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How Much Margin Is Left for Degrading Agricultural Soils? The Coming Soil Crises

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Perspective

How Much Margin Is Left for Degrading Agricultural Soils? The Coming Soil Crises

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Abstract: Agricultural soils are in peril. Multiple lines of observational and empirical evidence suggest that we are losing the world's fertile soils at an alarming rate, worsening the on-going global food crisis. It is increasingly clear that the risk of soil crises driven by erratic precipitation, warming air, and farming mismanagement is coming sooner rather than later. At this critical time, society cannot avoid looking for ways to curb soil crises. We argue that now is the right time for science-based mitigation strategies and new insights to protect soils. We offer four research priority areas that society needs to address. Arresting and reversing the ongoing soil degradation are tantamount to safeguarding humanity and the environment. To the extent that we continue to treat soil crises as a problem for farmers only—not as a global challenge—we only escalate the scale to which the problem will grow in time and complexity.

Keywords: soil health; drought; soil organic carbon; reduced tillage; cover cropping; soil organic matter; agricultural work force

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1. Introduction

Agricultural soils are at a breaking point. Through action and inaction, people have transformed soils in wide-ranging subtle and not-so-subtle ways, with devastating consequences. About 34% (1660 million ha) of Earth's agricultural land is degraded [1], and 90% of the Earth's land area could become degraded by 2050 [2]. Although large uncertainties remain [3], the 2017 FAO Global Soil Partnership report showed that each year, an estimated 75 billion metric tons of fertile soil is eroded from arable lands globally [4,5]. The modern era teaches us that soils are not infinitely resistant or resilient to shocks and mismanagement [6], but require careful and sustained management and stewardship for a food-secure planet [7]. The widespread misunderstanding that soil is infinitely mineable has led to crop failures, often with crippling economic and human costs globally [8–10].

The loss of fertile soils profoundly affects farming and farming communities directly, but the consequences go beyond the soil realm and are pervasive [7,11]. The 1930s' Dust Bowl in the United States and the 1990s' Sahel droughts in Africa are grim reminders to better prepare for future soil crises [12–14]. The world faces tremendous challenges with resource degradation including soils, water, air, and natural vegetation. Considering that soils are under threat globally [11,15], we are compelled and required to make sustained investments in soils, climate smart farming practices, and practices that enhance soil quality [16], and much is expected from soil science and practitioners to respond to these challenges [17,18].

The current soil degradation crisis brings to mind President Franklin D. Roosevelt's quote: "A nation that destroys its soils destroys itself." His message remains true today as it was some 85 years ago. The warning came when much of the United States' croplands were challenged by unprecedented soil erosion, threatening the economy and millions of livelihoods. At the height of the Dust Bowl (1934 and 1935), an estimated 1.2 billion tons of soil was stripped from 40 million ha of farmland across the Great Plains of the United States [5,19]. This resulted mainly from a combination of climate anomalies, soil mismanagement, and climatic and edaphic factors [13,14,20]. Today, we are reminded of that legacy of neglected soils and the grave human and economic consequences it brings to society should our indifference continue. Arguably, for the United States and for many countries worldwide, research to achieve healthy soils is one of the defining challenges of the moment [21,22]. Additionally, beyond recognizing that soils are an essential component of our ecosystems, insights and perspectives are emerging that frame soil health as one of world' s grand societal and environmental security priorities [23,24].

This complex and entrenched relationship between soil and humans is increasingly becoming tenuous in the face of a changing climate [25]. An estimated 3.2 billion people are harmed by global land degradation [2,7,10] with the highest number in South and East Asia, the Sahara Region of North Africa, and the Middle East [1,8,26]. This is against the backdrop that while 90–95%of global food comes from soils [1,27], only 11% (~15.6 million km^2) of the globe's land surface (134 million km^2) is used in crop production [28,29]. Our time demands we find comprehensive solutions to soil degradation. A key step to making soils sustainable is evaluating—and subsidizing—suites of cropping and soil management interventions, not only on the basis of economic profitability, but also by the multiple ecosystem services that soils render [24,27].

