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PERSPECTIVE

Soil security and global food security

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KEYWORDS

Agriculture, soil security, food security, regenerative

HIGHLIGHTS

- Much of the world's agricultural land has been degraded through soil loss and degradation of soil organic matter.
- Regenerative farming practices based on combining cover crops, reduced tillage, and diverse crop rotations can rebuild soil, soil organic matter, and soil health.
- In the coming decades, global food security will increasingly depend on agricultural policies that respectively support soil-building practices.

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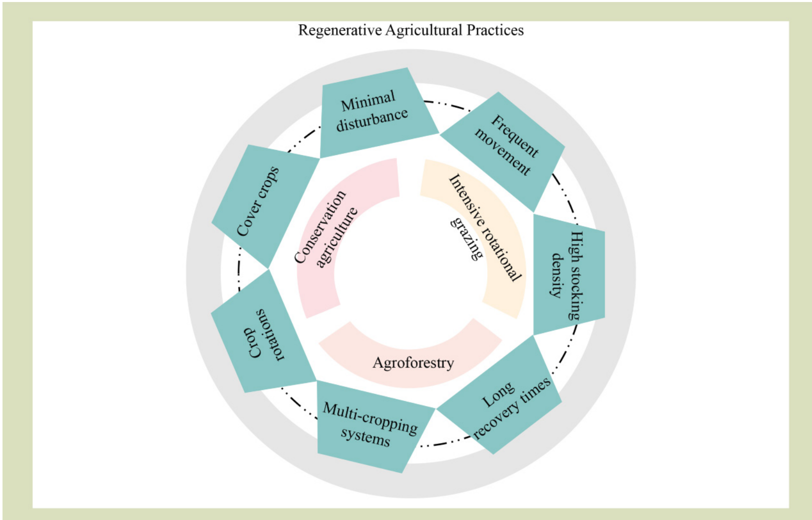
GRAPHICAL ABSTRACT



ABSTRACT

Over the course of the postglacial period has managed to add degrade a substantial portion of the world's potential agricultural land. The soil loss and degradation that has repeatedly impacted regional societies around the world resulted from agricultural practices that increased the physical loss of soil (erosion), reduced soil organic matter, changed pH (acidification) or salinity, and disrupted or altered communities of soil life. In the coming century, as continued soil degradation threatens global food security while the global population keeps rising it is imperative that farmers develop and adopt soil-health building (regenerative) practices to solve a problem that has plagued societies throughout history. Growing evidence suggests that agricultural systems that combine cover crops, reduced tillage, and diverse crop rotations can reduce erosion, enhance soil health and rebuild soil organic matter to cultivate beneficial soil life and harvest both economic and environmental benefits. In the coming post-oil world, global food security would benefit from a global effort to promote soil restoration to help addresses the challenge of sustainably feeding the world, increase soil-based carbon sequestration, protect on-farm biodiversity and reduce off-farm water pollution. Because soil security sets a solid foundation for global food security, agricultural policies and subsidies should be reformed to encourage farmers to adopt regenerative, soil-building practices.

1 Introduction

Throughout history fertile land supported the rise of agricultural civilizations that soil loss and degradation eventually undermined to their descendants lasting misfortune[1]. While the recent disruption of the global food supply due to the Russia-Ukraine conflict tragically illustrates the interconnected fragility of the global food supply, agriculture faces another serious, though far slower threat arising from the side-effects of modern farming practices on the world's agricultural soils. At least that's what a 2015 United Nations Food and Agriculture Organization report[2] implies in its conclusion that under current practices soil erosion and degradation would reduce global crop yields each year enough to reduce global harvests by about a quarter by the end of this century.

Time and again, from Classical Greece to the 1930s Dust Bowl, soil loss and degradation undermined agricultural civilizations around the world[1]. To be sure, global recognition of the problem of soil erosion increased dramatically in the aftermath of the Dust Bowl, leading to greater awareness and substantial soil conservation efforts. However, even though this reduced the pace of soil loss in some countries, the global problem remains acute[3]. Half a century ago, Brink et al.[4] warned about the potential for soil deterioration to collide with growing world demand for food. Pimentel et al.[5] later estimated that a third of the world's cropland had been degraded since the Second World War, reducing food production by as much as an additional 1% each year. The twin problems of soil erosion and degradation are not just ancient history.

Although grazing and crop lands cover more than a third of Earth's land surface, the amount of arable land decreased from 0.45 ha per capita in 1960, to around 0.22 ha in 2020[2]. Paired with a rising human population, the ongoing degradation and loss of agricultural land means it will become progressively more challenging to keep feeding the world. Indeed, the strategic importance of soil security—the continued provisioning of healthy, fertile soils capable of sustaining intensive agricultural production—is hard to overstate for the future of humanity in a post-oil world.

