Zero Carbon Analytics

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Relying on soil-based carbon capture to offset livestock emissions is risky

Key points:

- Soil carbon sequestration is the process through which atmospheric carbon dioxide is captured and stored in soil, forming part of the natural global carbon cycle.
- In undisturbed natural ecosystems, carbon may be stored in the soil for thousands of years. However, the conversion of natural land into farmland has depleted soil organic carbon stocks and released this stored carbon into the atmosphere.
- Livestock grazing systems are responsible for the loss of significant amounts of soil carbon over the past six decades.
- Regenerative grazing – which involves rotating livestock on land for short durations – has been proposed as a solution for improving soil carbon stocks and offsetting emissions from livestock farming.
- Recent estimates suggest that improved grazing management could potentially take-up around 63 gigatons (billion metric tons) of carbon in vegetation and soils.
- However, once methane and nitrous oxide emissions from grazing animals are considered, an estimated 135 gigatons of carbon take-up would be needed to offset these emissions.
- Relying on soil carbon sequestration to offset emissions from grazing systems is risky as carbon storage is finite and reversible, and increased emissions of methane and nitrous oxide could offset any gains from carbon sequestered in the soil. The impacts of regenerative grazing are also highly context-dependent.
- Despite uncertainties, sequestering carbon in soil could contribute to climate change mitigation in the medium term in certain regions of the world.
- Management practices aimed at maintaining or improving soil carbon offer other benefits, such as improved soil health, erosion control and reduced emissions intensity, with positive outcomes for yields and farmers' incomes.

Soil carbon sequestration: the basics

Soil carbon sequestration is the process through which atmospheric carbon dioxide is captured and stored in soil. Plants capture atmospheric carbon dioxide through photosynthesis, and the carbon is stored in its organic form in plant tissues while the oxygen is released back into the atmosphere. As the leaves, roots and other tissues of plants decay, the carbon contained in these tissues is released into the soil through microbial activity, enriching the soil carbon pool. The carbon pool is also enriched through the exchange of carbon between plant roots and soil microbes.

Soil carbon sequestration is a natural process that forms a critical part of the global carbon cycle – whereby carbon is exchanged among all life on earth, the soil, water, minerals and the atmosphere. Soil organic carbon is important because it regulates the functioning of ecosystems, provides energy for soil microorganisms and improves the structure of soil. It is also an important carbon sink – the soil organic carbon pool contains up to 2,400 gigatons (or billion metric tons) of carbon, which is more than double that of the atmospheric carbon pool.

In undisturbed natural ecosystems, carbon may be stored in the soil for thousands of years. However, the conversion of natural land into agricultural land from human activities has depleted soil organic carbon stocks by reducing the amount of plant tissues in soil and encouraging erosion, thereby destroying soil structure and speeding up microbial breakdown. It is estimated that over the last 15,000 years, and particularly in the last 200 years, the growth of farmland has released 133 gigatons of carbon from the top two metres of the soil layer. This is equivalent to about 80 years' worth of present-day US emissions.

This deficit of soil organic carbon has created an opportunity to draw earth-warming carbon dioxide from the atmosphere and store it in the soil in an effort to mitigate against climate change.

Grazing systems and soil organic carbon

Grasslands are a significant reservoir of soil carbon, storing around one-third of the global soil organic carbon pool.[1] However, estimates suggest that livestock grazing is responsible for the loss of 46 gigatons of soil carbon over the past six decades - which is more than four years' worth of current global fossil fuel emissions.

While moderate to heavy livestock grazing depletes the soil organic carbon pool on average, light grazing has been found to increase soil organic carbon stocks. This is because grazing can stimulate plant productivity and the allocation of carbon to the roots for microbes, thereby increasing carbon sequestration.[2] As a consequence, 'regenerative grazing' - which involves rotating livestock on land for short durations to allow soil to recover and draw carbon dioxide from the atmosphere - has been proposed as a solution for improving soil carbon stocks and mitigating the climate change impacts of livestock grazing. Currently, global grazing systems emit more greenhouse gases than they sequester.

A 2021 analysis found that 'adaptive multi-paddock grazing' - a form of regenerative grazing - increased soil carbon stocks compared to conventional grazing. The authors emphasised the importance of carbon being stored in the mineral fraction of the soil - meaning it is tightly bound to soil particles. This makes the sequestered carbon more resistant to disturbance and means it will be stored for a longer duration. The study is backed by a global meta-analysis, which found that regenerative practices, particularly integrated crop-livestock systems, have significant potential to increase soil organic carbon pools because they enhance the storage of carbon in the mineral soil fraction.

