How can better soil health transform our response to climate change?

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1. Objective and Scope of the Paper

In 1938, Charles Kellogg (USDA, n.d.), one of the foremost experts in the field of soil science, summarized soil thusly: "Essentially, all life depends upon the soil… There can be no life without soil and no soil without life; they have evolved together." Soils support over two-thirds of the world's biodiversity and enable nutrient recycling (FAO 2020), which is important for both plants and animals. Kellogg's fundamental insight into the interlinkage between soil and different forms of life is pertinent as we seek to build technocentric solutions to the ecological crises facing the planet today.

Soil health is defined as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans (Doran and Zeiss, 2000). It is a vital component of terrestrial ecosystems and encompasses soil's physical structure, chemical composition, and biological properties, which collectively support essential ecosystem services, including food production, carbon sequestration, water filtration, and biodiversity maintenance (Kibblewhite et al., 2007). Climate change is causing rising temperatures and unpredictable rainfall, which disrupt natural resources, ecosystems, and livelihoods. Note that climate mitigation refers to reducing the emission of greenhouse gases, such as carbon dioxide (CO_2), into the atmosphere; and adaptation refers to efforts to manage the impact of such changes on vulnerable communities and ecosystems.

2. Understanding the Relationship Between Soil Health and Climate

"Soil organic matter contains around 60% carbon," making it "the second largest active store of carbon after the oceans"; however, this carbon flows constantly across plants and the atmosphere through biogeochemical cycles (European Commission, 2011). The ability of soil to hold or release carbon depends on its biological, physical, and chemical properties as well as the changing climate.

The soil-climate relationship operates in an interdependent manner, as shown in Figure 1.

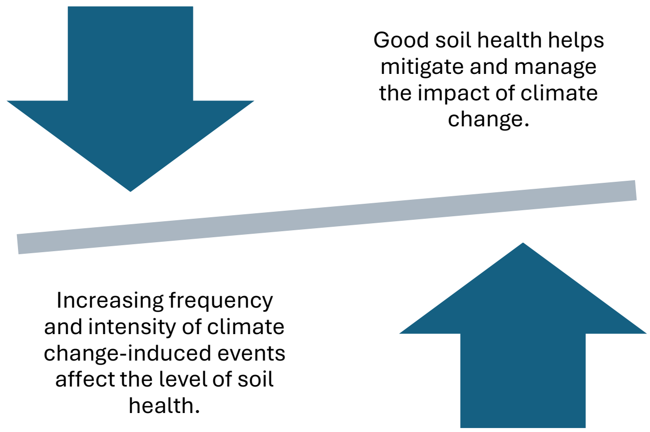

Figure 1. The Soil-Climate Interdependency

Healthy soils play a crucial role in climate change mitigation through carbon sequestration, storing approximately three times more carbon than the atmosphere (Schwartz, 2014). Conversely, climate change alters moisture regimes, accelerates organic matter decomposition, and influences microbial communities in soils (Davidson and Janssens, 2006). Understanding and managing these interactions is essential for developing effective strategies to maintain soil health and address climate change challenges.

3. The Role of Healthy Soils in Mitigating Climate Change

This section explains the principal relationships between good soil health, climate change, and climate action efforts. Two pathways, direct and indirect, connect good soil health with the level of soil organic carbon (SOC) captured in the soil, leading to climate mitigation.

3.1. The Direct Relationship Between Soil Health and Soil Organic Carbon

Healthy soils are vital in addressing increased concentrations of CO_2 (Cho, 2018). Through photosynthesis, plants convert atmospheric CO_2 into biomass, which decomposes into SOC. SOC stabilization occurs through microbial processes, aggregate formation, and interactions with mineral surfaces, particularly in deeper soil horizons (Fontaine et al., 2007). Soils currently store an estimated 2,400 Gigatons of carbon globally, three times the carbon in the atmosphere (Batjes,1996). Several soil health management practices, particularly agroforestry and biochar, have been reported to enhance SOC storage. Agroforestry systems, for example, have demonstrated increases in SOC stocks of up to 33% due to root biomass inputs and litter decomposition (Beillouin et al., 2023; Cardinael et al., 2017). Similarly, biochar application has been shown to increase SOC by 10-35% over a decade, with the added benefit of long-term stability, ie; it is less likely to be converted back into C02 by microbes. (Lehmann et al., 2021). Additionally, Ouédraogo et al., (2006) report that in semi-arid West Africa, no-till practices have been found to reduce SOC loss and reduce carbon mineralization in the fine fraction and enhance organic matter incorporation in the coarse fraction compared to tilled plots, promoting SOC stabilization. Furthermore, they also state that use of crop residues increased SOC by improving organic matter incorporation and lessening the decline in stabilized soil fractions.

