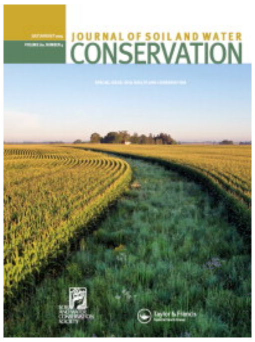

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A SECTION: DISCUSSION

Soil organic matter: The heart of soil health

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Soil, the "skin of the Earth" or *geoderma*, is the basis of all terrestrial life. It is the ultimate source of critical ecosystem services (ESs) for nature and humans. It is the only entity in the universe that can transform or resurrect death into life. However, soil as a resource is finite, unequally distributed over the landscape, and prone to degradation by natural and anthropogenic factors. Because of its importance to nature and humans, the protection, restoration, and sustainable management of soil and its health are more important now than ever before. Indeed, there exists a strong need for cooperation between public and private sectors, scientists and extension agents, and the general public from all walks of life to judiciously manage this finite, fragile, and precious natural resource.

OVERVIEW OF SOIL ORGANIC MATTER

The term *soil health*—meaning the capacity of soil to function as a living ecosystem that sustains plants, animals, and humans (Doran and Zeiss 2000)—has received a lot of attention since the onset of the 21st century. Being a highly dynamic entity, soil and its health have a strong spatial and temporal variability. Therefore, soil health refers to the state of the soil at a given location, time, land use, and management within a specific environment. Soil health is also a relative term, and so it has to be compared with some known or preestablished baseline. *Health*, being an attribute of a living and dynamic body, emphasizes that soil is a living entity, a concept similar to that of the Gaia hypothesis (Lovelock 1979). In other words, soil is teeming with life and is a habitat for as much as 59% of all living organisms (Bardgett 2023). Being the energy source of all soil biota, the concentration and properties of soil organic matter (SOM) content in the root zone (which is the top 30 to 50 cm of a soil layer) are key determinants of soil health. Simply put, a decline in SOM content to below a critical level can severely jeopardize soil's functions and related ESs that it generates. Global soil health is critically important to meeting the demands of food and nutritional security for a growing and increasingly affluent human population. As the medium in which to grow plants, the source of plant nutrients and water, and a provider of supportive environments for root growth and proliferation, the quantity and quality of food produced for humans depend strongly on soil health and its sustainable management.

Soil health, dependent on its SOM content, moderates several pedological processes that affect plant growth directly and indirectly. Among its direct effects are being a medium for root growth, providing storage and uptake of water and nutrients, cultivating symbiotic relationships with soil microorganisms, and recycling biomass. Notable among its indirect effects are the reduction in pests and crop diseases (Schlatter et al. 2017), enhanced flavor of food, and the adaptation to and mitigation of anthropogenic climate change by sequestrating atmospheric carbon dioxide (CO_2) and reducing methane (CH_4) and nitrous oxide (N_2O) emissions. Soil health is also effective at moderating air quality by serving as a filter and reservoir for pollutants and

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supporting plant growth that is a source of oxygen (Giltrap et al. 2021; Keesstra et al. 2012).

Despite being a source of numerous ESs (Figure 1), soil is often taken for granted and left to fend for itself. As much as 40% of global land area is degraded because of land misuse and soil mismanagement (Dickinson 2024). Thus, the objective of this article is to highlight SOM content's capacity to moderate soil health and generate critical ESs.

