Prototype uses light to gauge composition, density of subsoils

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Nuwan Wijewardane, postdoctoral researcher in biological systems engineering, prepares to hydraulically plunge a penetrometer prototype into soil. Credit: Greg Nathan | University Communication

On the surface, it resembles a stainless steel spear, roughly 6 feet long with a silver-dollar diameter that ends in a 30-degree point.

But that point—the entire point of the aptly named penetrometer—is about delving beneath the surface, where it can shine some visible and near-infrared light on the agriculturally and environmentally vital properties of the subsoil lying beneath topsoil.

By characterizing that subsoil on the fly and in the field, University of Nebraska–Lincoln engineers Yufeng Ge and Nuwan Wijewardane believe the prototype could emerge as a time- and cost-saving tool that informs precise irrigation and fertilizer application. And they envision it allowing more farmers to participate in a burgeoning, climate-friendly marketplace that incentivizes farmers to capture carbon in their soils.

That potential stems from a simple principle: All substances, including the organic matter and minerals present in soil, reflect light differently. More to the point, every substance reflects different wavelengths of light, including the visible and near-infrared regions of the electromagnetic spectrum.

Knowing that, Ge, Wijewardane and their colleagues embedded the prototype with a broad-spectrum halogen light that pours through a quartz aperture, nestling it below a parabolic mirror and fiber-optic cable that collect whatever wavelengths bounce back.

Another device, connected to the penetrometer, then measures the intensity of about 2,100 different wavelengths across the visible and near-infrared spectra. The intensities of certain wavelengths in that spectral signature correlate with the presence of certain substances and types of soils. Carbon- and nitrogen-rich organic matter, for instance, contributes to darker soils that reflect relatively few visible wavelengths. Soils with less organic matter or lots of iron, by contrast, will often reflect yellows or reds.

After being hydraulically plunged several feet into a given patch of soil, the prototype can take spectral readings from every 1-inch cross-section that resides between the prototype's tip and the soil's surface. The five- to eight-minute process eliminates the need to dig soil pits or extract soil cores, which are traditionally sent to the lab for costly analyses that can take weeks yet still examine far fewer cross-sections.

Ge said the prototype also represents an improvement over most portable soil-sensing technologies, which typically take readings no more than 6 inches deep.

"That's OK, because that topsoil is the most significant," said Ge, associate professor of biological systems engineering. "But if you look at something like the corn production system, the roots go deep. For some properties, like water uptake or nutrient uptake by a crop, the surface level of soil is just part of the story. You really want to consider the entire root zone."

The team, which includes Cristine Morgan of the Soil Health Institute, Jason Ackerson of Purdue University and Sarah Hetrick of Texas A&M University, wasn't satisfied with estimating just the composition of subsoil. The researchers wanted their prototype to measure how tightly packed the soil is, too, as a means of discerning how well that soil might retain water and share it with crops. So they included a force-measuring load cell near the prototype's tip, along with an ultrasonic sensor that measures how deeply the prototype has delved, to estimate the soil's density.

"The texture really determines the water-holding capacity," Ge said. "If you have too sandy of soil, it just moves through the root zone very quickly. But if you have a too clay(-like) soil, it's going to hold the water very tightly, and the roots can't fully extract it."

With the prototype built, the researchers sought to compare its spectral signatures with a library of about 20,000 signatures that the U.S.

Department of Agriculture collected from soil samples throughout the country. Because the USDA also reported the actual concentrations of carbon and certain minerals in those samples, comparing the new signatures against the USDA's would allow the team to better calibrate the model it was using to estimate concentrations in its own samples.

There was, naturally, just one problem. The USDA had collected its spectral signatures after drying its soil samples in the lab, meaning that they contained none of the moisture that virtually all field samples do. And given that water interacts with light, the lab-drying seriously altered those signatures.

Fortunately, an existing algorithm helped the researchers minimize the statistical noise drummed up by the water, transforming their spectral signatures into a form that more closely approximated the USDA's. To test its corrections, the team took readings from 11 total fields across Nebraska, Illinois, Iowa and South Dakota. As expected, the team found that the prototype's estimates of carbon and nitrogen levels hewed closer to actual levels after applying the algorithm than they did before.

A readout of spectral signatures produced by the team's prototype, which collects the visible and near-infrared wavelengths that bounce back from soils. Credit: Greg Nathan | University Communication

Guiding light

While conceding that the prototype's accuracy could stand to improve—and that he expects it to—Ge said that even the current version might aid farmers looking to use irrigation and fertilizer more strategically.

Most forms of precision agriculture, Ge said, involve dividing a field into a grid and sampling the soil from a certain number of its cells. The relative expense of lab-based measurements might limit that number, he said, making in-the-field estimates of subsoil composition an appealing alternative on a hypothetical farm of 160 acres.

"Let's say you have the resources to go out and collect five very accurate measurements," Ge said. "You take the average, and you get the standard deviation, and you think, 'Well, that's the mean and variance for the sample of soils in that field.'

"I would disagree with that sort of mentality, because I would argue (that) five isn't enough. No matter how carefully you place those five locations, you're not going to capture the entire view of the field. My argument would be: You really have to do this many times. Even though your measurements may not be as accurate as a lab-based measurement, you can still get a really good estimate and potentially be more useful than the first scenario."

Ge expressed just as much enthusiasm for a less-obvious but promising application of the prototype—carbon sequestration—that could ultimately help farmers diversify their revenue streams while addressing the leading cause of global warming. The world's soils stash more than three times the amount of carbon that currently resides in the atmosphere, even as atmospheric carbon dioxide has reached levels unseen in the last 3 million years.

In 2019, an agricultural technology startup named Indigo Agriculture launched an initiative that offers money to farmers who engage in practices—planting cover crops, rotating crops, limiting tillage—that encourage soils to capture and store the carbon left over when crop roots and leaves begin decaying.

"That is additional income for the farm economy," Ge said. "I don't think that we have figured everything out yet, because you have to verify that you have actually sequestered that carbon on the farm. And that's why measurement becomes really important."

Though the team would first need to up the accuracy of its prototype's carbon estimates, Ge said he sees the design as a cost-effective way of helping farmers verify the success of those sequestration efforts.

"I really think that this technology can get a foothold in that carbon market," said Ge, who cited some initial interest from General Mills. "We have been talking about this for a long time. I'm hoping that, in a few years, this can expand to a much larger scale—to the point of providing additional income for a farm—and people can realize the importance of being able to manage soil in a way that it can store this carbon."

In the meantime, Ge and Wijewardane are examining whether it's possible to shrink the diameter of their prototype, which could make it more feasible for users to ditch the hydraulics and manually plunge the penetrometer into subsoils.

At its current diameter, embedding the prototype into harder soils can require 300 to 400 pounds of force, Ge said. But in much the same way that focusing light to a smaller point increases its intensity, reducing the contact area between two surfaces will increase pressure even when the same force is applied.

"Further reducing that diameter means having an even smaller space to work with (for the instrumentation)," Ge said. "So we are facing a lot of engineering challenges, for sure. But challenges are what we, as engineers, live to address."

Provided by University of Nebraska-Lincoln