to the fauna predating civilization, in a bold effort to send us back to the icy epochs when humanity first thrived.

REMAINS TO BE SEEN: Zimov carries a mammoth's femur along the Kolyma River. The science station's original lab is painted fluorescent green to combat winter depression.

MIMI CHAPIN (TOP); ADAM WOLF (BOTTOM)

The big message from the final report of the Nobel-winning Intergovernmental Panel on Climate Change was the asymmetry between those who benefit from fossil fuel use (mostly those of us living in the temperate mid-latitudes) and those unintentionally impacted by the CO_2 that is emitted (mostly poor people in the tropics who live near the rising ocean or whose crops will yield less in a warmer climate). As a kind of corollary to this phenomenon, the CO_2 respired from soils at this very edge of the Arctic mixes through the rest of Earth's atmosphere within a year, incrementally warming the rest of us.

What brings me to Siberia is its place at the center of several contemporary scientific mysteries that have accompanied global warming; there is no substitute for going there and collecting data to put together the different pieces of the puzzle.

INNER SIBERIA (Yakutia) is the most hydrologically isolated territory on Earth. This means nearly all its rain comes from evaporation from land, so it is unusually sensitive to the ecophysiology of plants as they respond to drought, heat and cold stresses. Yakutia is also the coldest place on our planet; if your compass were a magnet of temperature, it would point to Verkhoyansk, the Pole of Cold in eastern Yakutia, which reached minus 90 F (minus 67.8 C) when explorers wintered there in 1885 and has stayed about that cold ever since. As a consequence this region is underlain almost entirely by frozen ground. This geographic peculiarity takes on significance in contemporary climate change, because eastern Siberia has experienced the greatest 20th-century warming on Earth.

Changes here have global consequences. The Arctic Ocean derives most of its fresh water from the giant Siberian rivers Ob, Yenisei, Lena (so great that Lenin named himself after it) and Kolyma. River gauge records that have recently come to light show a marked increase in runoff, the underlying cause of which is still somewhat murky. Because precipitation has not changed substantially in the region, greater runoff is likely to be linked to reductions in plant evaporation, perhaps a consequence of increased atmospheric CO_2. Alternatively, Siberia's forests may be evaporating less because the spring snowmelt is happening too fast for the water to infiltrate. The shift in timing of water availability affects plant productivity and may leave them drought-stressed in the late season, even though the annual supply of water hasn't changed. (California's farmers, dependent on a slow supply of snowmelt for irrigation water, are anticipating that similar changes there will accompany higher temperatures.)

Warming is also implicated in the strong increase in Siberian forest fires that make the air quality in some years worse than Los Angeles. Fires send carbon that is stored in wood into the atmosphere and also reduce the ability of the ecosystem to remove CO_2 from the atmosphere by photosynthesis. Fire weather is a concept used by foresters to combine the effects of temperature, precipitation, humidity and wind into a single metric of "dryness." As a warming Siberia experiences more frequent and intense fire weather, we may see a gradual erosion of the boreal forest carbon storage sink.

The real wild card in Siberia's response to warming is its permafrost, which shapes every facet of the climate, hydrology and ecology. As sophisticated as permafrost science has become in the past century, its models are fundamentally small-scale and purely physical. The important news from Siberia is the key role of the organic matter locked up in permafrost, which threatens to become a "carbon bomb" as the soils warm and start to decay. (See sidebar, page 68.)

Only recently have scientists begun to decipher the key role of plants and ecological processes in the global warming equation. Climatologist Mikhail Budyko first conceptualized an important regulatory role of vegetation in the earth system in the 1960s, but the major models for understanding the aggregate behavior of entire continents of plants have come in the past three decades from the work of plant ecologists Joe Berry and Chris Field of the Carnegie Institution, and Stanford biology professor Hal Mooney.

Unlike physical components of the hydrologic system, such as soils, rivers and air, plants are individual agents making choices on how to exploit scarce resources, among them water, in light of all the other constraints to growth, such as nutrients, CO_2 and the length of the growing season. It is possible to predict much about the responses of plants to their environment if you understand the nature of the various constraints they face.

