Soil carbon science for policy and practice

Soil-based initiatives to mitigate climate change and restore soil fertility both rely on rebuilding soil organic carbon. Controversy about the role soils might play in climate change mitigation is, consequently, undermining actions to restore soils for improved agricultural and environmental outcomes.

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We argue there is scientific consensus on the need to rebuild soil organic carbon (hereafter, 'soil carbon') for sustainable land stewardship. Soil carbon concentrations and stocks have been reduced in agricultural soils following long-term use of practices such as intensive tillage and overgrazing. Adoption of practices such as cover crops and silvopasture can protect and rebuild soil carbon. Given the positive effects of soil carbon on erosion resistance, aeration, water availability and nutrient provision of soils[1], benefits of soil restoration can include improved fertility, reduced fertilizer and irrigation use, and greater resilience to stressors such as drought[2]. Rebuilding soil carbon is thus the foundation for many soil health initiatives[1–5].

At the same time, there is disagreement about the advisability and plausibility of rebuilding soil carbon as part of climate mitigation initiatives[1,3–7]. The urgency to address climate change elevates these disagreements to the public sphere, where they are portrayed as strongly adversarial, and indeed opinions on soils as a mitigation strategy appear diametrically opposed within the academic literature[1,4,5,7]. We suggest that the debate about the role of agricultural soils in climate mitigation is eroding scientific credibility in the related but distinct effort to protect and restore these soils by rebuilding carbon (Fig. 1).

We synthesize the science supporting actions to rebuild soil carbon for improved fertility, highlight areas of uncertainty, and suggest how to move forward to promote confidence in the scientific credibility of soil health initiatives.

Agreement in soil science

There are agreed foundations in soil science that support intentions to protect and rebuild soil carbon (Fig. 1). All soils — from the most marginal to fertile — are vulnerable to soil carbon losses and fertility decline[2]. In agricultural landscapes, including cropland, grazing land and plantation forestry, soil carbon losses via erosion and decomposition have generally exceeded formation rates of soil carbon from plant inputs. Losses associated with these land uses are substantive globally, with a mean estimate to 2-m depth of 133 Pg carbon[8], equivalent to ~63 ppm atmospheric CO_2. Losses vary spatially by type and duration of land use, as well as biophysical conditions such as soil texture, mineralogy, plant species and climate[8]. Adopting regenerative approaches such as conservation agriculture and agroforestry can protect soil carbon and recoup some losses, by minimizing soil disturbance and maximizing root inputs[3].

New soil forms at decadal-to-centurial timescales, making soils effectively non-renewable; yet fertility can be restored by rebuilding the organic carbon concentrations in the remaining topsoil[2]. The rate and total amount of carbon that can be rebuilt is dependent on biophysical conditions, meaning that the effects of management on soil carbon will differ from place to place and are hard to predict with high certainty for any one locale[3,9]. However, the biophysical controls are understood well enough to set realistic bounds for soil carbon maxima and accumulation rates, and to guide appropriate actions to achieve them. The bounds for accumulation rates do, however, remain poorly constrained: the lower bound is generally agreed to be above zero (that is, there is potential to accrue carbon) and soil scientists generally agree when the upper bound is unrealistically high.

It is hard to narrow the bounds because detection of change in soil carbon at management-relevant time (for example, <5 years) and within-field spatial scales is logistically challenging[9,10]. This is because approximately half of the organic carbon in soil is relatively unaffected by management, meaning that total stocks change slowly[2]. Further, there are pronounced local-scale differences in the amount of carbon stored because biophysical conditions such as soil moisture, that affect the amount of soil carbon, vary markedly within a field. Even within seemingly homogenous fields, a high spatial density of soil observations is therefore required to detect the incremental 'signal' of management effects on soil carbon from the local 'noise'[11]. Given the time and expense of acquiring a high density of observations, most current soil sampling is too limited to reliably quantify management effects at field scales[9,10].

