Cover story

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Carbon farming gets off the ground

Replenishing depleted soil can combat climate change—if science, policy, and markets align

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Courtesy of Full Circle Mushroom Compost

CREDIT: OREGON STATE UNIVERSITY

Kelly Garrett has an audacious goal for his farm this season. "I want to set the state record for corn in Iowa, and I want to do it in a sustainable way," he says. That means harvesting more than 442 bushels per acre (27,742 kg per hectare), the record set in 2002 by Francis Childs.

Garrett, a self-described extreme farmer, sounds confident in his chances. He is the seventh generation in his family to grow corn and graze cattle in western Iowa. "Everything we do is important," he says. But when it comes to huge corn yields, there is one crucial element: carbon.

Garrett says his farming methods accomplish two laudable goals at once: they remove carbon dioxide from the atmosphere, and they use the carbon to build healthy soil. "Everyone needs to understand that carbon is energy to the soil," he says. "The more carbon you can put in the soil, the more your plants can become. We need to put carbon in our soil to improve our yields and to make the world a better place. We need to put as much carbon in the soil as we can to improve our bottom line."

The idea that farmers can capture carbon and improve their bottom lines at the same time is gaining ground in the agriculture community and among business leaders and policy makers. They would like to pay farmers for adopting practices, such as using cover crops and low-till methods, that take carbon from the atmosphere and store it, presumably for centuries, in the soil. Large-scale adoption of so-called carbon farming, proponents say, can transform the industry from a greenhouse gas emitter to a global carbon absorber.

One way farmers can get paid is to sell carbon credits for each metric ton of carbon dioxide equivalent they sequester. Private marketplaces for those credits are popping up now, and while their methodologies for verifying carbon practices and certifying credits appear robust, they are not all the same.

The Biden-Harris administration has directed the US Department of Agriculture to help farmers adopt practices that sequester carbon. And in the Senate, the bipartisan Growing Climate Solutions Act would enable the USDA to standardize private carbon credit markets and certify third-party verifiers to boost farmers' confidence in the schemes. The European Commission is crafting similar farm supports and plans to launch a verified carbon market this year for the European Union.

But opinions vary in the farm and environmental communities about the best ways to help growers transition to climate-smart practices. Some experts say focusing just on carbon credits takes too narrow a view of soil health practices, while others fear the programs will benefit only large landowners. Meanwhile, scientists are still researching the mechanisms of soil carbon sequestration, including how much carbon can be stored, for how long, and how to measure it.

As one of the first farmers in the US to sell carbon credits, Garrett acknowledges that not everyone is on board. "There's a lot of skepticism out there," he says.

In brief

Can the world's food producers help combat climate change? Experts in soil health say yes, and some farmers are already getting paid to do that. They grow crops that take in carbon dioxide from the atmosphere and store it in the ground in the form of organic matter. But in most croplands and pastures, the organic matter has been used up or washed away, leaving the soil depleted. That makes today's agriculture industry a greenhouse gas emitter. When growers stop plowing fields and turn instead to practices like growing cover crops, they can store atmospheric carbon in their soil for centuries. Read on for a look at the market for agricultural carbon credits, a new way that companies and governments plan to reward farmers for taking on the climate challenge.

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How carbon programs work

For hundreds of years, farmers have cultivated lands that provided fertility, in the form of soil organic matter, to their crops. Much of that organic matter originated from the lands' original cover of forests or native grasslands. But over the generations, a large fraction of that organic matter washed or blew away.

These days, most agricultural soil is considered degraded. Crops still grow because farmers supply them with fertilizers and water and protect them with pesticides.

It costs farmers a lot of money to raise crops and animals on degraded soil. But scientists say that soil is an opportunity wearing a dusty disguise. Farmers and ranchers can build back their soil by adding organic matter. Made up of decaying plants and the bodies of soil microbes, that organic matter can trap carbon for hundreds and even thousands of years.

Garrett was invited to be the first farmer to sell carbon credits on Nori's new carbon credit marketplace because he's the first to try a lot of new things. He's a member of a group of farmers around the US that test new agriculture products and post their results on the website xtremeag.farm.

