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Scientists can measure the carbon-storage capacity of various types of soil.

FARMING TECHNIQUES THAT PROTECT THE PLANET

A generation of farmers and scientists are finding ways to sequester carbon in the soil while improving crop yields. **By Bianca Nogrady**

When it comes to carbon, humanity has two pressing problems. First, there's too much of it in the atmosphere. The atmospheric concentration of carbon dioxide has increased by about 50% since the start of the industrial age, from 280 parts per million to nearly 420 parts per million in 2023 (see go.nature.com/2j4heej). Much of that comes from the combustion of fossil fuels, but agriculture is a major contributor. Each year, around 13.7 billion tonnes of CO_2 or equivalent greenhouse gases is released into the atmosphere by agricultural processes, with more than one-quarter of global greenhouse-gas emissions arising from food production[1].

The second carbon problem is that there isn't enough of it in the soil. Soil carbon has been drastically depleted around the world, thanks to intensive farming practices that have been developed to feed the growing population. One estimate suggests that around 133 billion tonnes of carbon – about 8% of total organic soil carbon – has been lost from the top 2 metres of soil since the advent of agriculture some 12,000 years ago. Around one-third of that loss has occurred since the Industrial Revolution in the 1800s (ref. 2).

This imbalance means that agriculture has an ace up its sleeve: although it's currently a carbon source, it also has the potential to be a carbon sink, which could alter the planet's climate-change trajectory (see 'Green horizons'). It's not only possible, but it's relatively easy to recharge soil organic carbon stocks by supporting and enhancing the natural processes that draw and convert CO_2 into soil carbon.

The latest Intergovernmental Panel on Climate Change (IPCC) synthesis report[3] puts carbon sequestration in agriculture as one of the highest potential contributions to reducing net emissions. At around 3.5 gigatonnes of CO_2 or its equivalent greenhouse gases per year, this is greater than the emissions from the entire European Union in 2022 – exceeded only by a conversion of current energy supplies to solar or wind energy, or reduced destruction of natural ecosystems. The challenge is to ensure that this happens fast enough, and at a low enough cost, for it to make a substantial contribution to achieving global net-zero carbon emissions by 2050.

The agricultural techniques that can help to increase soil carbon sequestration aren't necessarily complex. But with the looming deadline of net-zero carbon emissions by 2050, as set by the Paris climate agreement, the pressure is on scientists to identify the most efficient, effective and rapidly scalable methods for soil carbon sequestration and how these can help to achieve the dual goals of mitigating climate change and improving soil health.

Carbon farming

Soil organic carbon is the result of the CO_2 that plants have extracted from the atmosphere and incorporated into their structure, especially root systems, being used to nourish other living organisms in the soil.

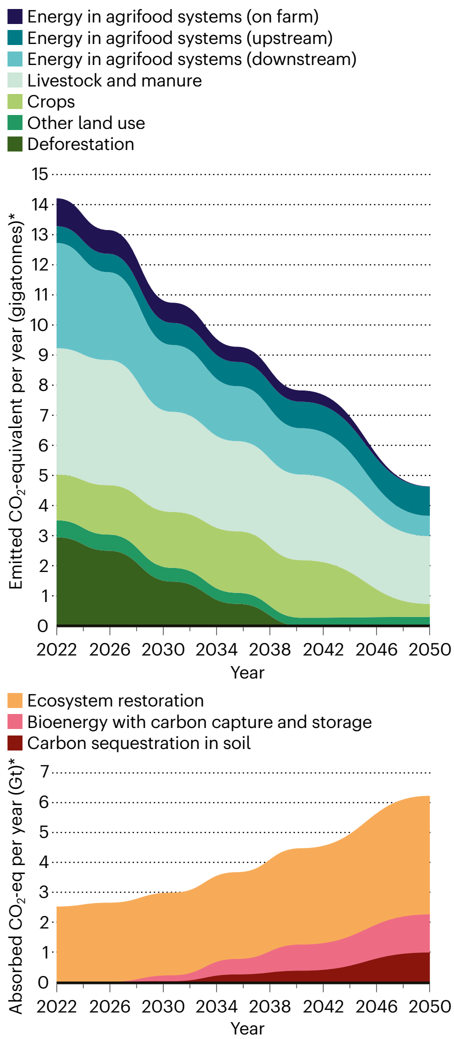
"Before soil carbon was even a thing from a climate-change perspective, people were promoting the increase of organic matter in the soil to improve its fertility, to improve water-holding capacity and resilience to droughts, and to prevent erosion," says Peter Smith, a soil scientist at the University of Aberdeen, UK, and science director of Scotland's ClimateXChange centre in Edinburgh, UK. "Nobody disagrees that increasing the amount of soil organic matter is a good thing," Smith says.