Even with the measurement and verification challenges, most soil scientists agree with the basis for soil health initiatives. That is, that rebuilding soil carbon will translate to outcomes such as reduced erosion and yield stability[2]. Well-demonstrated relationships between soil carbon and desired soil properties (for example, macroaggregation) support these expectations. Further, emerging global datasets support the notion that increasing soil carbon in croplands will increase yields[12]. It is unresolved as to whether these spatial relationships adequately represent outcomes of rebuilding soil carbon over time. Additionally, without proper nitrogen fertilizer management, greater soil carbon can increase emissions of greenhouse gases such as nitrous oxide from agricultural soils[13]. Equally, the effects of soil health practices such as no-till are mixed: while losses of sediment-bound phosphorus to waters may be reduced, dissolved reactive phosphorus losses can increase[14]. Thus, although there is agreement about needing to rebuild soil carbon, quantification of the benefits and potential undesired outcomes is required to specify soil carbon targets that reap the greatest net benefit.

Uncertainty in soil science

The measurement challenges for quantifying change in soil carbon go hand-in-hand with a paucity of large-scale verifiable observations of management effects. Together these challenges make it difficult to adjudicate whether reasonable lower or upper limits for soil carbon change are more likely[1,4–7]. Such uncertainties are

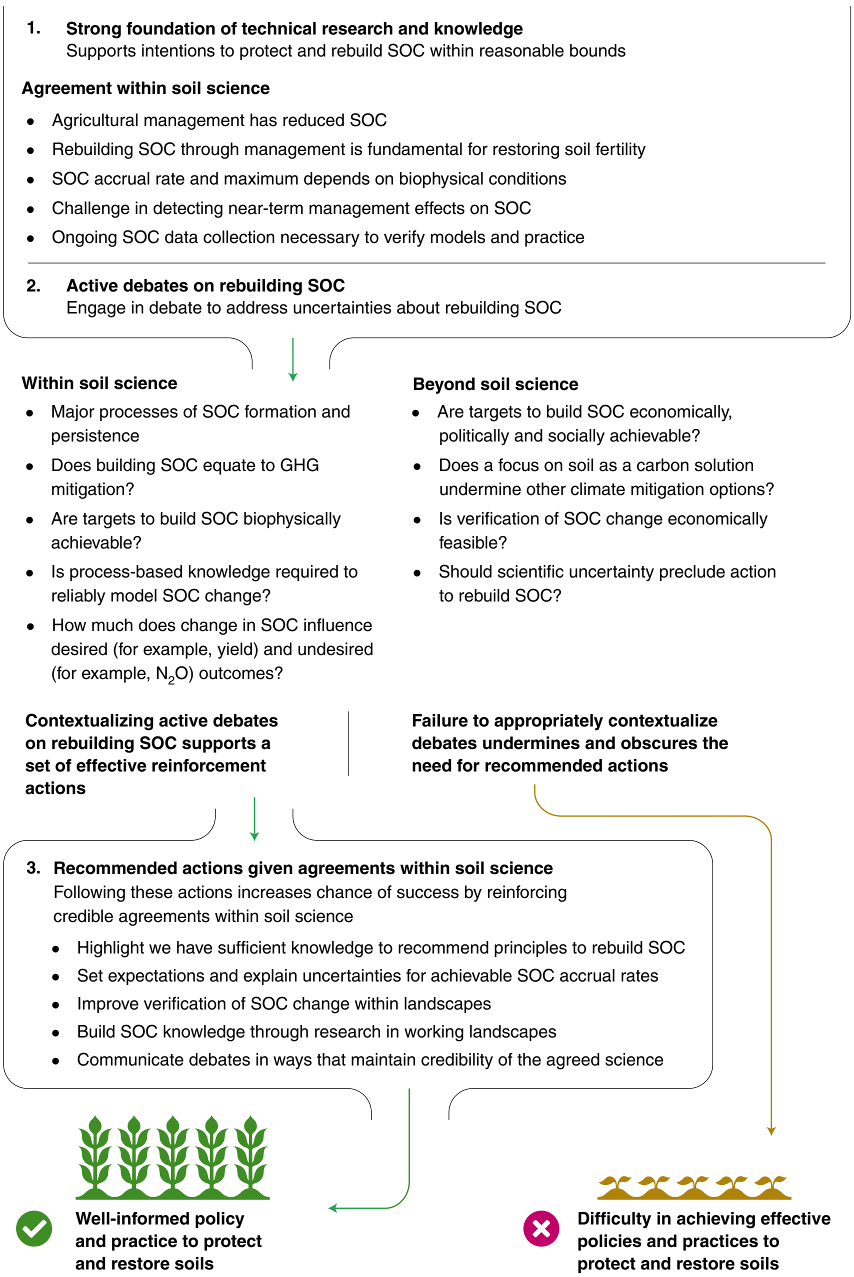

Fig. 1 | Pathways through which knowledge in soil science can flow to inform soil restoration by rebuilding soil organic carbon (SOC). Debate within and beyond the discipline of soil science is critical for addressing uncertainties related to building SOC. However, the way the debate is being conducted — in particular with regards to soils as a climate mitigation solution — is undermining the flow of credible and agreed soil science to inform soil restoration. We suggest that appropriate contextualization of the debates leads to a set of recommended scientific actions that will advance policies and practices to restore soils on working lands. GHG, greenhouse gas. Credit: graphic by Luminant Design.

exacerbating tensions about whether enough carbon can be rebuilt and retained in soils at a rate that meaningfully mitigates climate change. The uncertainty is conflated in the public sphere with the plausibility of soil health initiatives because they similarly rely on rebuilding soil carbon.

Notably, much of the debate about soils as a climate solution extends beyond the traditional expertise of soil science into policy and human behaviour sciences. For example, there are concerns that a focus on soil carbon distracts resources from emission reduction efforts in energy and transportation sectors[1]. Such arguments do not apply to soil health initiatives where the primary goal is to restore soil fertility. The success of climate mitigation and soil health initiatives may, however, both require widespread change in grower practices to rebuild soil carbon at scale[1], necessitating expertise and policy innovation from a wide circle of disciplines. Yet uncertainty about the likelihood of widespread adoption of new practices does not challenge the credibility of the soil science underpinning initiatives to restore soil fertility by rebuilding soil carbon (Fig. 1).