Another study reported that over a four-year period, the emissions from adaptive multi-paddock grazing on a beef farm could be completely offset by the carbon sequestered in the soil. Some advocates of regenerative grazing have gone as far as claiming it can 'reverse climate change'. They argue that increasing livestock production could help sequester more carbon from the atmosphere into the soil.[3]

A long-term field experiment found that rotational grazing accumulated more soil organic carbon than other management systems. However, the findings have been questioned by

[1] This definition of grasslands includes some savannas, woodlands, shrublands and tundra.
[2] Some studies show that grazing-induced changes in vegetation are not correlated with changes in soil organic carbon.
[3] This is in contrast to experts who believe that managing livestock numbers will be essential, together with other strategies, for reaching Paris Agreement commitments.

other scientists, who point out that the analysis did not consider the contribution of methane and nitrous oxide - two significant greenhouse gases associated with livestock farming - and the method for measuring the permanence of soil carbon was unsuitable. According to these scientists, "grazing cattle, well-managed or not, has no role in enhanced C sequestration."

How much carbon could these strategies sequester?

An analysis published this year estimates that improved grazing management could take-up around 63 gigatons of carbon in vegetation and soils globally. This number is three times higher than IPCC estimates, which the authors attribute to the overly simplistic model used by the IPCC. To put the number into perspective, 63 gigatons is about six years' worth of emissions from fossil fuels globally.

A separate analysis published in 2022 suggests that 148 to 699 megatons (or million metric tons) of carbon dioxide equivalent could be sequestered in the soil globally every year through improved grazing management.[4]

Sequestration potential overstated

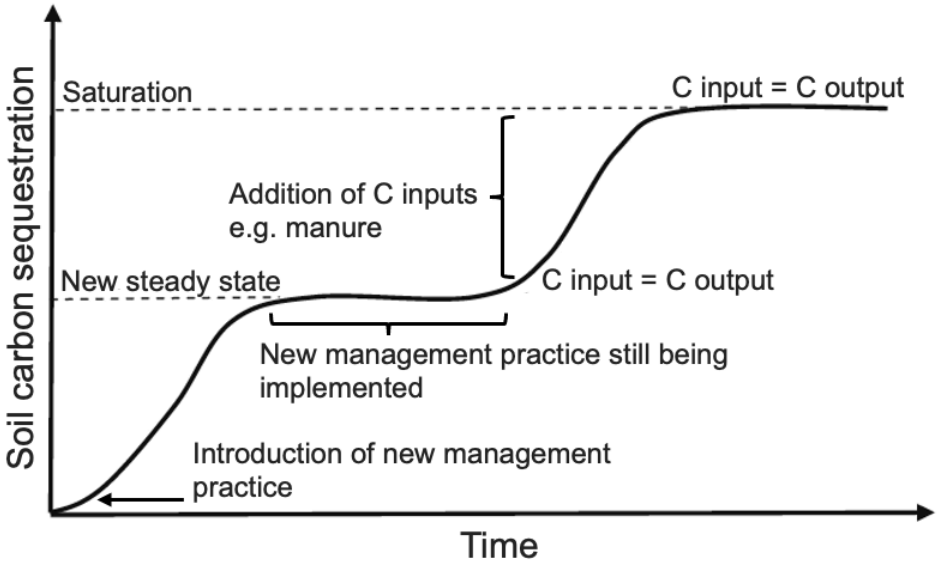
Some scientists are more cautious and suggest that the potential for soil carbon sequestration under regenerative agriculture to offset emissions may be greatly overestimated. There are several reasons why relying on soil carbon sequestration to offset emissions from livestock systems is risky.

1. The capacity for soil to store carbon is finite

In long-term undisturbed ecosystems, soil carbon stocks are assumed to be equal to soil carbon emissions because the system has reached a state of equilibrium, or a steady state. When the ecosystem is disturbed - such as a grassland being overstocked with cattle - carbon is released from the soil due to, for example, erosion from reduced vegetation cover. Once a new land management practice aimed at enhancing soil carbon sequestration - such as rotational grazing - is introduced on this disturbed land, the rate of soil carbon sequestration follows a sigmoid curve, being high during the initial period after adoption of the practice and then slowing down upon approaching a new soil carbon steady state (Figure 1).

[4] Other estimates suggest that improved grazing management could sequester 0.28 megatons of carbon per hectare per year.

Figure 1. Soil carbon sequestration after a new management practice is introduced



Note: Figure has been adapted from Considering the influence of sequestration duration and carbon saturation on estimates of soil carbon capacity, 2006. The graph is theoretical and the axes are not true to scale.

The new steady state reflects a balance between carbon inputs and outputs under the new management practice, with soil carbon stocks no longer increasing. For grassland management, estimates suggest that the time until the maximum sequestration is reached is, on average, around five years, with declining rates for another 45 years. In other words, the rate of carbon sequestered within the first several years of a new practice being introduced does not reflect the long-term total sequestration rate.