In much of the world, and in high latitudes particularly, the economy faced by plants is changing in many ways at once. Some constraints are easing just as new limitations are emerging. This is a key reason why the prediction of climate, particularly precipitation, is so challenging.

No one has a good handle on how the land is responding to warming in Siberia, partly because it is so vast, partly because it is geographically and politically inaccessible, and partly because the technique to measure ecosystem-scale photosynthesis and evaporation has only become widely available in the past 15 years. The technique, called eddy covariance,

KAREN MINOT

measures the turbulent eddies that carry heat, water and trace gases. While it is conceptually simple, it is practically challenging. Terry Chapin, who earned his PhD in biological sciences in 1973 under the direction of Mooney, was among the first Western scientists to establish experiments in Russia to directly monitor the interactions between plants and the atmosphere in Siberia's unique larch-tundra ecosystem.

These experiments have been maintained by Sergei Zimov for nearly a decade by diesel and willpower, and they have the potential to break open our understanding of ecosystem-level responses to climate change in the far north. However, the data have been collected from a half dozen sensors on three meteorological towers at 10 times per second for that entire time and have accumulated on a stack of CD-ROMs nearly a yard tall.

This is the firehose of data that I have come to Siberia to sip. You would think it would be easier to send CDs back to the United States to be analyzed, but we hear rumors that Russian customs officials have been confiscating CDs and laptops, causing the loss of untold time and money, not to mention enthusiasm and goodwill. And a bicycle is probably faster than file transfer protocol in Siberia. The best approach to rescuing this data is probably the most sustainable for continued research; I am here to teach micrometeorology to Sergei's son, Nikita, a mathematician trained at Akademgorodok, Russia's brain trust for the physical sciences.

THE SECRET to the station's success is lots of walking and seven months of winter to think about it. Sergei will take you to a lake a short hike from his house and persuade Nikita to trudge around in the brackish water, dislodging bubbles as if from a carbonated pond. Nikita shuffles backward with a washbasin upside-down to catch the fizz he has stirred up, until Sergei asks him to hold still for a moment. Producing a lighter, Sergei starts a torch of methane from the washbasin that lasts more than a minute. We are dumbstruck, until we cheer for more. This is the science you could imagine Calvin and Hobbes conducting, but the methane from this very lake was the topic of the Best Dissertation in Science last year, awarded to Katey Walter, an American student of Sergei's.

SIBERIAN SIGHTS: Wolf, seated center, joins a weekend steamboat cruise to the Pillars of the Lena, a UNESCO world heritage site near Yakutsk that is home to a dozen wood bison from Canada, originally destined for Pleistocene Park.

ADAM WOLF

Walter will make a career out of the fire ignited by this spark, but it is peripheral to a concept Sergei has slowly built since he first arrived. He argues passionately and unceasingly that between the Last Glacial Maximum 20,000 years ago and the closing of the Bering Land Bridge 10,000 years ago—a time and a place known as Beringia—there occurred an abrupt transition in the Earth's ecology and climate that completely severed modern life from the epoch that preceded it, and shapes the world as it is now.

The past 2 million years have been dominated by cycles of glacial and interglacial periods that, taken together, are some of the coolest and driest climates the Earth has experienced. This era is called the Pleistocene. The dryness in older periods led to the evolution of grasses and other plants adapted to dry climates, and these plants came to be widely distributed. The abundance of grasses led to the evolution of herbivores, among them the woolly mammoth, creating an ecological mutual admiration society: the Mammoth Steppe ecosystem. About 10,000 years ago, there came a time when no more mammoths walked the Earth. The demise of that society marks the beginning of the Holocene period, which persists today. Hardly any animals walk here, and in the place of steppe grasses are only larch, moss, blueberry and other flora of the taiga, the vast Eurasian boreal forest.