SEQUESTERING SOIL ORGANIC CARBON IN AGROECOSYSTEMS

Soil carbon (C) has two distinct but related components: soil organic C (SOC) and soil inorganic C (SIC). SOC is derived from the input of biomass, which undergoes microbial decomposition to form humus and organo-mineral complexes. Thus, one strategy for managing SOM content is to create a positive soil C budget so that the input of biomass C into soil exceeds its losses. In general, soil agroecosytems are depleted of their SOC stock because the loss of SOC has been greater than its biomass C input due to accelerated soil erosion, decomposition, and leaching. Losses of SOC by these and other processes are aggravated by the use of extractive farming practices: plow-based methods of seedbed preparation, indiscriminate use of chemicals (fertilizers and pesticides), residue removal or in-field burning, excessive grazing, and flood irrigation with poor-quality water. Because agroecosystems have lower SOC stock than soil under natural ecosystems, agroecosystem soils have a C sink capacity that can be harnessed by site-specific adoption of appropriate land use and best management practices (BMPs). Agricultural practices that create a positive SOC budget, called C sequestration or C farming (Lal 2023), fall under the general term of *regenerative agriculture*. Since there is no one-size-fits-all solution, a wide range of practices fall under the broad umbrella of regenerative agriculture (Lal 2020), and thus, site-specific decisions are critical.

SOIL ORGANIC MATTER AND SOIL HEALTH

Increasing SOM content by C sequestration has a positive impact on soil health, especially in significantly depleted and degraded soils. Increasing SOC content or C sequestration has a strong effect on the physical, chemical, biological, and ecological properties and processes that moderate soil health (Figure 2).

The process of SOC sequestration is moderated by plant-microbe interactions (especially bacteria) through the application of compost in managed grassland ecosystems (McClelland and Schipanski 2025). An increase in SOM content often leads to changes in pedological processes and improvements in the soil health index (Liptzin et al. 2022; Nunes et al. 2021b; Wulanningtyas et al. 2021). Experiments with compost in India by Das, Liptzin,

Figure 1. Some of the essential ecosystem services provided by a healthy soil.

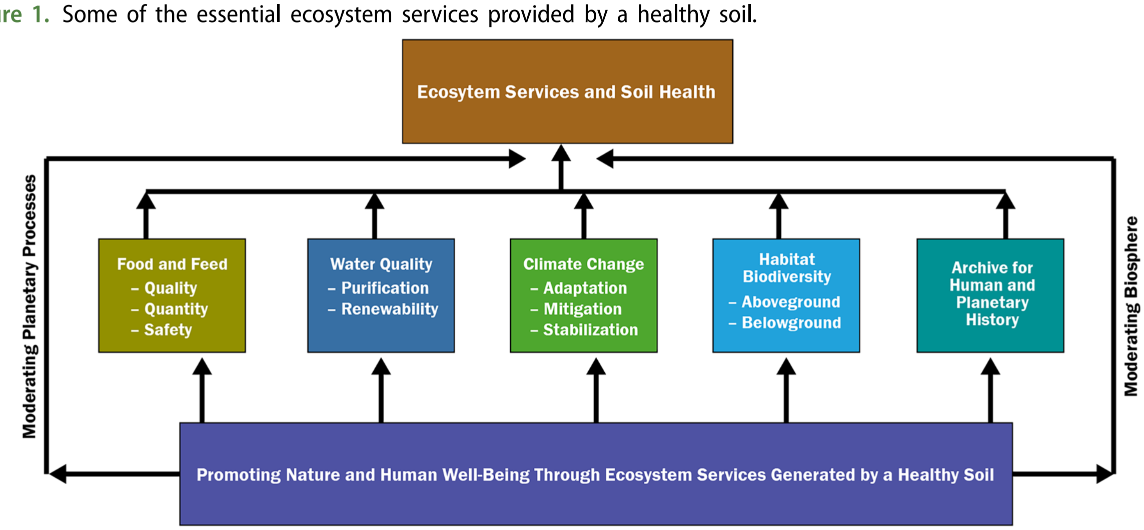
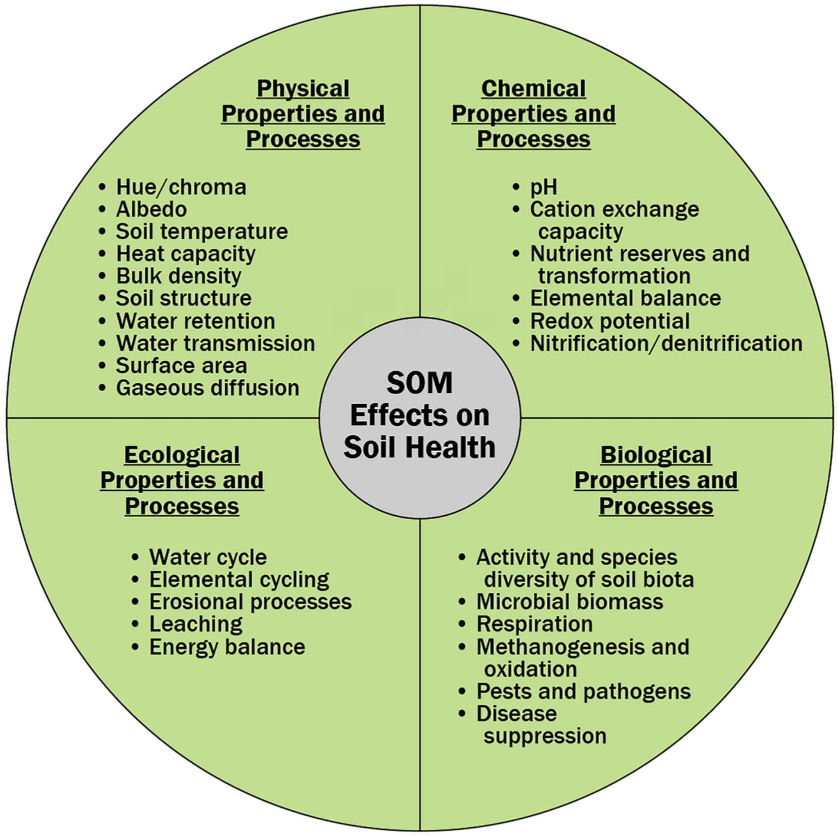