"It is an honor, and I'm excited to be the first," Garrett says. So far, he's sold $150,000 of carbon credits; the first buyer was the e-commerce firm Shopify. He expects to make $340,000 from his first year's participation when all are sold.

Garrett worked with Locus Agricultural Solutions to generate his credits and certify them. Locus sells soil microbes that consume organic matter, trap carbon, and make nutrients like nitrogen available to plants. The company has launched a credit-generating program called CarbonNOW.

In addition to using Locus's Rhizolizer Duo microbial product, Garrett planted cover crops that protect his fields from erosion and add organic matter. He skipped tilling his fields and added liquid compost. Garrett also brought in calves and cattle to graze on cover crops and crop residues.

Kelly Garrett pilots a high-tech tractor on his farm in western Iowa.

CREDIT: LOCUS AGRICULTURAL SOLUTIONS

Soil scientists have been advocating the same practices, sometimes called regenerative agriculture, for years because they support the biological mechanisms needed for healthy soil. "Everything that we talk to farmers about the principles of soil health management all build soil organic carbon and retain soil carbon," says Cristine Morgan, chief scientific officer for the nonprofit Soil Health Institute.

Now many companies in the agriculture supply chain are launching programs to reward farmers who transition to practices that pull measurable amounts of carbon from the atmosphere. Some programs generate their own funding by selling carbon credits to companies that want to offset greenhouse gas emissions from their operations.

Those suppliers include another purveyor of agricultural microbes, Indigo Agriculture, which is also working with growers to create and sell carbon credits via its Indigo Carbon program.

Technology firms that supply precision agriculture tools, including Farmers Business Network and Farmers Edge, are helping farmers gather and track data to qualify for carbon credits. The start-up PastureMap, which emerged from stealth in 2020, has a program for ranchers called Grassroots Carbon.

Big companies that sell seeds, pesticides, and fertilizers, including Bayer, Nutrien, and Yara, are recruiting farmers for their own programs. Food companies like Cargill, General Mills, and the dairy cooperative Land O'Lakes also have programs that help growers shift to regenerative techniques that put carbon in soil.

At a minimum, a soil carbon program asks farmers to start one or two soil health practices—usually cover crops and low- or no-till farming—and pays them a set amount per land unit or per estimated ton of carbon stored.

The most sophisticated programs aim to scientifically account for all greenhouse gases absorbed and emitted by farms. They

Carbon farming by the numbers

- **10%:** Share of US greenhouse gas emissions that came from agriculture in 2020[a]
- **0.5–7.5 metric tons:** CO_2 equivalent that can be sequestered per hectare of soil (0.2–3 metric tons per acre)
- **$15:** Value of agricultural carbon credit representing 1 metric ton of captured CO_2 equivalent in 2020
- **58%:** Carbon component of soil organic matter, on average
- **5.1%:** Rate of adoption of cover crops in US in 2017
- **21%:** Proportion of US corn, cotton, soybean, and wheat growers reporting low- or no-till management for 4 years in 2017
- **85%:** Proportion of US corn farmers using soil health management systems who reported increased net income, according to a 2021 report

US agriculture's greenhouse gas emissions by type

58.0%	40.8%	1.2%
Nitrous oxide	Methane	Carbon dioxide

Total: 628 million metric tons of CO_2 equivalent in 2019

Sources: US Environmental Protection Agency, US Department of Agriculture, 2021 study from Soil Health Institute and Cargill, C&EN. **a** Includes animal sources.

generate third-party-verified carbon credits that corporate purchasers can use to fulfill net-zero carbon pledges. Currently, buyers are paying about $20 per metric ton of carbon dioxide equivalent, of which $15 goes to the farmer.

In addition to Shopify, firms including IBM, JPMorgan Chase, Marathon Oil, Microsoft, and New Belgium Brewing have bought some of the first certified carbon credits in the US.

