Permafrost Carbon

What soil science has to say about its distribution and fate

by Madeline Fisher
restoration amid the lab’s star projects in energy, supercomputing, and nuclear physics. Then a few years back, the Department of Energy took notice of her skill at measuring soil carbon and asked her to apply it in a new direction. Jastrow didn’t entirely welcome the change, thinking of all the loose ends that needed tying up on existing projects.

She’s over that now.

“I think, ‘Forget about that other stuff—well, maybe not completely,’” she jokes. “But this is really cool.”

Jastrow’s new passion is permafrost soil carbon, a subject that’s getting enormous attention today thanks to mounting concerns about climate change. According to recent estimates, some 1,300 billion tons of carbon are stored in the perpetually frozen soils of the circumpolar regions and some alpine areas. That’s about a third of all the terrestrial carbon in the world, soil and vegetation included. It’s also at least 1.5 times the carbon currently present in the atmosphere.

In the meantime, there is growing evidence that permafrost is warming, and warming quickly, leading to increasing focus on a key question. “How can we predict, given the current warming and projected warming, how much of that [stored] carbon will go back into the atmosphere as carbon dioxide and methane,” says Jim Bockheim, an SSSA member at the University of Wisconsin–Madison who has researched frozen soils for as long as Jastrow has worked at Argonne, “and act as a positive feedback on climate change?”

Answering this begins with knowing how much carbon is in permafrost to begin with. But acquiring reliable numbers at local and regional scales has been tough, helping explain why researchers from other fields, like Jastrow, are now pitching in. One reason for the uncertainty is that permafrost soils are woefully undersampled compared with soils in other regions. And when they are sampled, accurately capturing their properties is hampered by their huge spatial variability. One soil sample may contain 30 to 40% carbon, Jastrow explains, while another taken just a foot away may be 5%. “It’s unreal,” she says.

Yet another reason is that for years permafrost wasn’t investigated much—except by a few like Bockheim and SSSA Fellow Chien-Lu Ping of the University of Alaska–Fairbanks, who bucked their departments’ traditions early on of studying agricultural soils.

Jastrow often pondered this as she and her Argonne colleagues embarked on a permafrost carbon project in 2012 with Ping, Gary Michaelson, and other giants in the field. “I thought who are we to approach people like Chien-Lu, who has been working in this area forever, and say, ‘We’re here to improve the estimates of soil carbon stocks in the Arctic?’” Jastrow says with a laugh. But like her initial worries about making a late-career research shift, she’s since put those fears to rest.

“Everywhere you turn, people are interested in how they can help each other,” she says. “There’s just so much to be learned and so much to do.”

Accounting for Cryoturbation

Most people think of carbon storage in permafrost strictly as the balance between plant photosynthesis and soil respiration: When cold and water-logging slow respiration, soil carbon builds, and when permafrost warms and microbes grow more active, carbon reserves shrink. What’s surprising is that today’s permafrost carbon models employ...
the same simple accounting, but this doesn’t capture the full picture, Ping says. The other crucial influence is cryo-
turbation: the mixing and churning of permafrost soil that comes with repeated cycles of freezing and thawing.

In Arctic tundra soils that aren’t cryoturbated, Ping explains, most of the carbon resides in the upper layers: the O (organic) horizon and the horizon directly below—as you would expect to see in temperate soils. But in the 60% or more of tundra soils that do experience cryoturbation, the process constantly moves organic matter downward where it’s preserved by cold.

As a result, significant amounts of surface-derived carbon are stored at depth in permafrost-affected soils, leading to an intriguing question. If a warmer Arctic causes more thawing, more churning of soil, and more transport of carbon to depth, could this counteract somewhat the impact of faster decompo-
sition rates? Bockheim, who investigated this some in the late 2000s, thinks it’s possible. “I’m not saying that warming isn’t an issue, because it is,” he says. “But we need to give some thought to the [carbon] sink that’s induced by cryoturbation.”

“In the past decades, there has been a lot of empha-
sis on carbon flux,” agrees Ping, “but less emphasis on understanding soil processes and how the soil evolved.” Another example: Large areas of permafrost in northern Siberia, Interior Alaska, and the Yukon Territory of Canada originated as windblown, loess deposits during the Pleisto-
cene—long before the era of modern tundra vegetation. As a result, these “Yedoma” deposits contain significant stocks of ancient carbon that confound present-day models.