2. Soils in Crisis

Soil, as the foundation for much of life on Earth, requires careful management and an understanding that its health and protection are paramount to ensuring a food-secure world [30]. According to the United Nations to Combat Desertification report, an estimated 24 billion tons of the world's fertile soil is lost annually to erosion [2,10]. This trend, characterized by a slow and steady decline in soil quality, has a ripple effect on productive farmlands, especially on dry-land agriculture, and is projected to continue as climate change intensifies [31,32]. Of central importance are efforts to curb soil degradation and erosion. For example, despite a national response to soil losses of the 1930s' Dust Bowl era, a new study showed that nearly one-third of the land devoted to growing major crops across the United States Corn Belt has lost its fertile topsoils [33]. In the United States, estimates of soil erosion from cultivated croplands range from 4.6–11.5 t/ha/y, [34] with much higher losses following extreme weather events [35]. According to the Union of Concerned Scientist, U.S. croplands could lose an estimated 28 billion tons of soil by 2035 and 148 billion tons by 2100 [36].

Current soil degradation may not have the presence of other crises societies are accaccustomed to, such as energy and food crises, but the complexity and magnitude of ongoing soil loss is real, great, and compelling. Soil is a finite and grossly underrated, human-enabled natural resource. Soil degradation, through erosion, compaction, acidification, salinization, contamination, and urbanization, substantially narrows the limited margins left in agricultural soils for safe operation [37] and is stretching farming and farming communities to their breaking point globally [1]. Left unchecked, these factors, combined with a changing climate, have far-reaching ramifications across a range of scales, from the local to the global farming community.

To the extent that we continue to treat the soil problem as a problem for farmers only—not as a global challenge—we escalate these problems, which will grow with time and in scope and severity. Soil degradation and loss of soil health are multidimensional—they threaten a nation's capacity to feed its population, create food insecurity, disrupt peace and stability, and cause civil strife and conflicts [38,39]. According to the World Bank's Development Report, the world's food production must increase by 70% between 2005/2007 and 2050 to feed projected population growth [40]. With current and projected rates of soil degradation [2,10] and considering unmet needs and future research priorities, the promise of meeting this goal looks uncertain [28]. Far too many studies that address changes within soil ecosystems have taken a relatively narrow approach limited to a soil's capacity for a specific function. We need a systems approach that embraces holistic and synergetic crosscutting research focus on soil health [17,41]. This fact underscores the extent to which soils are inextricably linked to human and environmental wellbeing. We offer four crosscutting soil research priorities (soil health, soil organic carbon and conservation practices, climate change and soil organic carbon loss, and training the new agricultural work force) that we suggest are necessary to mitigate soil degradation and restore its health.

3. Research Foci

3.1. Enhancing Soil Health—The New Paradigm

Soil means different things to different people. To soil scientists, the very thin layer of soil sitting on the Earth's crust is a natural, non-renewable resource (at least at the human scale) without which life on Earth is all but impossible [42]. We have learned at high cost [43] the important lesson that no farming system can be better than the quality of its soils [44]. Without soil health, there is no human health. Agronomists and soil experts make a compelling case that the current environmental crises could be with us in one way or another until soil health is restored.

Soil health, which is a qualitative descriptor of a soil's capacity to deliver ecosystem services [45], is often described as a "wicked" environmental problem [23]. Most studies that address changes within soil ecosystems have taken a relatively narrow approach limited to a soil's capacity for a specific function. For farmers, soil productivity is a dominant issue [46]. Such approaches often miss important interconnections and linkages [47]; there is limited appreciation of soil's complexity. Traditionally, a healthy soil can be valued for the multiple benefits it provides to agriculture and the environment [48]. However, the traditional definition of soil health is limited in scope and does not provide a clear definition of what "needs to be improved" other than focusing on what healthy soil would mean.