If you follow the discussion on what possible trajectories global warming might take, the crucial ingredients are: first, how much CO_2 from fossil fuels we are releasing; next, how much the atmosphere will heat from that; and finally, how the land and ocean will react to mitigate or amplify the warming. Few scientists argue that grazing animals make any mark on the global climate, perhaps in deference to a longstanding idea in ecology known as the Green World hypothesis, which notes that despite ravenous insects, burrowing prairie dogs, leaf-eating koalas and trampling elephants, the landscape remains largely green. This suggests that in the timeless struggle between herbivore and herb, the plants have the upper hand, and therefore it is plants that shape terrestrial weather, not animals.

But isolation from computers means isolation from scientific consensus and groupthink. Sergei looks at the bones buried everywhere under this landscape and proposes that those mammoths would have crushed nearly every tree in Beringia, leaving an extensive grassland. Much as we watch with alarm as Arctic sea ice melts and reveals a dark ocean to absorb the sun's rays, the loss of mammoths and consequent northward expansion of forests would have an unambiguous warming effect. In springtime, while grasses lie dormant under a thin blanket of snow, black trunks of trees tower above the surface and absorb the sun's light as it emerges from polar winter. The difference between energy absorbed by trees or energy reflected by snow in those first weeks of spring is what determines the accretion or thaw of permafrost. This is a major reason why land in high latitudes is warming faster than any other place on Earth.

Just as many authors argue that the northward advance of forests is accelerating warming today, Sergei reasonably suggests the corollary: mammoths and other herbivores kept the climate of their day cool.

The mass extinction of the fauna of the Mammoth Steppe—mammoths, bison, horses, rhinos, cave lions, beavers, reindeer, elk, deer and many others—is still a source of active debate between two camps: those who argue that the animals died out and others who argue that human settlers in Beringia slaughtered the animals en masse on their way to North America. Sergei is unreservedly in the latter group: "In America, 500 men with guns killed 50 million buffalo in five years. In Australia, the 23 largest herbivores were extinct in the first century