Initial soil carbon sequestration rates from short-term studies on regenerative grazing should therefore not be extrapolated to estimate the total soil carbon sequestration potential of the practice. In some cases, the carbon sequestration potential can be improved beyond the new steady state with the addition of inputs, such as manure.[5] Soil carbon saturation then occurs when further inputs no longer lead to increased carbon stores, representing a cap on the carbon storage capacity.[6]

2. Soil carbon storage is reversible

For the sequestered carbon to remain in the soil, and for the rate of sequestration to reach its full potential, the new practice needs to be implemented permanently. However, disturbances such as fires or floods - which can be difficult to predict and control - could reverse the practice and cause the release of stored carbon. Climate change is contributing to this reversibility, causing the release of decades-old soil organic carbon by thawing permafrost and accelerating microbial decomposition. This creates a positive feedback loop that further accelerates global warming. As soil organic carbon is sensitive to temperature changes, it is estimated that the potential storage capacity could decrease by 14% by 2040 under a moderate global warming pathway.[7]

[5] Importantly, inputs such as manure can also increase the emissions of other greenhouse gases, offsetting soil carbon sequestration gains.
[6] Estimates suggest that saturation is reached at 82 g C kg-1 silt+clay for 2:1 clay dominated soils and 46 g C kg-1 silt+clay for 1:1 clay dominated soils.
[7] The SSP3–7.0 pathway from CMIP6.

3. Warming potential of other greenhouse gases

Land management changes that enhance soil carbon sequestration may increase the emissions of other, more potent, greenhouse gases. In certain cases, even small increases in these other gases may offset the benefit from the change in soil carbon stocks offered by the practice. Ruminant (cows, buffaloes, sheep and goats) farming emits nitrous oxide (from manure), which has a global warming potential 265 times that of carbon dioxide, and methane (from belching animals), which has a warming potential 28 times that of carbon dioxide. They are both also shorter-lived gases than carbon dioxide and have a stronger initial warming effect. Estimates suggest that ruminants emit 110 megatons of methane and 2.4 megatons of nitrous oxide every year, in addition to carbon dioxide.[8] Studies claiming regenerative grazing systems have a net benefit have been criticised for failing to consider the warming contributions of these gases.

A 2023 study estimated the potential for ruminant emissions to be offset through soil carbon sequestration in grasslands, considering the different warming potentials and lifespans of these greenhouse gases. The analysis suggests that around 135 gigatonnes of carbon would need to be sequestered in order to offset global methane and nitrous oxide emissions from ruminant farming – more than double the carbon sequestration potential of improved grazing management. For some grasslands, the soil carbon stock would need to increase by up to 2,000%, which emphasises how infeasible grassland management might be for offsetting ruminant emissions once the warming from other gases is considered.

4. Context is important

Though moderate to heavy grazing consistently reduces soil carbon stocks on average on a global scale, the impacts are highly context-dependent and will vary depending on a number of factors such as the climate conditions, type of soil, type of grazer, the vegetation type and the grazing strategy used. For example, sheep have a greater negative impact on soil carbon sequestration than cattle; the impacts of a higher grazing intensity will be more severe in warmer climates but less severe when water availability is high; and certain types of grasses will improve carbon sequestration, even under heavy grazing.

Due to this wide variability, some scientists argue that it is difficult to anticipate the soil sequestration potential of regenerative grazing practices. There are also concerns that farmers' skills and motivation levels could limit the outcomes and scalability of practices. Difficulties in measuring the results also makes monitoring soil carbon stocks challenging – it typically takes a decade of monitoring to determine how much carbon a practice is sequestering.

Soil carbon markets

Through soil carbon markets or 'carbon farming', farmers implement a management practice that allows them to sell 'carbon credits'. The credits, a quantifiable amount of carbon dioxide that has been sequestered in the soil from the management practice, are being proposed as a solution to mitigate climate change, with millions of dollars' worth of credits already sold. However, the uncertainties around the permanence, monitoring and accounting of soil carbon make soil carbon certificates unsuitable for climate change

[8] The ratio of emitted methane: carbon dioxide in ruminants is 4:1.

mitigation.[9] As emphasised by a prominent soil scientist, "It's really hard to evaluate the actual greenhouse gas benefit of these programs".

Sequestration offers important benefits

Despite several limitations, sequestering carbon in soil could make a meaningful contribution to climate change mitigation in the medium term in certain regions of the world, depending on the management strategy that is used. For example, converting arable land to grassland or forest will almost always have a positive effect on soil carbon sequestration. In addition, many management strategies are well-established and are not reliant on the development of new technologies, meaning they can be implemented quickly and with relative ease.

Additionally, management practices aimed at maintaining or improving soil carbon typically offer multiple other benefits, such as improved soil health, erosion control, increased water availability and reduced emissions intensity, with positive outcomes for yields and farmers' incomes.

[9] While permanence is a necessary condition for creditable carbon offsets – which are typically issued over a 100-year period – this permanence refers to the duration for which the sequestration practice is carried out rather than the stored soil carbon. Therefore, when the practice ends and the carbon is lost to the atmosphere, it is no longer a permanent removal.