

Thousands of tons of mercury are trapped in permafrost

As Earth's frozen soils thaw, they'll have a significant effect on the global mercury cycle.

The brunt of global climate change is being borne by the Arctic, which is warming twice as fast as the planetary average. In a bitter irony, the more the Arctic warms, the more it contributes to climate change. As sea ice shrinks, it reflects less of the Sun's energy back into space. (See the article by Martin Jeffries, James Overland, and Don Perovich, *PHYSICS TODAY*, October 2013, page 35.) And the thawing of previously frozen soils frees up more carbon to be transformed into the greenhouse gases carbon dioxide and methane.

The amount of carbon potentially in play is enormous: more than a trillion tons, the equivalent of more than a century of anthropogenic carbon emissions at the current rate.¹ Not all of that carbon will end up in the atmosphere at once, but if even a fraction of it does, it could have a big effect on climate. An international effort has been under way for decades to quantify and map the carbon content of northern-latitude soils and to understand what happens as the soil warms and thaws.

Piggybacking on that research, the US Geological Survey's Paul Schuster and colleagues have now looked at the related question of how much mercury is stored in permafrost regions.² Mercury enters Arctic soil when it's taken up by plants,³ so where there's organic matter, there's also mercury. Using 13 soil cores collected from geologically diverse sites in northern Alaska (including the one shown being taken in figure 1) and a database of soil organic carbon maps, they deduced that permafrost regions contain a total of 1700 ± 1000 kilotons of mercury, which is around twice as much as all other soils, the ocean, and the atmosphere combined. About half of that mercury is in the permafrost itself, the



subsurface soil that stays frozen year round; the other half is in the overlying active layer, which freezes and thaws seasonally.

Soil on ice

Mercury has always circulated in the environment—it's spewed into the air by volcanoes, for example—but human activity has increased the amount. It's abundant in deposits of metals, their ores, and coal, and it's released when those materials are extracted and used. Humans have been mining metals since ancient times, and particularly significant mercury emissions accompanied the silver and gold mining of the 16th-century

FIGURE 1. PAUL SCHUSTER (LEFT) and John Crawford, both of the US Geological Survey, drill a soil core near Nome Creek, northeast of Fairbanks, Alaska (nowhere near the city of Nome). The core, which extended 112 cm beneath the surface and 55 cm into the permafrost, was one of 13 the researchers used to estimate the mercury content of Northern Hemisphere permafrost regions. (Photo by Seth Spawn, USGS; from ref. 2.)

Spanish colonies and 19th-century North America.

These days anthropogenic mercury emissions amount to some 2 kilotons per year, mostly from coal-fired power plants and small-scale gold mining. The

emissions are mostly in the form of gaseous elemental mercury, whose atmospheric lifetime is 6–12 months. That's long enough for mercury to circulate globally but not for it to accumulate significantly in the atmosphere. Mercury leaves the atmosphere when it falls onto land and water surfaces, and it's taken up by plants when it binds to cellular receptors in place of nutrients such as iron and magnesium. When the plants die, their remains decompose into soil.

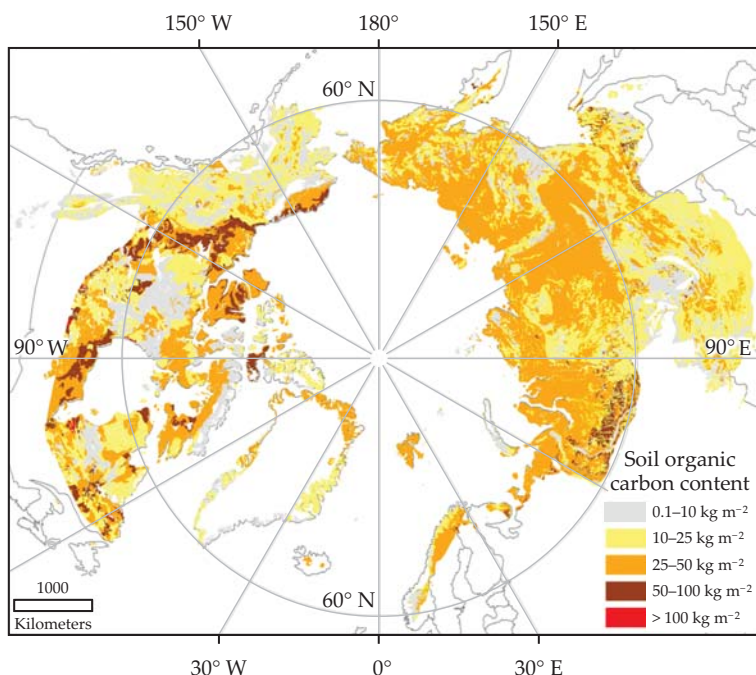
Nonpermafrost soils can store carbon—and mercury—for decades or even centuries through the complex interactions between organic matter and mineral grains (see *PHYSICS TODAY*, March 2014, page 14). But soil microbes steadily break down organic material and transform its constituent elements into forms that can evaporate or wash away.