Conceptually, soil health treats the soil as a unique ecosystem that sustainably supports plant, animal, and human life through the interaction and interdependence of multiple physical, chemical, and biological factors (Figure 1). Optimizing soil health is best achieved through measures and actions where the three underlying properties (physical, chemical, and biological) are improved concurrently, not independently. The soil health indicator (e.g., soil structure, soil organic carbon) should also be one that lends itself easily to quantification and management.

The key research areas associated with this new paradigm are evidence-based sustainable management strategies to enhance the three components. The traditional concept of assessing soils from disparate views of physical, chemical, or biological properties separately is outdated. Rather, we need to redefine soil health embracing the interconnectedness of the three elemental properties, along with ecosystem and human impacts [49–51]. Additional research areas include the valuation of soil health and, with it, quantifiable parameters that can be measured to show changes in soil health [52].

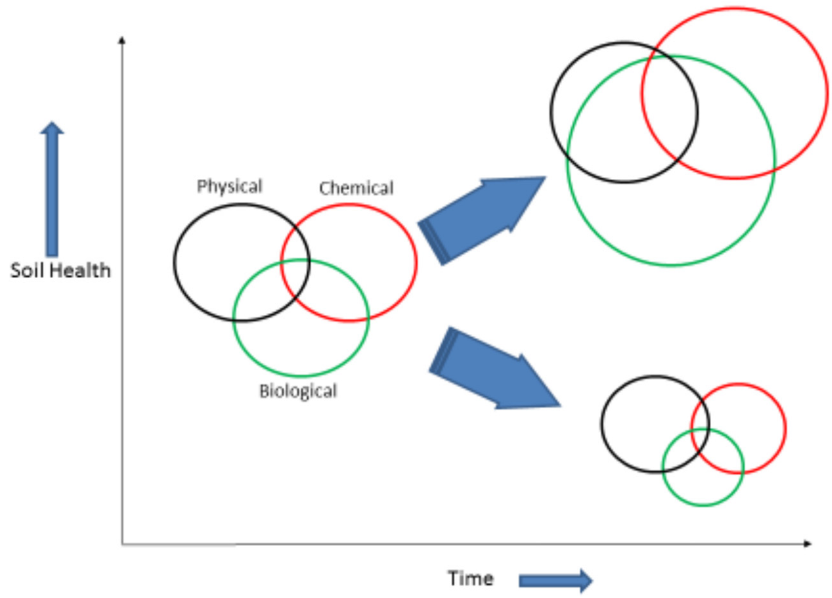

Figure 1. Soil health combines physical, chemical, and biological properties that interact sustainably to support animal and plant life. These properties (represented by circles in this diagram) respond differently to management, some changing quickly (the circles growing much larger, such as the biological properties) and some not (such as the physical properties). The goal with time is to create a soil state in which the intersection of the optimal physical, chemical, and biological properties is as large as possible. Depending on soil management, soil health can therefore be improved (upper right) or degraded (lower right) if one or more of the supporting components is ignored or degraded.