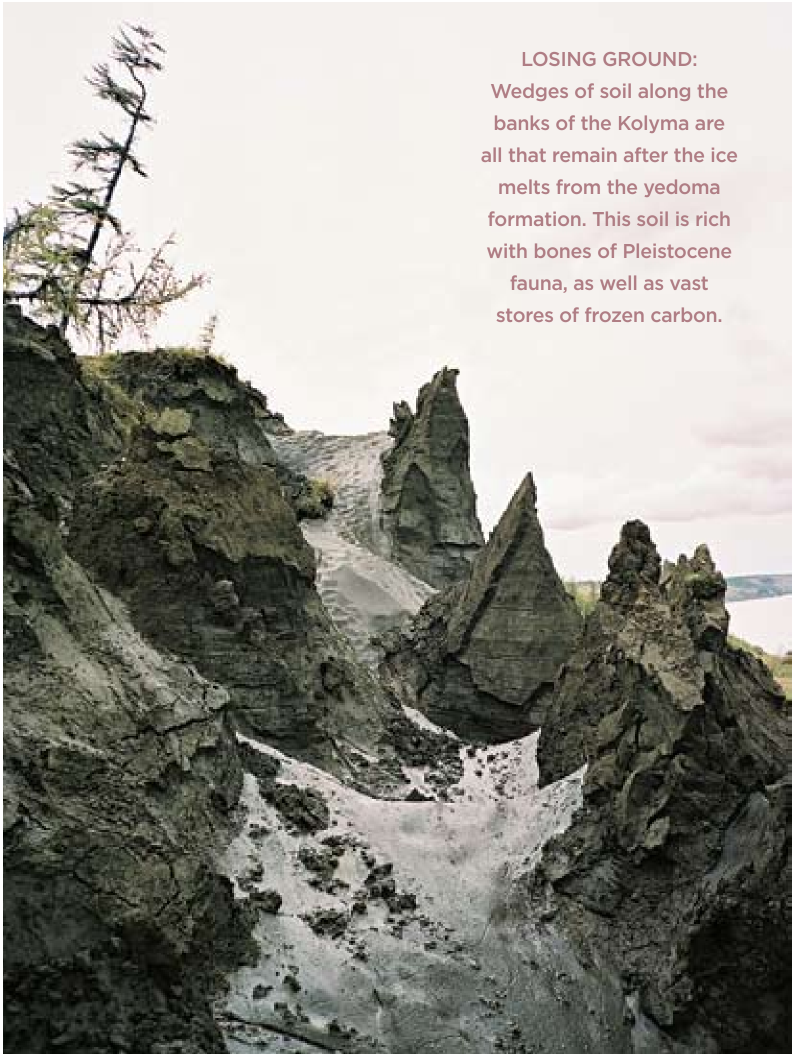
From MAMMOTHS to METHANE

The helicopter ride to Cherskii affords a schematic view of a battlefield where earth, air, water and fire (and fire's inverse, photosynthesis) struggle for supremacy. The field is churned, scarred, pitted—no wonder the study of landforms there has reached its apotheosis. This is a landscape for connoisseurs of form: line, dimension and color and their arrangement with each other all have meaning and give insight into the battle between the elements, both contemporary and ancient. On the horizon is a collection of lakes, thousands of them, all triangular and pointed in the same direction. Below us, adjacent to the Kolyma River, defunct channels form long, narrow oxbow lakes. These eventually drain and give way to long stripes of mosses or trees that reveal the pace of the river's meander. The river itself is the least interesting part of the braided skein.

Most bizarre are the polygons. Like the storming of a citadel, water finds a small chink in the armor of the earth and exploits this crack, expanding it as it freezes so as to allow more water to penetrate after the next year's thaw. This process is amplified over years until the soil becomes filled with ice wedges and it is unfair to still call it soil; it is now an ice-complex, or yedoma. From above, this can look like polygons—quadrangular, hexagonal, with straight sides and distinct corners.

It would appear ice rules this landscape. But no: enter fire. As it burns off the insulating layer of moss, the black soil warms, melting the ice below. In a couple of summers the ground will collapse, one meter, two meters, 10 meters. What was once a tranquil, tussocky but flat landscape is shattered into giant mounds and pits owing to the now-absent ice. Like walking on the beach, any violation of the tranquil surface leaves a wet depression. The wetness absorbs the sun, and warms. The puddle now makes a small pond, now a lake, as the ground below it collapses, and it collects more and more runoff from the surrounding landscape.

As the lake expands and grows deeper, the surrounding landscape starts to melt, collapse into the lake and slide to the bottom. The yedoma sediments are particularly high in organic matter, containing not just soil humus but frozen roots, leaves and bones from tens of thousands of years ago. Once they settle at the bottom of the lake, there is a small family of microbes that makes its meager living exploiting the stored energy in this matter, creating methane in the process. This methane bubbles up from the lake bottom and into the atmosphere, where it is invisible but very effective at trapping the long-wave radiation emitted from Earth. The greenhouse effect heats the world atmosphere. One theory holds that the methane from these lakes is partly responsible for the runaway warming that happens at the end of an ice age, accelerating the melting of permafrost.



LOSING GROUND: Wedges of soil along the banks of the Kolyma are all that remain after the ice melts from the yedoma formation. This soil is rich with bones of Pleistocene fauna, as well as vast stores of frozen carbon.

ADAM WOLF

after humans arrived. What makes you think Siberia is any different?" He perceives great resistance to this idea and has amassed a large arsenal of evidence. He will point out that pollen records show a very productive landscape before, during and after the megafaunal extinction. He will name every climatic zone on Earth where mammoth remains have been found—clearly an adaptable creature.

For Sergei, this means that in principle, there is no reason why mammoths could not exist here now. As he mulls over the warming following the end of the Pleistocene, the contemporary taiga overlaying the frozen roots of a grassland fauna just two feet below, the history of humans and extinction, he wonders: What if driving the mammoth extinct at the end of the Stone Age brought us this warm climate we have today? If we recreated the Mammoth Steppe, could we engineer global cooling?