Carbon farming is shaping up to be good business for agriculture companies offering climate change mitigation products and services, Laurence Alexander, a stock analyst for Jefferies Financial Group, tells investors in a recent research report. It can drive sales for companies that sell seeds and chemicals, including herbicides and fungicides, because conventional farmers use more of them to control an uptick in weeds and diseases during the transition to no-till operations.

Verifying carbon credits

For the agricultural carbon market to gain ground, the science supporting the greenhouse gas impacts must be credible. Companies learned a lesson from the Chicago Climate Exchange, says Jonathan Hennek, global head of product for carbon at Indigo. The marketplace operated from 2003 to 2010 and set its own standards for what constituted a credit.

"They were playing in their own sandbox. When people lost confidence in the quality of the standards, the market collapsed," Hennek says.

More recently, some forest carbon credits and systems, including credits sold by the conservation group the Nature Conservancy and a program administered by the California Air Resources Board, have been criticized by environmental watchdogs as not representing actual new carbon storage.

To avoid those outcomes, Indigo worked with the third-party climate standards organizations Verra and Climate Action Reserve as well as nongovernmental organizations, scientists, and growers to develop methodologies to prove that the practices the firm promotes improve farms' greenhouse gas footprints.

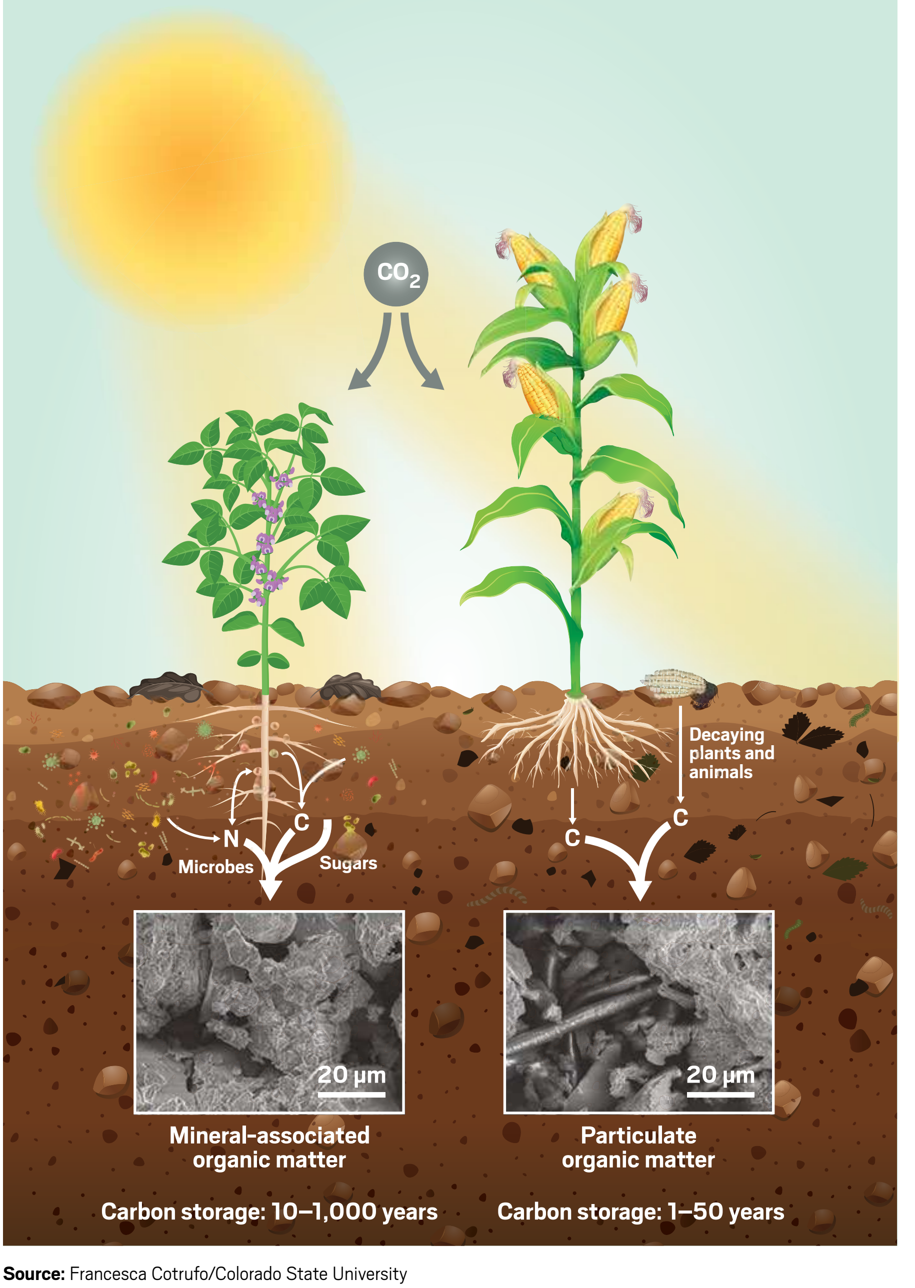
Verra and Climate Action Reserve maintain an inventory of practices that have been scientifically shown to boost the ability of crops or pastures to transfer carbon from the atmosphere into the soil or to reduce the amount of nitrous oxide and methane that a farm emits. Farmers can choose the practices they'd like to start using as well as the amount and location of fields where that change will happen.