3.2. Understanding Soil Organic Carbon—Its Loss, Protection, and Accretion

Soil organic carbon (SOC), one of Earth's most important natural resources, is a key indicator of soil health [53]. Terrestrial soils are a major C reservoir, with estimates ranging between 1500 Gt C and 2400 Gt C (~5500–8800 Gt CO2) stored in the top meter of soil alone [54,55]. Soil organic carbon has many crucial roles: providing nutrients for macro-faunal populations, improving water soil moisture retention and infiltration rates, supporting soil-derived ecosystem services, ensuring agronomic productivity, and therefore food security, and maintaining human and animal welfare [56]. Recent attention to climate change perturbation has renewed interest in understanding how fast and by how much SOC changes with time (its formation and destruction) and across relevant ecological spatial scales [57]. A key step to making soils sustainable is evaluating cropping and soil management interventions not only on the basis of narrow ranges of profitability, but also by the multiple ecosystem services rendered, including benefits associated with SOC sequestration and its long-term stability [58]. Specifically, we need to develop a predictive understanding of where SOC exists through a combination ground-based SOC measurements, lab experiments, spatial statistics, and remotely sensed information and by linking point measurements to large-scale applications, to better map landscape-scale SOC [58,59]. Research during the last three decades has provided many insights into the importance of SOC to soil's physical properties [60] and ecosystem services [61] such as climate regulation [62], water retention [63], climate change and carbon cycling [64,65], and crop yield and productivity [66,67]. For example, studies in Michigan [68] and Maryland [69] demonstrated substantial benefits to yield by small increases in SOC.

Taken together, these properties and services, including biodiversity, are central in the accumulation and distribution of SOC arising from stabilization and destabilization processes. These, in turn, are influenced by biotic, abiotic, and anthropogenic factors determining soil health. The challenge is to understand how to decrease net emissions of greenhouse gases from agricultural soils while building SOC content to sustain future food production. The importance of increasing carbon in soils is a global concern. Most soils around the world are far from being C saturated. According to the Food and Agriculture Organization's (FAO's) Global Soil Organic Carbon Map (GSOCmap), ten countries (Argentina, Australia, Brazil, Canada, China, the Democratic Republic of Congo, Indonesia, Kazakhstan, Russia, and the USA) hold about 65% of the total SOC stock [70]. Cropland soils are more heavily depleted of SOC having lost 40–60% organic carbon as carbon dioxide (CO_2) under intensive management. The launch of the global "4 per 1000" initiative in 2015, which is intended to increase global soil organic matter stocks by 0.4% per year [71,72], has moved land-based measures of capturing CO_2 from the atmosphere to the forefront. Attention has also focused on how to incorporate SOC as a realistic metric to monitor and evaluate the extent of soil degradation (e.g., the framework of the United Nations' Sustainable Development goals and soil health in general) [73].

In managed ecosystems, there is growing recognition that SOC loss from agricultural soils can be partly attributed to tillage management practices and cropping methods [74]. The balance between CO_2 emissions and other losses (e.g., through dissolved organic C leaching) ultimately defines the net GHG sink strength of intensively managed soils, and thus, there is intense interest in increasing organic materials by adding plant residue.

Notably, global cultivated cropland soils have lost 50–70% of their original stored carbon [75]. Intensive tillage enhances greenhouse gas (GHG) emissions, but several tillage practices (e.g., no-till, minimum tillage, and conservation tillage), cropping methods (e.g., crop rotation, reduced fallow, intercropping), and soil amendments (e.g., use of manure, biochar, plant residue) increase SOC and reduce the emission intensity of GHGs [76]. Much of the focus is to introduce and incorporate SOC-enhancing approaches, but we also need to recognize that there are synergies and trade-offs that may arise from these mitigation options [77]. For example, in the U.S., an estimated 20% of all croplands (~22.3×10^6 ha) have been under conservation tillage (NT) management [78] primarily on three major crops of wheat, corn, and soybean [79]. Soil organic C loss from agricultural soils has been attributed to intensive tillage [80]. Long-term studies have shown that the SOC pool in the top 30 cm of the soil profile is significantly higher under NT than under conventional tillage (CT). The benefits of switching from conventional to no-till can be significant in terms of the amount of soil carbon that can be sequestered. For example, a study by Marland et al. (2003) showed a net soil carbon sequestration of 1.2 t CO_2/y, averaged over 20 y, after switching from conventional tillage to no-till [81]. Despite these advantages, most farmers, however, are usually reluctant to adopt NT because their impact on grain yield can sometimes be quite variable [76,82]. Although the mechanistic details of SOC storage are not fully understood, these differences have been attributed to higher surface CO_2 fluxes from intensively tilled soils. We still have very little knowledge about the transport and contribution of subsurface CO_2 to the overall flux.