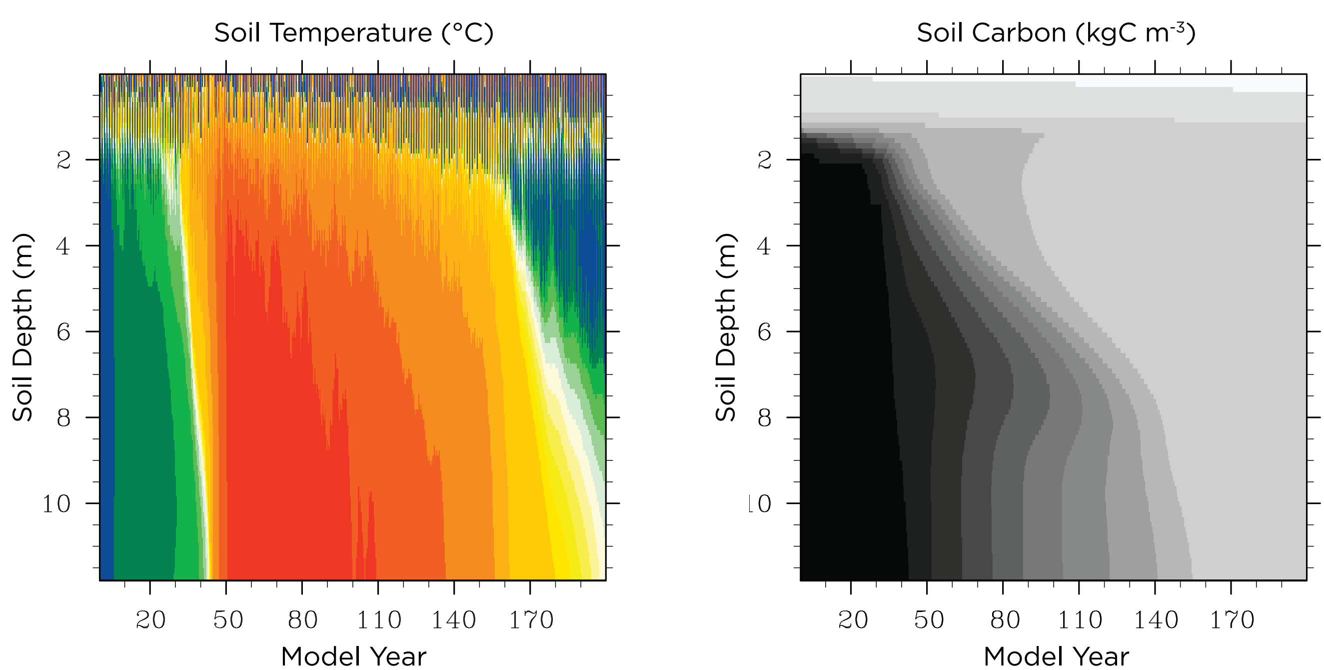
Thus was born Pleistocene Park, a grand scientific experiment to recreate the complex set of interactions between fauna, flora and their physical setting and test whether re-establishing the Mammoth Steppe could alter the direction of the climate system.

Where do you find animals to fill a park devoted to extinct herbivores? The local species of wild horse survived into the modern era, then was finally killed off with the arrival of Russians in the past 300 years. However, Sergei has accumulated a small herd of Yakutian horses, a southern variety that has a two-inch-thick layer of fat on its back to keep it warm through the winter. Although reindeer are nearly extinct locally (and so too the ancient Yukagyr tribe that herded them until recently), some are raised commercially in northern Sweden; Sergei has written to the king to ask for a grant of some reindeer. The original Beringian bison are long gone, but Sergei was given some modern bison (*Bison bison*) by the Canadian government some years back. They have been diverted to a nature preserve close to Yakutsk for now. Musk-oxen? A reserve in Alaska doesn't have many to spare, but the ranger is working to get permission for some export, and maybe they will come next year.