Theoretical advances within soil science do, however, introduce uncertainty into projections of how soil carbon will respond to changing conditions. Specifically, technologies permitting direct observation of the chemistry, form and location of soil carbon are overturning long-held beliefs that the biochemical resistance to microbial breakdown — of plant-carbon inputs and of large macromolecules thought to form through chemical reactions in soils — are primary mechanisms through which soil carbon persists[15]. Instead, the new paradigm suggests that relatively simple molecules, which are otherwise readily consumed by microbes, persist in soil because of their physical location and chemical attraction to mineral surfaces[15]. The rapid generation of fresh insights[16] stimulated by this recent paradigm means there are multiple technical explanations as to how practices might translate to accrual of persistent soil carbon.

Representation of this emerging understanding in soil models is underway[17]. Nevertheless, the more than 40-year history of soil biogeochemical modelling in agricultural systems is based primarily on the long-held paradigm of biochemical resistance[18]. Confidence in the accuracy of projections of soil carbon responses to combined management and environmental change will increase as new modelling efforts represent — often with new data science approaches — the emerging suite of new ideas about controls on soil carbon persistence[11]. In addition, assuming high-resolution field measurement technologies are broadly adopted[19], uncertainty will be reduced as datasets emerge to benchmark predictions and refine parameterizations. Given that these modelling and measurement efforts are relatively nascent[9], in the near term it will remain challenging to state with high certainty the biophysical feasibility of annual-to-decadal target rates for rebuilding soil carbon.

Moving forward

Despite uncertainties, it is important to communicate that a credible scientific basis exists for restoring agricultural soils by rebuilding soil carbon that has been reduced by management (Fig. 1). The message is increasingly obscured by disagreements about whether soil carbon should be included in climate mitigation portfolios[1,4–7]. The conflation of arguments relating to climate mitigation and soil health is not surprising, because many initiatives (for example, 'California's Healthy Soils' and '4 per 1000') share carbon sequestration and soil restoration goals[4]. The confluence of these goals arises from their mutual reliance on rebuilding soil carbon. Yet regardless of one's position on the potential for soil carbon to contribute to mitigation, we submit that rebuilding soil carbon in agricultural soils should be treated as a distinct objective that is well supported by soil scientific knowledge (Fig. 1).