The good news is that increasing soil carbon isn't high tech. Evolution has already done most of the hard work by giving plants the ability to extract CO_2 from the atmosphere through photosynthesis, turning it into carbohydrates and oxygen. The plants assimilate that carbon into their cells and tissues, which eventually become integrated into the soil when the plant sheds matter in the form of leaves, branches, flowers or fruit, or when it is consumed by other organisms, or when the plant dies and decomposes.

The biggest barrier to this process is humans and the bad habits that we have developed to squeeze better short-term yields out of soil. One of these is tilling, particularly the deep ploughing that is commonly used to prepare the soil for planting. "A century ago, one of the things that made the prairie regions across the globe so fertile is that when we tilled them, the organic matter degraded and that released tremendous amounts of nutrients and produced bountiful crops," says David Burton, a soil scientist at Dalhousie University in Halifax, Canada. That process breaks up the soil, including the root systems of the crops and grasses, causing the release of CO_2 into the atmosphere.

GREEN HORIZONS

The Food and Agriculture Organization (FAO) of the United Nations unveiled the first instalment of its agrifood roadmap at the COP28 climate meeting in 2023. It highlights several carbon-producing domains — particularly for methane — that can be targeted to reduce net emissions from the global agrifood system (top) and that can be used as carbon sinks (bottom).



*Based on GWP100 AR5 (global warming potential values from the IPCC's Fifth Assessment Report, AR5). CO_2, carbon dioxide.

SOURCE: FAOSTAT FOR 2021 AND MODEL PROJECTIONS FOR FUTURE YEARS

Tilling also destroys the structure of the soil and increases the risk of erosion by wind or water, which can in turn cause more CO_2 to be released.

Therefore, one way to potentially keep that carbon in the soil is to reduce or eliminate tilling in what's called no-till or zero-till agriculture. Instead of turning over large amounts of soil to plant seeds or seedlings, farmers use equipment that creates either a narrow channel or a hole into which the seed or seedling can be planted. The residue of the previous season's crop – stubble, stalks and stems, for example – is left in the soil and on the surface. The idea is that this reduces the disturbance of the soil structure and leaves more of the soil organic carbon in place.

Although carbon sequestration through no-till is promising, the evidence is mixed. Research suggests that the amount of soil carbon sequestered with no-till farming varies with climate and soil type. One analysis found evidence that the greatest increase in soil carbon with no-till agriculture occurred in warmer and wetter climates rather than in cooler and drier climates[4]. However, less tilling does mean less fuel consumption – because farmers don't have to plough as often and as deep – and therefore lower emissions. For example, the use of low-till farming in the United States is estimated to have saved the equivalent of around 3,500 million litres of diesel annually, enough to offset the annual CO_2 emissions of around 1.7 million cars[5].

Another method to increase the retention of soil carbon is to grow cover crops alongside the main crop, instead of manually pulling up or poisoning weeds that appear. This keeps the root structure and its soil carbon contribution intact and in place. A study of two Australian vineyards found that allowing grasses to grow in between the rows of grape vines was associated with a nearly 23% increase in soil organic carbon over a 5-year period compared with the conventional method of using herbicide to control grass growth[6]. The practice is gaining momentum in North American vineyards , and it is already well established in European ones, where cover crops such as clover and barley have been shown to improve soil carbon levels while reducing weeds[7].

There is also a growing interest in the carbon sequestration potential of adding inorganic, or mineral carbon, to agricultural soils through a process called enhanced weathering. This involves adding ground-up silicate rock, such as basalt, to the soil. The minerals in the rock dust – mainly magnesium and calcium – interact chemically with CO_2 in the atmosphere to form carbonates, which remain in the soil in a solid form or dissolve and gradually drain out to the ocean through the water table[8].

A four-year study, which was published in February, of the US corn-belt region found that applying crushed basalt to maize (corn) and soya bean fields was associated with sequestration of an extra 10 tonnes of CO_2 per hectare per year, while also increasing crop yields by 12–16% (ref. 9). "It's one of the most intensively managed areas of agricultural land in the world, so if it works there, then you've got kind of instant scalability," says study co-author David Beerling, a biogeochemist and director of the Leverhulme Centre for Climate Change Mitigation at the University of Sheffield, UK.