But what about the mammoths? Left to his own devices, Sergei has come up with a pragmatic solution. Approaching the tower he built to monitor the plant

Siberia's 'CARBON BOMB'

Microbial decomposition generates its own heat, a phenomenon Sergei Zimov and colleagues explored in permafrost soils in a 2001 Russian publication. Dmitry Khvorostyanov and Philippe Ciais of the Laboratoire des Sciences du Climat et de l'Environment (LSCE) in Paris recently incorporated this microbial heating effect into a model of the carbon and heat budget of yedoma soils. They found that atmospheric warming can kick-start a microbial engine that thaws the entire frozen soil column tens of meters deep, seen in the left panel as a transition from cool colors to warm colors around model year 30 (the time period represented by the horizontal axis is arbitrary). The heating is fueled by the decomposition of the organic matter in the process, seen in the right panel where soils transition from high soil carbon (black) to low soil carbon (white). Once the organic matter that fuels the microbes is exhausted, the soils freeze again, but with only a fraction of the carbon left. The whole process takes only about 100 years to complete and begins when just 10 percent of the organic matter has decomposed.



physiology of the park, he points to the wrecked underbrush strewn about the path. “Three mammoths came through here, two female mammoths, one child,” he announces. I am bewildered, unable to imagine what it is like to walk around in the present, all the time aware of ghosts of the deep past. He continues: “But today we have no mammoths, so I use a tank.”

Among the assorted vans, Jeeps, boats, ATV, motorcycle, barge, float plane and hovercraft at the station there is a tank. A real tank, with Caterpillar treads. Sergei bought it new in Yakutsk a decade ago and drove it to Cherskii himself, several hundred miles in the dead of winter by dirt road (and, as necessary, overland). It is easy to see where this tank has been: in place of the shrubs and larch surrounding us everywhere there is a trail of succulent brome grass, spontaneously emerging and continuing to thrive several years later. Only after seeing the tank does it begin to dawn on me what life here used to be. Mammoths were the tanks of the former world.

Sergei has a personal collection of mammoth tusks in his home, but even sitting in their shadow around the kitchen table, he makes a strong effort to divert one’s attention from the allure of bones to the layers of grime accumulated around them. The real goldmine, he says, is not the bones, but the black yedoma soil unique to this region. When most of the world was covered in ice at the peak of the Wisconsinan glaciation, eastern Siberia was cold and dry but free of glaciers, permitting the existence of the flora and fauna of the Mammoth Steppe ecosystem. Pollen records and carbon dating testify to the presence of grasses, birch trees and other plant life more characteristic of southern Russia in the present day. These grazing fields supported the wildlife whose bones are found everywhere.

COLD CASE: Zimov and Davydov use small Yakutian horses to fill the ecologic role of extinct herbivores, whose remains are readily collected in Siberia. An intact mammoth tusk might fetch $50,000 in Moscow.

SERGEI ZIMOV (TOP LEFT); ADAM WOLF (2)

The animals had to endure a harsh, continuous wind, because continent-sized glaciers wreak havoc on atmospheric circulation, causing a dramatic increase in the power of cyclones bringing heat north to quell the polar cold. The aftermath of these Pleistocene storms is seen everywhere in the world, from the Palouse hills in eastern Washington state to the extensive loess deposits of Manchuria and Inner Mongolia. In eastern Siberia, the dust settled slowly on top of the grasses, gradually adding millimeters to the surface while being chased by the formation of permafrost a foot below. Tens of thousands of years later the plain is elevated 150 feet or more, a great stockpile of roots and bones frozen in time.

While in some sense Pleistocene Park is an attempt to understand the Mammoth Steppe ecosystem before the age of man, the real mission may as well be to see how restoration of that ecosystem can prevent the runaway warming mankind has never experienced. In the same can-do style that keeps diesel motors running here far beyond their stated longevity, Sergei calculates that 5,000 head of bison shipped from Canada would be enough breeding stock to start a continental-scale effort to restore the Mammoth Steppe and keep 500 billion tons of Pleistocene carbon frozen in permafrost.

At the kitchen table, Sergei considers the current price of CO_2—around $5 per ton at the low end—and reckons his yedoma is worth about $9 trillion on the world market. His greatest asset is that he knows how to keep this carbon locked up: with a tank and some bison. ■

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