“The models are changing,” Jastrow says. “But as they exist right now they don’t do a good job of simulating the processes that stored carbon in those soils because they’re not like the processes anywhere else in the world.”

One goal of the project she now directs is to improve estimates of permafrost carbon stocks by using geospatial modeling methods that factor in the soil-forming factors. Led by Umakant Mishra, an ASA, CSSA, and SSSA member at Argonne, the effort employs LIDAR-based, high-resolution digital elevation models (DEMs) to represent micro-
topography, for example. Remotely sensed land cover data get at the impacts of vegetation. And long-term climate da-
tasets provide numbers on temperature and precipitation.

This information on soil-forming processes is then combined with actual soil measurements to predict and map how carbon is distributed across the landscape. Different field data are later used to validate the model calculations. Such maps have obviously been made before. But geospa-
tial techniques deliver much finer spatial predictions than are possible with older approaches and traditional soil sur-
vey information, Jastrow says. “In fact, if NRCS were going to create a new soil map for southern Illinois, they would probably take a similar approach to what we’re trying to do”—with one critical difference.

“They’re going to have much better observational data to put into their geospatial models.”

“There has been a lot of emphasis on carbon flux [from permafrost], but less on understanding soil processes and how the soil evolved.” —Chien-Lu Ping
Smart Sampling to Get a Better Picture of Carbon Amount, Distribution

Gary Michaelson—a permafrost carbon expert who is Ping’s colleague at the University of Alaska—has some numbers to back Jastrow’s statement. Based on whole-pedon data taken from the USDA-NRCS National Soils Database, he estimates that slightly more than 59,000 pedons have been sampled today in the United States minus Alaska—an area of 3,142,700 mi². In Alaska, in contrast, the number is just 706 pedons across 663,300 mi².

Put another way, that’s one soil sample per 52 mi² in the United States minus Alaska, versus one for every 940 mi² in Alaska. But even this is a bit misleading because the Alaskan soils data are far from evenly distributed. Many soil measurements parallel the Dalton Highway—the pipeline service road connecting Prudhoe Bay’s oil fields with Fairbanks to the south. Or they follow the Alaska Highway between Fairbanks and Anchorage. They’re peppered about major research sites, such as the Toolik Field Station. And upland areas have been surveyed more than lowlands.

By and large, though, soil maps of Alaska’s (and the world’s) permafrost regions are still awash in blank space.

Sampling permafrost soils also isn’t straightforward, adds Ping, who for two decades has led a yearly Alaskan field course aimed at driving this point home. Thanks to cryoturbation, their horizons are warped and discontinuous, he explains, rendering standard methods of sampling at 0 to 5 cm, 5 to 10 cm, and so on, virtually useless. “I’ve done most of my work here in Illinois and in Tennessee with soil cores. But up there, you have to dig pits,” agrees Jastrow. “And they have to be good-sized pits to really get a feeling for the variability and to guide your measurements.”

To better benchmark its regional and global models, the Argonne group was initially interested in filling the voids in the world’s permafrost carbon maps with new measurements. But when they realized how remote and inaccessible most permafrost was, they settled on a two-pronged alternative. They would exploit existing data and samples as much as possible and then concentrate on select locations for new data collection.

After much discussion, they’re now sampling regions typified by “ice-wedge polygons.” These features form where contraction of surface soils with freezing and thawing creates a net of giant cracks; the cracks then feed water each summer into expanding wedges of ice in the permafrost below. They’re attractive targets for two reasons, Jastrow says. The polygons are a prevailing feature of flat, cryoturbated lowlands, where some of the greatest uncertainties in soil carbon estimates lie. And they’re easily spotted in satellite photos and other remote-sensing images. Even the different polygon types—flat, low-, and high-centered—can be distinguished from the air.

Led by Ping, the team is now measuring soil carbon in all three types, taking care to sample the cracks as well as the centers. The group is also examining them in locations with different parent materials and soils across Alaska’s North Slope: Along the Dalton Highway; near Barrow, AK, amid a huge concentration of “thaw-lakes”; and, this season, in the central Coastal Plain, where younger polygons dominate.

