REPORT FROM SAVE SOIL, PUBLISHED JULY 2025

SOIL DEGRADATION AND BIODIVERSITY LOSS

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Abstract

This research paper investigates the critical nexus between soil degradation and biodiversity loss, highlighting the soil's foundational role in supporting terrestrial life and ecosystem services. It establishes that widespread soil degradation, affecting approximately 33% of global soils, significantly diminishes soil health and its inherent biodiversity. This loss, in turn, has a detrimental impact on broader planetary biodiversity and vital ecosystem functions, including agricultural productivity, water regulation, and climate modulation. The paper explores the mechanisms through which soil degradation, or the decline in soil health, negatively affects ecosystems, resulting in the loss of biodiversity. Through an analysis of eight distinct regional case studies (India, Australia, East Asia, Central Asia, Africa, North America, South America, and Europe), the global manifestations and consequences of this interconnected crisis are illustrated. These case studies primarily highlight degradation driven by unsustainable agricultural practices and posit regenerative agriculture, with a specific emphasis on practices that increase soil organic matter (SOM), as a scientifically sound solution. It argues that restoring soil's life and health through such practices can foster the flourishing of soil biodiversity, enhance ecosystem resilience, and contribute significantly to the conservation of biodiversity on Earth, while also offering benefits for sustainable food production and climate change mitigation.

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1. Introduction

Biodiversity, encompassing the vast array of life on Earth, and the health of our soils are inextricably linked, forming the foundation of a thriving planet. Soil, as a fundamental natural resource, serves as the basis for all terrestrial life and plays a crucial role in supporting its ecosystem services. In particular, a living, healthy soil is essential for agricultural productivity, water regulation, human health, environmental production, and climate regulation. [1] However, our planet is facing an escalating crisis of soil degradation, which has profound implications for the stability and resilience of biodiversity. [2] Alarmingly, approximately 33% of the world's soils are currently classified as moderately to highly degraded, with agriculture being a major driver. [3] This degradation does not merely refer to the amount of soil lost, but more importantly, to the declining health of soils - a trajectory that is likely to continue in the absence of timely and effective intervention. [4] The alarming rates at which soil is being degraded surpass its natural regeneration, posing a direct and significant threat to the intricate web of life. [5]

This analysis aims to elucidate the critical link between soil degradation and the decline of biodiversity on Earth. It will explore the complex mechanisms through which soil degradation affects the ecosystem functions and negatively impacts biodiversity on Earth. To illustrate the global impact of this nexus, the paper will examine case studies from various regions worldwide primarily highlighting degradation driven by unsustainable agricultural practices and proposes regenerative agriculture practices, with a specific focus on increasing SOM as the scientifically sound solution to restore soil health, ultimately contributing to the conservation of biodiversity on Earth.

2. The Nexus between Soil Degradation and Biodiversity Loss

Soil degradation is defined as a decline in soil health, resulting in a diminished capacity of the ecosystem to provide goods and services. Soil degradation occurs in various forms and include biological, chemical, and physical degradation. [3] Physical degradation of soil refers to the deterioration of the soil's physical properties, such as structure, porosity, texture, and bulk density. [4] Chemical degradation involves alterations in the soil's chemical properties such as soil pH, nutrient content, cation exchange capacity (CEC), and base saturation. Biological degradation primarily involves the loss of soil biota - the vast array of life that resides within the soil, encompassing a hierarchical system of organisms ranging from microscopic bacteria, archaea, and fungi to microfauna like protozoa and nematodes, mesofauna such as mites and springtails, macrofauna including earthworms, ants, and beetles, and even megafauna like certain mammals and reptiles. [6] Soil degradation is primarily caused by unsustainable human activities worldwide. Key human-induced drivers include urbanization, unsustainable agricultural practices, deforestation, industrial development, and waste disposal. [7] Within agriculture, common causes are unsustainable farming behaviors like frequent and excessive use of fertilizers and pesticides, use of heavy machinery, and intensive grazing. [8] These practices can lead to alteration in the characteristics of soil, causing degradation. [9] The impact of these drivers manifests as food insecurity, climate change, water shortage, migration, conflict, and biodiversity loss.