Over four decades, the International Fertilizer Development Center (IFDC) has developed and applied effective practices that improve soil health and its impact on SOC. IFDC projects have demonstrated that urea deep placement (UDP), a soil health and fertility management technology, minimizes nitrogen losses occurring through runoff and volatilization, reducing soil organic matter degradation, while balanced fertilization enhances biomass production and return of residue to the soil, promoting SOC buildup (Vanlauwe et.al 2023). Subsoil carbon sequestration, a relatively underexplored area, also holds significant promise. Research suggests that carbon stored at a depth of 30 cm or more contributes to more than half of total soil carbon stocks, with stabilization occurring over millennia (Shi et al., 2020). Deep-rooting crops and perennial grasses are critical in transferring carbon to these deeper soil layers (Kell, 2011).

However, climate change and its impact in terms of land degradation can adversely affect the ability of soil to store carbon. Storage of SOC faces challenges, including saturation limits and the vulnerability of stored carbon to disturbances, such as changes in land use and rising temperatures (Smith et al., 2008; Sanderman et al., 2017), driven by climate change. For instance, unsustainable agricultural practices have resulted in the loss of 133 Gt of SOC over the last two centuries (Sanderman et al., 2017). In this context, promotion of sustainable land and soil health management strategies, such as the use of organic amendments, agroforestry, and conservation tillage (systems of managing crop residue on the soil surface with minimum or no tillage), is needed to address these issues, such that the climate mitigation potential of soil is maximized.

3.2. The Indirect Relationship Between Soil Health and Soil Organic Carbon

Through various essential tasks, microbial activity plays a critical role in carbon stabilization and soil functionality. A healthy microbial community is frequently a sign of a strong and fertile soil ecosystem, as soil microbes are important markers of soil health (Suman et al., 2022). Microbes assist in the breakdown of organic matter, dissolving complex substances into vital nutrients that plants can absorb (Kumari et al., 2023). Microbes also improve soil structure by generating chemicals such as glomalin, encouraging soil aggregation and stability (Kumari et al., 2023). Previous studies have shown that microbial residues, or necromass, contribute significantly to SOC, particularly in deeper soil horizons (Liang et al., 2017). Microbial processes break down plant biomass into stable carbon forms protected by mineral associations and physical occlusion (Cotrufo et al., 2013). In fact, microbial-derived carbon accounts for 15-80% of stable soil carbon (Angst et al., 2021).

Additionally, IFDC-supported practices, such as organic input use, conservation tillage, and combined application of organic and mineral fertilizers, have been shown to enhance microbial activity by providing substrates for soil organisms, promoting nutrient cycling, and improving soil structure. These microbial processes are critical for SOC stabilization and overall soil health (Vanlauwe Et. Al, 2023). While microbial necromass is crucial for carbon stability, its accumulation and recycling are highly sensitive to environmental conditions, such as temperature and substrate availability (Buckeridge et al., 2022). The incorporation of practices to improve soil health, such as application of biochar, has the potential to improve microbial activity and carbon stabilization; however, field evidence is inconsistent across various soil types and climates (Lehmann and Joseph, 2015). Additional research is required to comprehend the long-term interactions between carbon sequestration, organic amendments, and microbial processes, particularly in subsoils. This in turn can strengthen the indirect pathway between good soil health and climate mitigation.