2 State of the soil

A crucial question is how much of Earth's 15 billion ha of land above sea level has been degraded so far. Depending on what source is consulted, it appears that the productive capacity of somewhere between 1 billion and 6 Gha (roughly 6% to 40% of global landmass) has been seriously degraded[6]. Even the low end of such estimates should prompt serious concern considering that only about 5 Gha of land is considered potentially agricultural. To some degree, this range of estimates reflects the methods and assumptions employed in different assessments of global land degradation, which have included expert opinion, satellite-derived estimates of changes in net primary productivity (the rate at which plants build up biomass), numerical models of biophysical systems, and estimates of the area of historically abandoned agricultural land[6].

The United Nations Food and Agricultural Organization (FAO) Global Assessment of Soil Degradation reported the first attempt to map the global impact of soil degradation based on the opinions of 290 national experts asked to assess the extent and degree of damage in their countries[7]. The approach arrived at a global estimate of 1.2 Gha of degraded arable land. Subsequently, a similar assessment also based on expert opinion landed on about twice as much degraded land, including almost three-quarters of the world's arid lands, half of rainfed croplands, and almost a third of irrigated croplands[8]. While expert-opinion-based assessments are highly subjective, they provide the only complete, methodologically uniform global assessments of soil degradation.

The later FAO's Global Assessment of Lands Degradation and Improvement project relied on satellite-derived measurements from 1981 to 2003 to assess differences in the normalized difference vegetation index, a vegetation condition proxy for net primary productivity[9]. The approach revealed a declining trend in biomass production across 2.7 Gha of land, more than 20% of global cropland. However, as this approach only measures net change in productivity it could not detect soil degradation masked by the increased use of mineral and synthetic fertilizers. This means that in this assessment lands on which agronomic methods maintain yields while degrading soil health would not show up as actually being degraded.

Historical data on the area of abandoned agricultural land offers another way to estimate the extent of global soil degradation. Over the last three centuries some 269 Mha of cropland and 479 Mha of pasture are known to have been abandoned due to land degradation, economic factors, or water scarcity[10]. Note, however, that these estimates exclude significant soil degradation dating from earlier civilizations[1].

In the Classical world, for example, evidence from Greek lakesediment cores indicate a period of dramatic soil erosion after the arrival of agriculture in the Bronze Age, ushering in a dark age predating the rise of Classical Greece[1,11]. Also, a global compilation of 600 lake-sedimentation cores documenting erosion rates over the last 12,000 years[12] found that more than a third exhibited a striking increase in erosion coincident with a dramatic decrease in arboreal pollen—a key indicator of land clearing, presumably for the spread of agriculture.

In some regions, ancient land degradation still affects modern societies. Consider, for example, Syria and Libya where Roman records of bountiful harvests sound unimaginable today. While the disaster of the 1930s Dust Bowl focused societal attention on the problem of soil erosion, less well known is the by then already substantial damage done to another broad swath of North America. Erosion of the Piedmont, or hill country, on the Atlantic slope of the American South-east offers an underappreciated example of a region where widespread agricultural erosion stripped topsoil from the land[13,14]. Across the Piedmont postcolonial soil erosion stripped off at least 10 cm of soil—virtually the entire topsoil from an area that was a breadbasket of colonial America[13]. Across the region today, subsoil exposed at the surface is evident in freshly plowed fields on farms dependent on mineral and synthetic fertilizers to maintain commercial harvests. The fact that this kind of land degradation is not included in global assessments that account only for land taken out of agricultural production makes such estimates all the more sobering.

Unfortunately, the soil loss and degradation that undermined past civilizations is not over. A regional review of historical topsoil erosion across the US Corn Belt found that the entire topsoil had been completely eroded from a third of the region, reducing crop yields by about 6% despite greatly increased reliance on chemical fertilizers[15]. Global soil loss from erosion due to tillage, water, and wind has been estimated at about 35 Gt annually [3]. That comes to more than 4 t annually for every person on the planet. A 2006 assessment considered 80% of the world's agricultural land already eroded enough to significantly impair crop yields[16]. Also, a 2018 United Nations report[17] concluded that global land degradation had already harmed the well-being of more than 3 billion people—more than a third of humanity.