To generate credits, a program has to show that new practices, when implemented in the field, measurably affected greenhouse gases. For example, showing that cover crops and reduced tillage added carbon to the soil requires many soil samples to obtain benchmark data and measure the change in soil carbon each year.

Farmers' records of past practices provide evidence that the new farming practice—say, using cover crops—and not, for example, great weather, is responsible for

Storing soil carbon for a millennium

Farmers store carbon in agricultural soils for the long term by using practices like cover cropping that promote biological activity underground. Cover crops foster diverse communities of nitrogen-fixing microbes (shown on the left). Using photosynthesis, the plants produce sugars, which enter the soil through the roots and feed the microbes. The excess sugars and the bodies of dead microbes attach to clay particles and soluble minerals to form stable, carbon-containing complexes called mineral-associated organic matter. In contrast, decaying plants and animals (shown on the right), form particulate organic matter. This type of organic matter breaks down more quickly and releases carbon, particularly when the ground is disturbed by tilling.



Source: Francesca Cotrufo/Colorado State University

CREDIT: YANG H. KU/C&EN/SHUTTERSTOCK (PLANT GRAPHIC); FRANCESCA COTRUFO/COLORADO STATE UNIVERSITY (MICROGRAPHS) the increased soil carbon. This concept, known as additionality, is core to the value of carbon credits. Additionality also means something more nuanced: that the farmer would not have adopted this practice if not for the carbon credit payment.

Verra's methodology for quantifying soil carbon runs 33 detailed pages. It governs how to assess a landscape, including its soil types, soil layers, and vegetation species. It instructs soil testers on how to create a soil-sampling plan: how many samples to take, where to take them, at what depths, and when. It says how to account for carbon content using soil mass, soil density, and soil volume, as well as how to measure changes in those variables over the growing season.

Not surprisingly, a major role for Indigo and Locus in helping farmers generate carbon credits has been to pay for the required third-party soil testing. The companies keep a portion of the credit sale to cover testing costs.

Hennek, who has a background in chemistry, says Indigo's approach captures the trade-offs that can happen when farmers embark on something new. "We don't only look at what a cover crop adds to soil carbon," he explains. "What happens if a farmer decides to put a synthetic nitrogen on that cover crop? It's essential to measure all of the potential emissions factors," such as additional nitrogen oxide.

US Department of Agriculture soil scientists collect a soil sample to assess how a cover crop, planted after corn, altered the soil's chemistry.

Industry takes the lead

Locus and Indigo say the pieces are in place for farmers to begin profiting from carbon credits, assuming they can meet the high bar for verification. And now is a good time because demand from buyers is strong.