4. The Role of Soil Health and Practices that Support It in Climate Adaptation and Ecosystem Resilience

Through their control of water cycles, reduction of erosion, and enhancement of biodiversity, healthy soils improve ecosystem resilience, strengthening the capacity of systems to adjust to climate . For example, organic matter-rich soils can better hold water, lessening the intensity of floods and droughts (Hinzmann et al., 2021). Organic amendments, such as compost, improve soil structure, increasing its capacity to hold water and nutrients while mitigating erosion in degraded landscapes (Lehmann and Joseph, 2015). Cover cropping protects soil from erosion, enhances organic matter inputs, and improves water infiltration, contributing to greater resilience during extreme weather events (Basche and DeLonge, 2019). Conservation tillage practices, such as reduced-tillage or no-till systems, maintain soil structure and organic matter levels, improving water and nutrient-use efficiency (Valkama et al., 2020). In agroforestry systems, the integration of trees improves soil porosity and stabilizes soil aggregates, leading to greater resilience to extreme weather events (Beillouin et al., 2023). Such systems also promote microbial biodiversity, key to maintaining nutrient cycling and ecosystem stability (Smith et al., 2008). However, field studies quantifying the long-term impacts of these practices across diverse agroecological regions are limited, creating a need for research into their broader applicability.

5. Challenges in Improving Soil Health Under a Changing Climate

While the advantages of healthy soils in mitigating climate change are evident, numerous obstacles remain. One significant constraint is that the potential for soil carbon sequestration is finite, and the potential for SOC storage is contingent upon environmental conditions, management practices, and soil types (Smith et al., 2008). Moreover, several additional interrelated challenges, such as knowledge and data gaps, governance shortfalls, and resource constraints, often limit the widespread adoption of sustainable soil management practices.

Incomplete knowledge of soil processes, particularly subsoil dynamics, impedes the development of targeted interventions. While topsoil has been extensively studied, subsoil processes play a critical role in long-term carbon sequestration and nutrient cycling but remain underexplored (Shi et al., 2020). Similarly, the effects of extreme weather events, such as droughts and floods, on soil health require further study; droughts can suppress microbial activity and carbon inputs, while floods exacerbate soil erosion and nutrient loss, undermining SOC retention (Radulov et al., 2023). Inconsistent soil monitoring systems further hinder the ability to accurately assess the long-term effectiveness of sustainable practices and to subsequently identify priority areas for intervention, particularly in regions where soils are most degraded (Sanderman et al., 2017).

Resource limitations also impede the implementation of sustainable soil management practices. Farmers in resource-limited regions often lack access to affordable inputs such as organic amendments or biochar, which are essential for enhancing soil health (Lehmann and Joseph, 2015). Limited access to agricultural extension services further restricts the dissemination of knowledge and technologies. In particular, advanced techniques such as precision agriculture, which optimize carbon inputs and reduce greenhouse gas emissions, are however hamstrung by their high upfront costs and technology complexity (Nguyen, Halibas and Nguyen, 2022). Additionally, the lack of reliable soil health monitoring systems undermines efforts to track progress and implement adaptive management strategies (Radulov et al., 2023).

6. Conclusion and Next Steps

The world's soils can thus provide the twin benefits of mitigating and managing the impact of climate change, but only if there are adequate efforts to build and maintain good soil health. Further, addressing these challenges requires a concerted effort to close knowledge gaps, strengthen governance frameworks, and improve resource availability. Precision agriculture techniques offer opportunities to reduce greenhouse gas emissions and optimize carbon inputs, but scaling these solutions requires targeted investments in research, infrastructure, and training. The following are key priorities:

6.1. Data collection and study on the effects of expanding soil health, microbiological processes, and subsurface carbon dynamics must absolutely be increased, and global consistency is essential. Establishing such studies will produce consistent data ready for use to guide focused treatments.

6.2. Integrating soil health into climate change policies and providing financial incentives to producers for the adoption of sustainable practices can motivate substantial change. Subsidies, training, and policy frameworks should support programs such as agroforestry, conservation agriculture, and biochar application.

6.3. Scaling up infrastructure for soil health monitoring and extension services and improving access to reasonably priced inputs would enable farmers to apply sustainable soil management practices, especially in resource-limited areas.

In summary, soil health management practices such as those outlined above can play a critical role in building up SOC levels, contributing to improved carbon sequestration. This improvement would have a significant long-term impact on global temperatures, enabling all life to thrive. In addition, better soil health would improve the quality of ecosystem services, improving their ability to manage the fallout of extreme weather events induced by climate change in the near term. With additional research on the specific topics mentioned above, we can improve our understanding of the per dollar value of soil health improvements and how institutions and regulators can enable these improvements to be made at scale.

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