Deforestation is another major contributor to agricultural sector carbon emissions, particularly in cattle farming[10], in which forests are bulldozed to create pastures for animals. Agroforestry — the integration of trees into farming systems — is one way to mitigate this problem. Growing trees and shrubs among crops and pastures not only increases carbon sequestration in the soil and the tree biomass, but also provides further benefits including wind-breaks and shade for cattle. Agroforestry is well established in many parts of the world, including in tropical areas where trees provide shade for crops such as coffee beans.

As promising as soil carbon sequestration looks on paper, it has a limit, says Smith. "If we're chucking it all up from geological sources, the biological sinks aren't enough to suck up all that carbon," he says. It's also finite — there is a limit to how much carbon an area of land can sequester. The question is: what is that limit?

Measure, monetise, incentivize

Soil scientist Rattan Lal, director of the Lal Carbon Center at Ohio State University in Columbus, says that if the world switches to non-fossil-fuel sources of energy, it will be possible to achieve a long-term positive soil carbon budget in which more carbon is absorbed by agriculture than is generated by it. "By 2100, the [carbon] sink capacity of the land is about 150 to 160 gigatonnes of carbon, and another of the same amount for trees," Lal says. That amounts to around two gigatonnes of carbon per year that could be sequestered in soils. Other studies suggest that number could be as high as 4–5 gigatonnes of carbon per year[11]. Given global emissions now sit at around 35 gigatonnes per year, this is a substantial proportion[12].

Even at the lower estimate, if the entirety of that atmospheric carbon removal is realized, Lal's research suggests it could reduce global atmospheric concentrations of CO_2 by around 157 parts per million[13], which would completely remove all the extra CO_2 emitted since the start of the Industrial Revolution. "Agriculture could be a part of the solution," he says.

However, the soil-science community is divided over whether sequestering carbon in soils could be part of the climate-change remedy, says Alex McBratney , a soil scientist and director of the Sydney Institute of Agriculture at the University of Sydney, Australia. Even today, there are some people who think it's simply too difficult because of the challenge of measurement.

Soil carbon content varies a lot geographically, even over short distances, so getting a reasonably accurate measurement at a point in time means taking lots of samples — and that can add up financially. Soil carbon also fluctuates naturally, depending on weather conditions and other factors. And the change in soil carbon levels over time might also be

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Agricultural practices such as ploughing release carbon dioxide into the atmosphere.

small relative to the overall amount of carbon in the soil, which makes it harder to record a significant change.

Soil carbon levels also change slowly. "We would say, as a rule of thumb, that it probably takes of the order of five years to show observable differences … that you can detect against the background of this natural variation," McBratney says. Combined with variability, this makes it challenging to show that extra soil carbon has been sequestered, especially in a cost-effective manner.

Cultivating change

Despite the uncertainties of soil carbon sequestration, it is a hot topic when it comes to emission reductions. Governments have leapt enthusiastically, and sometimes prematurely, into capitalizing on the possibility of buying and selling carbon credits from agriculture. These are credits earned from reducing carbon emissions that can be used to offset carbon emissions from other sources or sectors — a win-win situation, given the added benefits of improving soil health.

Marit Kragt, an agriculture and resource economist at the University of Western Australia in Perth, became interested in soil carbon sequestration shortly after the Australian government introduced the Carbon Farming Initiative act in 2011. Her concerns were that the policy had been formulated with little scientific or economic data on, for example, the best practices for sequestering soil carbon, the impact of climate, the cost to farmers and whether soil carbon sequestration would truly increase overall soil carbon.

This cost-benefit analysis will be crucial to overcoming the sociocultural barriers to change. There is resistance to changing farming practices, particularly when the advice to do so comes from scientists or policymakers, says Kragt. "Sociocultural change is actually really important in any society, but is often forgotten," she says. "When you have a group of people advocating for something and they're not part of the farming community or trusted peers, there is push back."

However, Kragt says that most farmers who implement carbon-positive farming techniques don't do it for the credits. "I think most people that have taken up carbon farming practices will have done so because they wanted to regenerate their environment," she says. Many farmers are also concerned about climate change because they can see the impact on their livelihoods. "They have seen the bushfires, droughts and extreme heat that's affecting their harvests, so they know that something needs to change ."

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