"We believe the carbon credit that is the highest quality will get the highest price, and we expect the prices to rise. That money flows directly to the farmers, which creates a virtuous cycle because it enables them to add more practices," Hennek says.

But to expand beyond pioneers like Garrett and attract large numbers of farmers, firms scaling climate-friendly growing practices will need simple, straightforward techniques.

One way to speed adoption is to make it easier for farmers to gather the data they need to earn certified carbon credits. Jeff Seale, director of climate policy and strategy at Bayer Crop Science, says there isn't enough money in climate credits to fund an army of soil sample takers and document wranglers.

Bayer's scientists have launched pilot programs in which farmers use the digital tools of its popular Climate FieldView platform to automate record keeping and gather the data needed to prove that they are sequestering carbon.

Farmers already use FieldView to map, plan, and manage their fields, inputs, and crops and measure their harvests in detail. Bayer's program pays corn and soybean farmers in nine states in the US Midwest $10 per acre ($24.70 per hectare) when they adopt cover crops or reduce tillage. A pilot program in Brazil helps farmers use FieldView data to comply with government requirements for preserving a portion of farmland as native forest.

Growers share their FieldView data with Bayer, which will use it along with other data to build proprietary carbon models. "What we're trying to do is have this integrated platform that drives the simplicity for the system," Seale says.

In the US, FieldView includes 80 years of USDA data on soil types, historical yields, and weather to estimate greenhouse gas emissions. On top of that, Bayer is building models of crop rotations and agronomic practices.

Other companies are working on technologies they say will provide data that can be combined with machine learning and artificial intelligence to model soil carbon. A number of agricultural technology firms, Indigo included, say they can use high-resolution satellite images to track and verify the use of cover crops and crop rotation. Scientists and start-ups are developing remote sensing technology to measure the carbon content in the top 15 cm of soils. Future advances will enable carbon detection deeper in the soil.

Another company, LaserAg, won an Indigo contest for its soil-sampling and lab-testing technology. The system analyzes GPS-tagged field samples with laser-induced breakdown spectroscopy to measure the organic content in soil and its density, texture, total nitrogen, and pH in less than 1 min.

The Soil Health Institute is working with the start-up Yard Stick on an in-field soil carbon sensor for researchers and ag consultants. The long probe measures carbon concentration at different soil depths with the help of data from US soil spectroscopy libraries.

Ryan Sirolli, global row crop sustainability director at Cargill, cautions against taking too narrow a view of soil health by linking it solely to captured carbon.

Practices that build soil organic matter do more than just trap carbon, Sirolli says.

"I do think there should be one standard practice for the science on how much we're sequestering."

—**Kelly Garrett,** farmer, Garrett Land & Cattle

CREDIT: USDA

They raise soil's water-holding capacity, make crops more resilient to weather stress, capture nitrogen, improve water quality, and increase biodiversity. "If you get stuck just working within the carbon market and get caught up in its limitations, you might miss all of these benefits that you can really lean into," Sirolli says.

As a buyer of grain, Cargill is familiar with the economics of farming and the demands of food companies and consumers. It has committed to working with farmers to transition 10 million acres (4 million hectares) of North American farmland to regenerative systems by 2030.

Cargill worked with soil scientists and economists at the Soil Health Institute to quantify the financial upsides of soil health practices by collecting data on 100 farms in nine states. Farmers reported spending more money on seeds—likely for those cover crops—but less on fertilizers and soil amendments, pesticides, fuel, labor, and equipment. They also earned more revenue, thanks to higher yields.

In total, the researchers found that 85% of farmers growing corn increased their net farm income by an average of $52 per acre ($128 per hectare), while 88% of soybean growers saw an average increase of $45 ($111 per hectare). Nearly all the farmers reported improvements in their crops' resilience to extreme weather.

But the farmers in the study have planted cover crops or followed no- or low-till methods for a decade or more, meaning they don't qualify for a program like Indigo's. So Cargill is piloting programs to help farmers more quickly qualify for carbon credits, water credits, and biodiversity credits. One example is Cargill's Soil and Water Outcomes Fund, which is enrolling farmers in Illinois, Iowa, and Ohio.