Figure 2. Effects of soil organic matter (SOM) content on soil health by its moderation of physical, chemical, biological, and ecological properties and processes.



and Maharjan (2023) indicated that it improved SOC stabilization and water holding capacity.

Effects of plant species

A study conducted by Chen et al. (2025) in the Huron Mountains in Michigan, United States, showed that aggregate size distribution and SOC stock differed significantly among forest types, with a white birch (*Betula papyrifera* Marsh.) and eastern hemlock (*Tsuga canadensis* [L.] Carr.) mixed forest exhibiting the highest proportion of large macroaggregates (>1 mm), which contributed to a favorable soil structure. Studies on pesticide-free, integrated farming systems show that, similar to the effects from trees, SOC sequestration and soil properties are affected by different crops and cropping systems (Colnenne-David et al. 2023; Finger 2024; Jacquet et al. 2022). A study conducted by Ankit et al. (2024) in India showed that soil under a rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.) cropping system had significantly higher total organic C (TOC) and SOC content compared to soil under a pearl millet (*Pennisetum glaucum* L.)–mustard (*Brassica juncea* L.). cropping system. The principal component analysis by Ankit et al. (2024) showed that TOC, SOC, pH, and electrical conductivity were reliable indicators for assessing soil health under different cropping systems.

Interactions among species, both above- and belowground, are also important to ecosystem functions, such as SOC content moderated by soil biodiversity. While some crop functional types and crop diversification are better than others, the effect varies among soils and environments (Wooliver, Kivlin, and Jagadamma 2022). A long-term study on soil health in semiarid drylands showed that perennial grasses could regenerate these lands, increase SOC storage, and improve soil health (Arije et al. 2024). A regression model showed that a permanent grass field would reach saturation of mineral-associated SOC in about 80 years at the 0 to 15 cm depth and 230 years at the 15 to 30 cm depth. These data show the enormous potential of SOC sequestration in arid and semiarid drylands with grassland restoration.