Once it has the new numbers, the group will marry them with remote-sensing images, begin extrapolating the results over wider areas—and hopefully lessen some of the ambiguity surrounding the amount and distribution of carbon in these immense lowlands.

Even then, another major question remains. “In the Arctic, the carbon in the soil is more than the carbon in the atmosphere, okay?” Ping says. “But is all of that carbon equally decomposable? The answer is probably not based on work we did earlier on the quality of soil organic matter. And therefore the feedback process [to the atmosphere] will be different.”

Using FTIR/MidIR to Determine Carbon Content, Chemical Makeup

The person enlisted to address this problem of carbon chemistry, quality, and decomposability is Francisco Calderón—a USDA-ARS soil scientist who, like Jastrow, is a newcomer to permafrost research. Calderón started his scientific career studying mycorrhizae and gas fluxes from soil.

Aerial photo of a region of ice-wedge polygons along the Alaska coast of the Arctic Ocean in August 2005. Photo by Gary Michaelson.
Soil formation and carbon chemistry aren’t the only factors to have been overgeneralized and underestimated as scientists work to predict greenhouse gas emissions from thawing permafrost. The actions of microbes—the agents that actually convert organic matter into carbon dioxide and methane—are often oversimplified, as well.

Microbial groups and species have frequently been dismissed as wholly interchangeable. Or their activity is likened to the flipping of a switch, says Jessica Ernakovich, a postdoc in soil microbiology at CSIRO in Australia. One storyline, for example, is that when temperatures rise above freezing, bacteria and fungi attack carbon, and when the mercury dips below zero, microbial activity ceases.

Ernakovich knows better, and her research embraces complexity at every turn. Most insights into permafrost microbes have so far come from experiments on bacteria isolated in test tubes and Petri plates, for instance. She instead conducts incubations with entire communities in intact sections of permafrost, and employs gene sequencing rather than culturing to document the various bacterial groups and species.

During her Ph.D. at Colorado State University, Ernakovich recruited USDA-ARS scientist Francisco Calderón to detail permafrost carbon chemistry with mid-infrared spectroscopy. And she measured microbial biomass carbon, enzymes, and “a ton” of other variables to up her chances of finding the key predictors of methane and carbon fluxes, she says.

The insight she’s most proud of, though, came during her first season in the Arctic. As she helped a colleague reach down and pull up sections of the active layer sitting atop permafrost, “it sounds kind of silly,” Ernakovich says, “but I realized my hands were really, really cold.”

It got her thinking about the temperature people typically target in incubation studies: 15°C. Was this low enough to truly understand how microbial processes will work in thawing—but still icy cold—permafrost? She later opted for incubations both at 15 and 1°C, the latter designed to see how carbon degrades “at these really low, in situ thaw temperatures,” she says.

One important finding of her work is that methane production in permafrost is not a binary, on-off process dictated solely by temperature and a switch to anoxic conditions. What she, Calderón, and her Ph.D. adviser Matt Wallenstein observed is that methane flux also depends on the type of permafrost carbon present (labile substrates, in this case) and on other anaerobic microbes.

Ernakovich explains that when iron-reducing bacteria, sulfate reducers, and other anaerobes higher on the “redox ladder” are active, they likely out-compete methanogenic bacteria for the substrates needed to make energy. Only after these competitors deplete soil of their preferred electron acceptors and shut down are methanogens free to do their thing.

This “textbook” phenomenon is well known in wetlands and other ecosystems with anoxic soils, she says, although the permafrost research community has yet to incorporate the concept into its thinking. But this is changing. “I’m starting to work with modelers to see if we can add some of this nuance into the permafrost models,” Ernakovich says.

Or should such intricacies be included, she asks? Perhaps it’s okay to gloss over some of the details when creating global models. Either way, Ernakovich believes the complexity that really matters today is the web of new connections being woven among disciplines. “I think we’re in a good spot,” she says, “to figure out more of what’s going on up there.”