Government wants a role

Just 1 week after his inauguration, President Joe Biden issued an executive order directing the USDA to seek input from farmers, conservation groups, and other stakeholders on developing a climate strategy, including voluntary programs for "additional, measurable, and verifiable carbon reductions and sequestration."

The exact strategy is still being developed. The USDA solicited comments from stakeholders from mid-March until April 29 and is now considering the options.

One way the government can help, according to comments from environmental and farm groups, is by setting standards that would build confidence in private carbon credit markets and encouraging farmers to participate. For example, the USDA could boost participation by funding existing public-private partnerships.

The US Congress is also considering legislation that would empower the USDA to widen participation in carbon markets. Sen. Debbie Stabenow (D-MI), chair of the Senate Committee on Agriculture, Nutrition, and Forestry, and Sen. Mike Braun (R-IN) introduced the Growing Climate Solutions Act (S. 1251), which would establish a USDA certification program to help standardize private carbon credit markets and boost farmers' confidence in the schemes. The USDA would certify third-party verifiers and technical assistance providers. It would also develop a website to serve as a one-stop shop of information for farmers who want to participate in private carbon markets.

Those ideas have caught on in the European Union as well, as part of the EU's Farm to Fork Strategy. The European Commission is promoting carbon farming to member states and will help fund incentives. It plans to launch a carbon market by the end of the year.

The Food and Agriculture Climate Alliance, a coalition of organizations representing US farmers, the food industry, state governments, and environmental groups, endorses the Growing Climate Solutions Act, pointing out that it "establishes a robust USDA advisory council composed of farmers, scientists and other climate stakeholders."

Meanwhile, USDA secretary Tom Vilsack is leveraging existing USDA programs, particularly the Conservation Reserve Program (CRP), which pays farmers to keep land out of agricultural production. The current CRP is estimated to mitigate more than 12 million metric tons of carbon dioxide equivalent annually. The USDA hopes to expand the program by up to 4 million acres (1.6 million hectares), which it says would mitigate an additional 3 million metric tons of CO_2 equivalent.

In April, Vilsack also announced increased funding for public-private partnerships that promote climate-smart agriculture, including $330 million for 85 Regional Conservation Partnership Program projects and $25 million for On-Farm Conservation Innovation Trials.

Finally, the USDA is considering creating a carbon bank with money from a $30 billion fund called the Commodity Credit Corporation. It would provide incentives for farmers to access carbon markets. But many Republican lawmakers are pushing back on that idea, claiming that Congress would need to approve any funding for climate purposes before the USDA could use it.

A Locus Agricultural Solutions expert evaluates the soil of a harvested soybean field.

CREDIT: LOCUS AGRICULTURAL SOLUTIONS

Some sustainable farming experts and business organizations warn that carbon bank and carbon credit programs may be limited in their effectiveness and unjust in distributing rewards.

In comments submitted to the USDA, the American Sustainable Business Council, a coalition of firms focused on sustainability and social responsibility, said carbon farming "should not be promoted as an alternative to adequate regulation of polluters, especially in environmental justice communities." The group also worries that carbon markets will benefit larger-scale producers at the expense of small-scale farmers.

Cargill's Sirolli adds that financial incentive programs will have limited impact if they don't address how benefits will be distributed when farmers grow crops on land that they don't own. "It's probably one of the biggest single hurdles to overcome," he says. "Nearly half of the acreage farmed in the US is on rented or leased land."

Another concern is that farms with very degraded soil could see large improvements and get outsize payments, says Yichao Rui, a soil scientist and the director of the Farming Systems Trial at Rodale Institute, an organic and regenerative farming research and education organization.

"I personally think that we should reward farmers by the practice and not their soil carbon measurement," Rui says. "There are also a lot of farmers doing great things already, and they need to maintain their carbon content. If they are left out of the system, that is not fair."

More to learn about soil carbon

Experts agree that scaling up carbon credit markets will require reliable models. But building models that link on-farm practices to sequestered carbon is challenging because soil carbon cycles are complex, and soils vary widely.