Conservation agriculture and cover cropping

There is a growing interest in conservation agriculture (CA) for soil and water management and SOC sequestration. The effects of CA on SOC content may also have interactions with cover cropping (Crystal-Ornelas, Thapa, and Tully 2021). Cropping system data from six sites in southwest Germany over 10 years by Attia et al. (2024) showed that the inclusion of commonly grown nonlegume and legume cover crops increased SOC content by 6% to 8% and organic nitrogen (N) content by 3% to 12%. Further, crop rotations with cover cropping increased the water productivity of cereal crops but did not increase the yield of winter and spring barley (*Hordeum vulgare* L.) or silage maize (*Zea mays* L..). Wulanningtyas et al. (2021) observed that a combination of no-till and cover cropping with rye (*Secale cereale* L.) is a good technique for restoring soil health in Andisols by improving SOC content. The effects of CA on SOC sequestration also depend on the rate of N application (Tigga et al. 2020), because decomposing crop residues can immobilize N and reduce its availability to plants. However, changes in crop yield may or may not be related to changes in soil properties. At 0 to 5 cm depth, the SOC content was up to 12% higher in cropland compared to that in soil under other farming systems, probably because of differences in the input of biomass C.

Agroforestry

Agroforestry, the deliberate growing of seasonal crops with perennial shrubs and trees, is widely practiced in the tropics. Based on a study in Tanzania, Kimaro et al. (2024) reported that the highest gain in soil health was observed in indigenous agroforestry systems, such as those involving mixed species. Sainju, Liptzin, and Stevens (2022) reported that the use of no-till with continuous cropping increased SOC but had only a limited effect on N fertilization. Furthermore, tillage and N management had little effect on SIC content, and they found that soil total C (STC) may be used as a potential soil health indicator (rather than SOC) in relation to crop yield and other ESs.

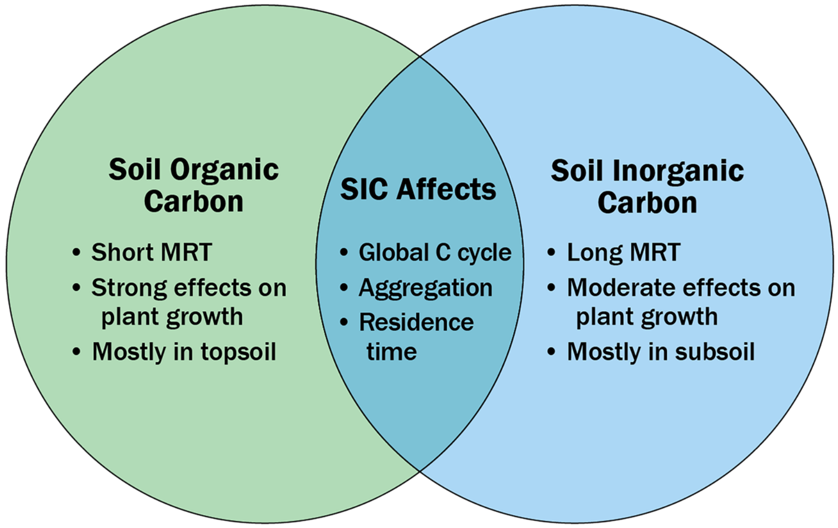
Biochar

Biochar, a popular amendment since circa 2000, is used to enhance soil health, sequester SOC, and increase productivity. However, responses to biochar are soil-, crop-, and environment-specific. Zhang et al. (2023) observed that biochar use is more effective in soils of the tropics, which register more SOC, total N, and crop yield with biochar than without biochar. Stover removal for other purposes (i.e., biochar or cattle feedstock) can also have a strong impact on SOC sequestration, depending on the site and soil. For example, Nunes et al. (2021a) reported that stover harvest increased the depletion of macro- and micronutrients but did not affect average grain yields for different crops, even though there were significant differences in SIC and SOC content, bulk density, pH, C, and cation exchange capacity. No effect of residue removal on crop yield may be due to the input of fertilizers and the short duration of the study.