In much of the United States, intensive tillage is still the most widespread practice on prime croplands, and it is believed that such practices are the root causes for the continued SOC loss and soil degradation [75]. To the extent that better varieties and increased fertilization have continued to improve crop yields only masks the long-term detrimental consequences of SOC loss. We argue that accurately quantifying SOC at local (field), land-scape, region, and global scales is a long-standing issue and has yet to be challenged with innovative measurement approaches and scaling methodologies. Even if there is considerable knowledge about the formation and development of SOC at a small scale (e.g., plot point measurements) along with its structure and function, there is still considerable un-certainty about the aspects of SOC's spatial distribution [83].

Other soil conservation practices in consideration include shortening the off-season period and switching from monoculture to rotational cropping, which reduce CO_2 emission intensity, but synergies and tradeoffs may arise from these mitigation options [71,73]. Cover cropping entails using vegetative crops (e.g., mixes of legumes and grasses) to prevent soil erosion, suppress weeds, and provide nitrogen to subsequent cash crops [84]. Cover crops have the potential to sequester carbon below ground, but the amount and type of residues produced by plants place a strong control on SOC storage [85]. Studies have shown higher rates of soil carbon sequestration on former croplands when planted with diverse mixtures of grass and legume [86,87].

Widespread interest among farmers in incorporating cover crops into management practices has increased worldwide [88]. Yet, managing cover crops for carbon sequestration has proven to be critically challenging [89]. For example, despite their benefits to soil health and climate mitigation [90], the extent to which farmers in the United States adopt these practices is still limited (e.g., cover crops are used on <5% of the total croplands in the United States and on only 8% of global croplands) [91–93]. We argue that evidence-based outcomes drawing on real and demonstration farms focused on truly soil-centered care can accelerate faster adoption, globally. While converting from plow to no-till cultivation may bring an immediate advantage in terms of sequestrating C, long-term studies are needed to fully understand the soil health benefits of these practices.

3.3. Climate Change—Temperature, Water, and Water Extraction

Climate change, whether natural or anthropogenic, can fundamentally affect soil processes, productivity, resistance, and resilience [94]. Because soil contains about twice the amount of carbon (C) as the atmosphere, small changes in the soil C pool could have drastic effects on the CO_2 concentration in the atmosphere [64,95], not to forget the significance of other greenhouse gases (CH_4, N_2O) also released during soil perturbation, including warming. For any soil type, the SOC pool can vary and may be determined by the balance of net C inputs to the soil as organic matter and losses of C from the soil as CO_2, dissolved organic C (DOC), and through erosion [96]. The effects of climate change include shifting mean temperatures, year-to-year temperature variability, altered precipitation patterns, and more frequent extreme weather events, which can profoundly alter the properties of soils and make soils sensitive to these changes [97].

The strategic goals of maximizing the soil water-holding capacity and minimizing evapotranspiration are important. Creative strategies are needed to develop the soil structure or improve the depth of soil able to hold water. Mitigating clay pans, fragipans, duripans, etc., through chemical, biological, and physical means would have this desired effect. In Uganda, newly introduced conservation farming tillage practices increased bean grain yield relative to conventional practices by 41% to 43% compared to conventional management [98]. In maize, the newly introduced conservation farming tillage practices increased the grain yield by 78% on average, relative to conventional practices. Utilizing deep-rooted crops in arid environments to pump water from buried aquifers is another application. Consider the application of precision cropping and seeding for the optimal use of soil water in precisely the same way one considers the precision application of fertilizer. If one cannot mitigate temperature change, research could at least better predict its influence and design strategies that minimize temperature change in the soil environment. For example, does conservation tillage provide an added benefit at night by keeping soils cooler and therefore reducing inefficient plant metabolism in important diurnal periods? Here, the strategic goals of maximizing soil water-holding capacity and minimizing evapotranspiration are important. Developing the soil structure (aggregate stability) or management that improves soil depth able to hold water could have the desired effect.