"Soil carbon depends on a lot of factors—temperature of region, climate factors, mineralogy, and vegetation that coevolved with these factors," Rui says.

Rui says lands managed for agriculture have lost 25–75% of their carbon-containing topsoil over the years. In Pennsylvania, where Rodale conducts its field studies, soil organic carbon has fallen to roughly 2% of soil mass from 4% before the start of widespread farming, he says.

Globally, that adds up to a lot of room to store carbon. In a 2020 white paper, Rui and coauthors say cover cropping alone could sequester roughly 4% of annual CO_2 emissions. If many regenerative methods are stacked together, the sequestration potential rises to nearly a third of global CO_2 emissions. And because so much land is used to graze livestock, regenerative pasture practices could store even more carbon.

Achieving that potential calls for more science backing soil carbon models, says Francesca Cotrufo, a professor of soil and crop science at Colorado State University. She is a member of Colorado State's Soil Carbon Solutions Center, a team of soil scientists, modelers, chemists, social scientists, and economists. Her research focuses on understanding and quantifying how carbon and nitrogen cycle in and out of soil.

To track how carbon ends up in soil, how much stays there, and for how long, Cotrufo measures old carbon put into the soil by past forests and compares it with newer carbon from corn crops using their different ratios of ^{13}C to ^{14}C. She also uses isotope labeling to trace carbon and nitrogen flows from plants to soil and microbes.

Cotrufo eschews soil analysis methods like combustion and chemical separation that measure total carbon. Instead, she separately examines the lighter, coarser soil fractions containing decomposing plant matter, called particulate organic matter, and the heavier, finer fractions of carbon stuck to inorganic matter from weathered rock, called mineral-associated organic matter.

"It's a better approach to identify fractions because they form differently, persist in soil via different mechanisms, and are differently sensitive to management, climate change, and disturbance," Cotrufo says.

The particulate organic matter primarily occupies the top 30 cm of soil, where microbes consume sugars exuded from plant roots and break down plant and animal matter, making nitrogen and other nutrients available to plants. That's how compost and other organic matter help boost crop productivity. But microbial respiration also sends a portion of that carbon back to the air as CO_2.

When those microbes die, the carbon in their cell walls, along with other carbon that has escaped microbial digestion, moves deeper into the soil, where it forms long-term associations with clay particles and calcium, iron, and aluminum oxides. The resulting mineral-associated organic matter is less accessible to microbes and plants; it can stay in soil as long as 1,000 years.

"Soil biology is the key to get the system going and maintain the system. But in conventional ag, the role of microbes has been ignored," Rui says. Adding beneficial microbes to the soil may help jump-start the revival of depleted soil, Cotrufo adds, but success depends on continually feeding them organic matter and may require yearly applications of microbial products.

Both particulate and mineral-associated organic matter are valuable to farmers. Cotrufo and Rui describe them as money in the bank. High-quality organic matter from crop residues, cover crops, or compost first fills a checking account to pay this season's bills. Over time, if the soil is not disturbed by plowing, a postharvest surplus builds up, forming mineral-associated organic matter—a farm's version of long-term savings.

In Iowa, Garrett didn't use a computer model to predict how much more carbon and nitrogen he'd get from soil health practices and the microbial product—he just tried them and measured the results. He measured the nitrogen level in his corn plants and was excited to see it had jumped 12%.

What's more, he says that during a stretch of July, when his corn hit its rapid growth phase, his soil's pH dropped 2 points, meaning that the hungry plants were producing huge quantities of acidic, carbon-laden sugars that they pushed into the soil through their roots.

"I thought, 'Holy cow, we're watching photosynthesis and carbon sequestration in real time,'" he says.

Last season, Garrett's hopes for his corn crop were flattened by the Midwest derecho. This year, he's going to try again to beat the state yield record. "For a farmer, it would be like breaking Roger Maris's home run record," he says. "If I can do that and show the environmental folks we can do it positively and sustainably, that's a big message." ■