Jessica Ernakovich heading out to sample permafrost soils at Sagwon Hills, AK, in August 2009. Photo by Shawna McMahon
Then he was introduced as a postdoc to Fourier-transform mid-infrared spectroscopy (FTIR or MidIR spectroscopy) and never looked back. The ASA and SSSA member is now a leading expert in using MidIR to quickly determine not only the total carbon content of soil, but—more importantly—the chemical makeup of that carbon. Most of his work has concerned agricultural systems, but he didn’t hesitate when Jastrow contacted him about joining the Argonne project.

“All the things that I had been studying through the years—gas fluxes and all of that—gain so much more global significance when you’re looking at permafrost,” Calderón says.

As with all soils, some of the carbon in permafrost will break down quickly upon thawing, some will resist degradation, and some will fall in between. Clearly, the truest test of this is to incubate a sample and decompose it, and the group is doing some of this. But incubation studies can take months or years, not to mention a lot of soil. “We don’t have that, so we need proxies,” Calderón says. “And FTIR measurements might be that.”

The method works by hitting a soil sample with mid-infrared light, some of which is absorbed by the various chemical bonds within soil organic matter, and some of which is reflected. The resulting spectrum of absorbance bands offers a profile, or fingerprint, of the sample’s carbon chemistry, including its complement of labile fatty acids or carbohydrates, and more degraded forms, such as humified material.

While interpreting the spectral data is no simple task, FTIR spectroscopy is extremely fast and non-destructive and produces reliable data from soil volumes as small as dime. Those are great advantages for a project that’s now acquiring or borrowing permafrost soil samples from all over the world, including sites in Siberia, Greenland, and Canada. Researchers have been very willing to share, Jastrow says. But after completing their own analyses, they often can’t offer much—maybe just a pinch or two of soil at the bottom of a vial.

“You cannot really do much with that in terms of wet chemistry,” Calderón says. “But you can do FTIR.”

A recent example of what FTIR can do appeared in the May–June 2015 issue of the Soil Science Society of America Journal (see http://bit.ly/1KnoJ4). Working with permafrost researchers Jessica Ernakovich and Matthew Wahlenstein at Colorado State University, Calderón used FTIR to characterize the soil organic matter in three layers of an Alaskan permafrost soil profile: the organic mat at the top of the “active layer,” which thaws each summer; the mineral active layer directly below; and the deeper, constantly frozen permafrost.

Not surprisingly, each layer had a distinct chemistry, Calderón says. But the organic active layer and top of the permafrost were the most similar, implying two things. “Newer,” less decomposed organic matter from the surface is being moved downward by cryoturbation. And the presence of this fresher, more labile material in the permafrost’s top layer suggests this layer will break down rapidly upon thawing.

These findings aren’t “terribly new” in the world of permafrost research, says Ernakovich, now a postdoc at CSIRO in Australia. However, their close mirroring of past results is positive, offering more evidence that FTIR can be used with confidence to evaluate permafrost carbon chemistry and decomposability. Argonne is now building a database of FTIR spectra for permafrost soils while simultaneously figuring out how best to interpret the data. The eventual goal is to add the information to permafrost soil carbon maps and further refine soil carbon models, Jastrow says.

“Eventual” is the key word: Meeting this particular objective is several years off, she estimates. Still, there’s likely no better time to be striving for rapid progress on permafrost. Not only are permafrost scientists worldwide connecting and collaborating as never before, but all sorts of expertise and technology are being leveraged now. Besides geospatial modeling and FTIR, Ernakovich and Jastrow think that information on soil carbon stabilization from other systems could be handy. And Ping sees the potential for soil fertility models—honed by agricultural scientists over decades—to inform questions of decomposability.

If warming continues apace, parts of Alaska may in fact become America’s new breadbasket, Ping adds only half-jokingly—making all sorts of ag research relevant. Gone are the days, in other words, when scientists like he and Bockheim had to justify their fascination with permafrost to colleagues.

“I think even for people with an agricultural mind this is interesting, and it has some feedbacks that may be important for agriculture worldwide,” Calderón says. “So we should all be learning about this stuff. No doubt about it.”

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An excavated permafrost soil showing dramatic evidence of cryoturbation. Photo courtesy of Julie Jastrow.