Permafrost soils have microbes too. Even at subfreezing temperatures, minute drops of liquid water cling to soil particles, and there the microorganisms can carry on with their work. But their activity is slowed to a crawl, and organic material can stay in the frozen soil for tens of millennia. As plants in the active layer push the remains of their predecessors into the frozen strata below, more and more carbon and mercury get locked away.

Now the frozen soils are thawing. As much as 99% of Arctic permafrost could be gone by the end of the century.⁴ And all of its contents are vulnerable to release.

Already happening

Schuster, a hydrologist, has a long-standing interest in mercury in the environment, particularly its effect on water quality in the Yukon River. As he and his USGS colleagues monitored the river from year to year, he began to wonder about the role of permafrost. “How much mercury has been accumulating in frozen soils since the last ice age?” he asked. “What happens if the soils thaw? And can we find evidence that it might already be happening?”



As a first step, he designed a study to assess the total amount of mercury carried by the Yukon and compare it to other rivers whose basins aren't dominated by permafrost.⁵ The results were striking: The Yukon's mercury yield was 6 times the St Lawrence's, 8 times the Mississippi's, and between 3 and 32 times that of every other major river in their comparison.

Suspecting thawing permafrost as the cause, Schuster and colleagues set out to quantify the soil mercury stores. They identified 13 sites that would capture the geological diversity of the permafrost regions. For logistical and political reasons, they limited their sampling to Alaska. “Even if we'd had the funds, getting permits and clearances from places like Siberia would have been next to impossible,” says Schuster, “and it would have greatly delayed the research.”

Even so, the research took years. The project wasn't an officially funded study, and money and resources had to be cobbled together from other work. “And there are the inherent dangers and tribu-

FIGURE 2. SOIL ORGANIC CARBON CONTENT to a depth of 1 m, as compiled in the Northern Circumpolar Soil Carbon Database. Organic carbon content and mercury content are correlated, so the carbon map can be used to estimate mercury content in the same regions. (Adapted from ref. 6, Hugelius et al., 2013.)

lations of working in interior Alaska,” adds Schuster. “We've been shot at, we've been caught between a mother bear and her cubs, and we've been herded into a bucket brigade by Inuit elder women to save their burning church.” The first soil cores were collected in 2004; the last not until 2012.

At each site, the researchers drilled down as far as they could. Usually that was between 1 and 2 meters beneath the surface, where the first 30–50 cm was active layer and the rest was permafrost. They cut each core into slices, for a total of 588 samples, and measured the mercury and organic carbon per gram of soil in each. For six of the cores, they also performed carbon-14 dating on each slice:



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The oldest of those samples, they found, had been in the frozen ground for an astonishing 23 000 years.

Although the mercury-carbon ratio naturally varied from sample to sample, mercury and carbon content were clearly correlated. Importantly, even though environmental mercury levels have increased over time, the researchers found no correlation between the mercury-carbon ratio and either soil depth or soil age. For any permafrost region, the researchers concluded, the soil's carbon con-

tent multiplied by the average mercury-carbon ratio, $1.6 \pm 0.9 \mu\text{g}$ of mercury per gram of carbon, gives an estimate of the mercury content.

For an estimate of the region's carbon stores, Schuster and colleagues used the Northern Circumpolar Soil Carbon Database, compiled by Stockholm University's Gustaf Hugelius and colleagues and based on decades of soil map data across the Northern Hemisphere.⁶ Figure 2 shows the carbon content for the first meter below the surface; the database

also includes data down to 3 m depth and for permafrost and active-layer soils. From the carbon data, Schuster and colleagues derived their estimate that permafrost regions contain 1700 ± 1000 kilotons of mercury, split roughly equally between the active layer and underlying permafrost.

To put that number in context, all other soils on Earth contain about 450 kilotons of mercury (the average of published estimates, which range from 235 to 1000 kilotons), the oceans contain some 350 kilotons, the atmosphere 5 kilotons, and the biosphere 10 kilotons. Even at the low end of Schuster and colleagues' estimate, permafrost regions represent a considerable mercury reservoir.

Uncertainties

Knowing how much mercury is there doesn't answer the question of what will happen to it. Permafrost is thawing, but at a rate that's difficult to determine. And even if most of the permafrost releases its mercury in the coming decades, how much harm is done to humans and wildlife depends on the mercury's chemical form. Elemental and ionic mercury are relatively benign compared with methylmercury, the potent neurotoxin that accumulates in fish. Methylmercury is synthesized by bacteria in anaerobic environments; to what extent those conditions will prevail depends on a complex and subtle interplay of biological, geological, and chemical processes.

For their part, Schuster and colleagues are working to better pin down the size of the permafrost mercury store. They're collaborating with researchers in Europe to collect and process soil cores from Norway, Russia, Sweden, and elsewhere. They're also working on models to better predict the timing, location, and amount of mercury release over the next century.

Johanna Miller

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