Global food security is linked to national security and international geopolitical stability through the simple fact that all people need to eat. As the global population keeps growing at a pace sure to strain the capacity to feed everyone, it is worth considering that food security counter-intuitively tends to lower birth rates and slow population growth, whereas anticipation of food insecurity tends to favor larger families and further population growth. This is particularly pertinent as demographers predict most population growth during the balance of this century to occur in sub-Saharan Africa, where food insecurity remains particularly acute[18].

It seems that from any perspective a substantial amount of the world's agricultural potential has already been inadvertently degraded. At the same time widespread adoption of fertilizer-intensive practices and crop varieties enabled agriculture to keep up with a growing human population. The question now is how best to sustain intensive agriculture over the long run as we look toward a post-oil future. While today we rely on synthetic fertilizers to maintain high yields and feed the world from degraded lands, restoring degraded land and rebuilding soil organic matter would help to sustain native fertility and meet the challenge of feeding a post-oil world.

3 Causes of soil degradation

The primary causes of land degradation include urban expansion, deforestation, and agricultural practices that accelerate soil erosion, disrupt soil life, and fuel the breakdown of soil organic matter. Agricultural land degradation can involve loss of the soil itself (erosion), loss of soil organic matter, disruption of soil life, salinization, and pH changes (acidification). In agricultural settings the primary drivers of soil loss and degradation arise through the effects of tillage (plowing), prolonged synthetic fertilizer use, nutrient depletion from lack of manuring and failure to return crop residues to the soil, and irrigation-induced salinization.

Frequent tillage accelerates microbial decomposition that diminishes soil organic matter[19] and leaves the soil bare and vulnerable to erosion by wind or rain[19]. Combining mechanical tillage with intensive nitrogen fertilization further accelerates microbial breakdown of organic matter and soil aggregates[21]. Prolonged use of nitrogen fertilizers not only depletes soil organic matter but can also result in soil acidification. A global compilation of data from studies on regularly plowed agricultural fields found average erosion rates 10 to 100 times faster than natural soil production and soil erosion under native vegetation, whereas no-till farming limited erosion rates to close to the natural pace of soil production[20]. A review of North American soil degradation found that postcolonial farming had depleted about half the original organic matter in the continent's agricultural soils[22].

A key problem with sustained reliance on synthetic nitrogen fertilizers arises from the form the nitrogen it comes in, whether as a soluble salt or wrapped up in organic matter. Soluble by design, synthetic nitrogen fertilizers are rapidly taken up and stimulate bacterial life to degrade organic matter, thereby accelerating depletion of native soil fertility. In addition, routine tillage and synthetic nitrogen fertilization also affect the soil microbiome, restructuring communities of soil life and disrupting their symbiotic relationships with crops[23]. Generally, soils low in organic matter (as is now typical on conventional farms) are typically bacterially dominated, whereas the rhizosphere of organic-matter-rich soils tends to host abundant beneficial organisms (particularly fungi). The net result is that crops growing in degraded soil lack the robust micronutrient provisioning and chemical signaling that organic-matter-rich soils enable. To be clear, nitrogen fertilizer use is not inherently bad, and can be quite useful in judicious applications based on soil tests or leaf color charts, but over reliance on synthetic nitrogen delivery disrupts key biological relationships at the heart of soil ecology.

In addition, soil pH changes resulting from long-term applications of nitrogen fertilizers present a growing concern on many conventional farms[24]. Over the long run, synthetic nitrogen fertilizers acidify soil because certain soil dwelling bacteria oxidize ammonia (NH_3) to nitrite (NO_2^-), and others oxidize the nitrite to nitrate (NO_3^-). Each reaction produces hydrogen ions (H^+) that acidify the soil, reduce cation exchange capacity, and thereby impair soil fertility (by depleting exchangeable cations). This causes soil pH to gradually decrease with sustained use of nitrogen fertilizers (especially ammonia)[24]. Notably, aluminum toxicity produced as pH falls below 5.5 can restrict plant uptake of critical nutrients[24] In short, acidification of agricultural soils impacts both the availability of exchangeable cations (e.g., Ca^{2+}, Mg^{2+} and K^+) and soil life. Although adding a lot of synthetic nitrogen can boost yields in degraded soils, doing so leaves farmers dependent on continued fertilizer applications. In medicine this kind of situation is called an addiction.

Urbanization presents another growing threat to soils as the world's surging urban population now exceeds the rural population. Expanding urban centers typically consume some of a region's most fertile land, the very thing that often drew people to an area. In urban settings topsoil is typically removed to facilitate construction as pavement and buildings displace fields and orchards. By 2030 urban expansion is projected to result in the loss of about 2% of global croplands, with most of the loss occurring in Africa and Asia[25]. In addition to these regions being where the human population is growing most rapidly urban expansion is expected to consume highly productive cropland, so the net loss could amount to as much as 4% of global crop production[25]. However, expansion of urban agriculture could offset some of the decline in production from agricultural land around cities[26].