3.4. Training and Preparing the New Agricultural Work Force

Twenty-first Century farming is changing and shifting based on consumer needs and evolving to plant-based and low-fat animal-based intake in developed countries [99] in contrast to developing countries where greater meat consumption is regarded as an indicator of economic progress [100]. The current labor force trends are shifting the agricultural sector globally as a result.

The farming enterprise is one of those economic sectors hard hit by a gradual workforce obsolescence [101]. Such trends have been evolving for much of the past 60 y [102]. Yet, it is only recently that the seriousness of the issue has become apparent in force. Although many acknowledge the shift was inevitable and has been occurring for some time, government agencies, agricultural academic, and research institutions have been slow to adapt to the changing face and needs of their clientele [103].

Multiple underpinning factors for the shift have eroded the traditional agricultural workforce [104]. Advancement in technology and global changes have strongly affected labor needs. In agriculture, the workforce comprises two populations: those involved in agricultural institutions and businesses that serve the second population—agricultural producers. While educational sectors such as schools, in-service training, extension, and other services need to remain vigorous for traditional producers, the greater challenges may exist in building appropriate public/private partnerships to serve the changing agricultural sector [105].

There is an urban agricultural renaissance and profound interest in regional agricultural provisioning. Whereas traditional producers intensify land use to accommodate time restrictions for a limited labor force, small-scale horticultural enterprises are expanding the growing season by adapting hoop houses on a large-scale basis. The ever-growing number of high tunnels are evidence of this trend. Over the last few decades in the United States, many vegetable growers have engaged in high tunnel cultivation to meet the increasing demand of food production. A pilot project by USDA NRCS was launched in 2010, with financial assistance to producers to construct high tunnels to extend the growing season, improve plant and soil quality, reduce nutrient and pesticide loss, and reduce energy use by providing consumers with a local source of fresh produce [106]. How can research adapt soil management strategies locally to meet these changing needs?

Over the past two decades, advances in soil conservation practices, cover cropping, and other improved soil amendments have demonstrated the potential to improve degraded soils, especially of marginal lands. However, as recent reports have noted, these exciting advances in knowledge have not widely penetrated farmers' practices [82,84,85]. While there are some exemplary programs (e.g., NRCS cover crop initiatives in the United States), the wide-scale changes needed to bolster wider adoption have yet to be materialized [107].

Preserving and protecting soil health require management levels and skills that are inconsistent with prescriptions for conventional practice. In developed countries, treating agriculture as a business and soils as a raw material is a recipe for soil degradation. Likewise, in developing countries, recruiting workers from urban areas with minimum skill levels who can only perform prescriptive practices also invites soil degradation. Central to this thinking is that it embraces farmers' participation and involvement, not only as recipients, but also as key players providing the platform and space to develop research initiatives on their own (i.e., citizen science), thereby promoting new and novel innovations. Technologies developed with stakeholders' involvement are more likely to be disseminated more quickly and have a higher impact than those developed in formal systems [76,82].

4. Conclusions

Perhaps the most consequential hallmark of modern agriculture is intensification and the injudicious use of synthetic fertilizers, pesticides, and extensive mechanical tillage, creating one of the greatest environmental challenges of the century. A changing climate, farming practices, and other external drivers further exacerbated these challenges. The gravity and urgency of soil degradation crises are starkly felt globally and most forcefully in much of the developing world. The current soil degradation crises present an opportunity to address the existential problem of climate burdens on constrained soils in world farming. Given the current trajectory of soil degradation, reversing soils to their natural state is all but impossible. Nevertheless, we need to take vigorous, evidence-based, collective, proactive actions to improve our understanding of soil systems and revise outdated approaches and attitudes toward soils. Our reluctance and indifference to addressing the current soil degradation crisis are self-defeating at best and devastatingly consequential at worst.

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