As with restoration initiatives for other natural resources (for example, forests), action can happen despite unanswered scientific questions[20]. For example, neither soil models nor data are yet sufficient for reliably predicting the agricultural and environmental net benefits of rebuilding soil carbon across a broad range of contexts[9,11]. However, soil science can provide technical knowledge to establish expectations for reasonable rates of carbon accrual (even if the difference between the upper and lower bounds is large) and to estimate uncertainties and verify changes in soil carbon. The logistic challenges of measurement at scale will be reduced by development of affordable, accurate, in-field measurement technologies for soil carbon[19]. Raising awareness of current and forthcoming soil scientific knowledge and capabilities should help scientists, policymakers and practitioners alike navigate ongoing debates about soil carbon, thereby ensuring the uninterrupted flow of information supporting soil health initiatives (Fig. 1).

Soil science must also be positioned as one of many fields required to develop effective action to restore agricultural soils through rebuilding carbon. Specifically, soil carbon restoration will likely only be practical through strategies that motivate change in agricultural management and that are consistent with other goals[1,3]. For example, incentives will be necessary in cases where the financial return to growers of adopting practices to rebuild soil carbon are delayed. Yet incentives are not a panacea and there may be instances where calls to build soil carbon may be incompatible with other goals, such as in some native rangelands used for cattle grazing where naturally low soil carbon and hence fertility is important for conserving high levels of endemic plant diversity. A singular focus on soil carbon, then, is unlikely to be consistent with all political, economic, social and environmental contexts under which soil science is applied. By recognizing this wider context of multiple and sometimes competing demands for human and environmental wellbeing, soil science can meaningfully be applied to guide effective policies and actions to protect and restore carbon in agricultural lands. ❐

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References

1. Amundson, R. & Biardeau, L. *Proc. Natl Acad. Sci. USA* **115**, 11652–11656 (2018).
2. Bünemann, E. K. et al. *Soil Biol. Biochem.* **120**, 105–125 (2018).
3. Poulton, P., Johnston, J., Macdonald, A., White, R. & Powlson, D. *Glob. Change Biol.* **24**, 2563–2584 (2018).
4. Rumpel, C. et al. *Nature* **564**, 32–34 (2018).
5. Vermeulen, S. et al. *Nat. Sustain.* **2**, 2–4 (2019).
6. Minasny, B. et al. *Geoderma* **292**, 59–86 (2017).
7. Baveye, P. C., Berthelin, J., Tessier, D. & Lemaire, G. *Geoderma* **309**, 118–123 (2018).
8. Sanderman, J., Hengl, T. & Fiske, G. J. *Proc. Natl Acad. Sci. USA* **114**, 9575–9580 (2017).
9. Harden, J. W. et al. *Glob. Change Biol.* **24**, e705–e718 (2018).
10. Saby, N. P. A. et al. *Glob. Change Biol.* **14**, 2432–2442 (2008).
11. Bradford, M. A. et al. *Nat. Clim. Change* **6**, 751–758 (2016).
12. Oldfield, E. E., Bradford, M. A. & Wood, S. A. *SOIL* **5**, 15–32 (2019).
13. Lugato, E., Leip, A. & Jones, A. *Nat. Clim. Change* **8**, 219–223 (2018).
14. Duncan, E. W. et al. *Agric. Environ. Lett.* **4**, 190014 (2019).
15. Lehmann, J. & Kleber, M. *Nature* **528**, 60–68 (2015).
16. Kravchenko, A. N. et al. *Nat. Commun.* **10**, 3121 (2019).
17. Sulman, B. N. et al. *Biogeochemistry* **141**, 109–123 (2018).
18. Smith, P. et al. *Geoderma* **81**, 153–225 (1997).
19. Viscarra Rossel, R. A. & Brus, D. J. *Land Degrad. Dev.* **29**, 506–520 (2018).
20. Chazdon, R. & Brancalion, P. *Science* **365**, 24–25 (2019).

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