The other ancient problem, salinization, has plagued agriculture since Mesopotamian times when early records document a shift to salt tolerant crops as salinity built up in irrigated fields[1]. Globally, about 830 Mha of land are now affected by soil salinization and some estimates forecast that salinity will adversely impact the productivity of half of all arable land by 2050[27]. Salinization may occur from either the rise of saline groundwater in fine-grained soils, or as salts accumulate from the evaporation of irrigation water. While the effects of salinization reflect the type and concentration of particular salts and the tolerances of different crops, salinization impacts far more land in Asia (194 Mha) and Africa (123 Mha) than in Europe (7 Mha) and North America (6 Mha)[27]. Deltaic environments in particular are subject to potential salinization of coastal aquifers, and sea level rise is naturally of special concern for farmlands in low-lying coastal areas.

A critically important thing that does not appear in existing global assessments of soil degradation is the loss of soil life and the organic matter that drives nutrient cycling in soils. Over recent decades growing recognition of the importance of soil life and ecology has emerged based on the substantial influence of microbes in the rhizosphere on nutrient acquisition, chemical signaling, and plant defense—and therefore on crop health[23,28]. This new perspective stresses the importance of soil organic matter as food for microbes that produce metabolites beneficial to soil health and the health of crops. Recent work also documents the important contribution of soil microbial life in building soil organic matter[29].

4 Regenerative solutions

Although humanity has already degraded, and continues to degrade a substantial portion of the world's agricultural land, soil degradation can be reversed through regenerative farming practices that build soil health. Restoring life to soils offers a means to rapidly and profitably reverse soil degradation[21]. According to a 2018 UN report[17], the economic benefits of land restoration average 10 times the costs, while failure to reverse land degradation typically cost three times what it would take to address the underlying problem. Also, rebuilding fertile soils has been described as one of the most promising ways to address hunger and malnutrition in Africa, where soil degradation presents a major impediment to agricultural production after decades of cropping without adequate manure or mineral fertilizers[30,31]. Recognizing that loss of soil nutrients due to extractive and erosive farming practices particularly impacts farmers in sub-Saharan Africa, a review of the effects of soil degradation in the region estimated that proven soil-building practices could quadruple local production of staple food crops[32].

Strategies for building soil fertility through intensive farming under regenerative agricultural systems include conservation agriculture, intensive rotational grazing, and agroforestry. Soil building practices also include green manuring, vermicomposting, and diversifying simple, two-crop rotations (e.g., rice/wheat or corn/soybeans) to include pulses and oilseeds. Conservation agriculture uses practices that combine the principles of minimal disturbance (no-till or low-till), cover crops, and diverse crop rotations. Intensive rotational grazing combines frequent movement, high stocking density, and long recovery times. Agroforestry integrates trees into diverse multi-cropping systems. Even producing commodity crops regenerative farming systems can prove more profitable than conventional systems due to lower input costs and comparable yields[21,33], although the transition period can present an economic challenge. Additional barriers to adopting such practices include risk aversion, resistance to trying new ideas, and lack of knowledge of how to implement new practices.

The key conclusion is that there is no need to repeat the story of ancient civilizations that squandered their soil resources. Human activity need not lead to soil degradation. Examples of indigenous soil management from the Amazon[34], Africa[35] and Europe[36,37] document the build up very fertile soil systems from farming practices that incorporated recycling of organic matter. The rich black-earth soils that developed over centuries around early human settlements in these regions hold two to three times more organic matter than native soils. The challenge for agriculture today is to do even half as well on farmland around the world.

As the pace of global soil degradation exceeds the pace of soil building by more than an order of magnitude[20], reversing the historical trend will require reorienting and transforming how conventional farming treats the soil. With most of the potentially farmable land in the world already degraded or actively under production, increased harvests will have to come from either technology-driven increases in yield on degraded soils or the adoption of practices that restore already degraded farmland. It would seem prudent to pursue both.

Soil erosion and degradation are among the most neglected of many pressing environmental crises humanity faces. However, regenerative farming practices can rebuild soil fertility as a consequence of highly productive agriculture[21]. Additional societal benefits of regenerative farming practices that build soil health include pulling carbon from the atmosphere and putting it back into the soil, greater drought resilience, and a lower environmental footprint from reduced use of agrochemicals[21]. Rebuilding healthy, fertile soils as a consequence of agricultural practices would provide a solid foundation for global food security and defines one of the critically important challenges that humanity faces in the 21st century.

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