CRITICAL LIMITS OF SOIL CARBON

Effects of CA on SOC content and soil health must be studied for deeper subsoils (50 to 60 cm depth) in addition to the surface layer (0 to 10 cm depth). Based on a nine-year-old study on CA in India, Modak et al. (2019) observed that in 0 to 5 cm and 5 to 15 cm layers, soil under CA (no-till) management had 26% and 15% more macroaggregate-associated C than that of soil under plowed plots. Similar trends were observed for microaggregate-associated recalcitrant C. Modak et al. (2019) concluded that CA practices in combination with crop residue retention have vast potential in enhancing deep C sequestration and the C stability of aggregates to sustain soil health and agronomic production. Variability in response to increases in SOC content on pedological and agronomic practices (plant growth and yield) depends on a range of soil, crop, land use, and management (i.e., fertilizer use, supplemental irrigation) factors. Based on a 67-year-old

Figure 3. Interactions between soil organic carbon (SOC) and soil inorganic carbon (SIC) affect the global carbon (C) cycle and other pedological processes. MRT is mean residence time.



study on composting, fertilization, and amendment use on an Alfisol in India, Rahaman et al. (2024) reported that SOC and total N contents were higher and bulk density lower in soil receiving manure compared with those that were not manured. Furthermore, the input of lime increased soil pH and enhanced microbial activity and nutrient availability, leading to a higher crop yield. Thus, Rahaman et al. (2024) recommended the integrated use of compost and fertilizers in addition to lime for a long period of time to improve soil health and increase agronomic productivity and sustainability. A study of high altitude soils in the northeastern region of India by Prasad, Ram, and Barooah (1981) showed that the critical level of SOC content is 1.5% to 2.25%.

RELATIONSHIP BETWEEN SOIL ORGANIC AND SOIL INORGANIC CARBON

Global drylands cover almost 45% of Earth's area and predominantly contain SIC more than SOC stock, affecting the dynamics of CO_2 in soil C (Helmrich, Ringsby, and Maher 2025). Yet, SIC is frequently overlooked in global soil research (Raza et al. 2024), even though SIC has a longer mean residence time (MRT) than SOC and a strong impact on the global C cycle. However, there are different drivers of SOC and SIC stocks, especially in relation to soil depth, that must be considered (Pan et al. 2022). Similar to SOC, loss of SIC from soil strongly affects the global C cycle (Raza et al. 2024) and must be taken into account in the context of mitigating and adapting to climate change. Regardless of the differences in properties and processes of soil formation, there exists some relationship between SOC and SIC, especially in soils of arid climates (Figure 3). Based on a study in the Loess cropland soils of Fengu Basin in China, Lu, Wang, and Zhang (2020) observed a significant negative correlation between SOC and SIC stock, probably due to erosion, redeposition of topsoil, and differences in soil pH. In dryland croplands of the United States, Sainju, Liptzin, and Stevens (2022) observed that crop yield is related to STC content (a combination of both SOC and SIC). Further, determination of STC is a more rapid process than separately measuring SOC and SIC content. Carter et al. (2024) measured STC by the dry combustion method. The lack of attention to SIC dynamics could undermine ongoing efforts to mitigate climate change by sequestering CO_2 in soil-based sinks (Raza et al. 2024).

CONCLUSIONS

Soil health is important for providing numerous ESs for humans and nature. Yet, soils of agroecosystems are often depleted of their SOC stock because of extractive farming practices. Maintenance of SOC stock to above the critical limit for a specific biome is critical to the sustainable management of soil health. SOM content is the heart of soil health.

In general, soil health is better with the adoption of system-based conservation agriculture, agroforestry, and soil fertility management that combines organic and inorganic sources of plant nutrients. Judicious management of soil health is more important now than ever before because of the growing and increasingly affluent human population with numerous demands on the geoderma of our planet.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

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