Enhancing soil health stands as the most critical and comprehensive solution for combating and reversing soil degradation. “Soil health is defined as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans.” [10] A healthy and living soil is characterized by a remarkable abundance and diversity of microorganisms; a single teaspoon of soil can harbor billions of individual organisms. [6] Healthy soil with diverse soil organisms contributes to the development and stabilization of soil structure, enhancing porosity and water infiltration, which are critical for clean water provision and reducing erosion. Fauna like earthworms and mites mix soil layers, improving porosity and water retention by creating channels and aggregates that enhance soil structure and aeration, which is important for plant growth. [11] Soil biota play a key role in natural pest and pathogen control, reducing the need for chemical inputs in agriculture. Beyond these functions, healthy and living soil ecosystems also contribute to climate change mitigation by sequestering carbon and regulating greenhouse gas emissions. [12]

Through photosynthesis, plants absorb atmospheric CO_2 and convert it into glucose and other compounds, which are transported to the roots and released into the soil as exudates. Microorganisms feed on this glucose, and in the process, they produce sticky substances like polysaccharides and fungal hyphae that help bind soil particles into aggregates. These aggregates protect organic carbon from decomposition, allowing it to be stored in the soil for long periods and contributing to climate change mitigation. [13] Additionally, through photosynthesis, plants absorb atmospheric CO_2 and convert it into glucose and other organic compounds, which are used to build plant tissues. When plants shed leaves, roots, or die, this organic matter enters the soil, where microbes decompose it and convert part of the carbon into stable forms like humus. This process stores carbon in the soil, indirectly reducing atmospheric CO_2 levels. In this way, soil microbial activity influences larger environmental processes that also affect biodiversity. [14]

Recent research suggests that soil is the single most biodiverse habitat, potentially harboring 59% of all life. Healthy soils promote a diverse array of life, which in turn contributes to the resilience and functionality of the larger ecosystem. [15] In consequence, the decline in soil health impairs multiple crucial ecosystem functions. These include decomposition rates, nutrient retention and cycling, soil structural development, the provision of clean water, pest and pathogen control, crop productivity, climate change mitigation, and more. The decline in soil health not only leads to a decrease in overall productivity and the impairment of regulatory functions that maintain ecosystem stability, but also to the loss of crucial habitats for various species. [16] For example, a decline in the diversity and abundance of soil organisms can lead to a decrease in the populations of predator species that rely on them as a food source in above-ground ecosystems. Conversely, plant diversity has been shown to have effects that extend from below-ground decomposers, all the way to herbivores and predators, highlighting the bottom-up influence of plant communities on multitrophic interactions. Reduced ecosystem complexity can impair vital services such as food production, pest control, water filtration, and even climate regulation, ultimately threatening livelihoods, food security, and public health. [4] For example, more than 75% of global food crops depend, at least in part, on animal pollination for their yield and/or quality loss of biodiversity threatens these vital populations, putting global agricultural output and food security at risk. [17]

3. Regional Studies: Manifestations of Soil Degradation and Biodiversity Loss

Soil degradation, in its various forms, occurs all over the world and exerts a detrimental impact on biodiversity. [18] Within agriculture, several notable unsustainable practices significantly cause a decline in soil health. For instance, the practice of tillage, while intended to prepare the soil for planting, disrupts the intricate soil structure and can directly kill beneficial microorganisms. [19] Soil compaction, resulting from heavy machinery or overgrazing, reduces the amount of pore space within the soil, which in turn threatens the underground habitats of many soil organisms. Similarly, soil salinization, the buildup of salts, can render the soil environment inhospitable for many microbial species, leading to their inactivation or death. [6] The widespread use of chemical fertilizers and pesticides in conventional agriculture poses a significant threat to soil biodiversity, as these substances can alter the chemical composition of soil and directly kill soil organisms, disrupting the delicate balance of the soil food web. [20] Furthermore, the practice of monoculture, growing the same crop repeatedly in the same area, can deplete specific soil nutrients and make the soil more susceptible to pests and diseases, which can further impact the diversity and health of soil organisms. Even deforestation, the clearing of forests, has a knock-on effect on soil biodiversity by removing important sources of nutrients and disrupting the natural recycling of organic material, ultimately reducing the amount of carbon stored in the soil, which is a primary energy source for many soil organisms. [6] Soil biota plays a crucial role in maintaining soil health. Disrupting the balance of the soil ecosystem leads to a decline in soil health, which in turn impacts the broader ecosystem.

3.1 India

India faces significant challenges regarding soil degradation, which in turn has profound impacts on its rich biodiversity. Various factors contribute to this issue, including deforestation, unsustainable agricultural practices, overgrazing, and industrial pollution. These pressures lead to soil erosion, loss of soil organic carbon, nutrient imbalances, and contamination, all of which degrade the habitats essential for a wide array of flora and fauna. [21] The Green Revolution led to the widespread adoption of intensive agriculture with high-yielding varieties and the extensive use of chemical pesticides to protect crops.

Studies have linked the heavy use of pesticides to a decline in farmland bird populations. Insecticides reduce the abundance of insects, which are a primary food source for many bird species, especially during their breeding season. Herbicides reduce the diversity of weeds, which also provide food (seeds) for birds. In states like Punjab and Haryana, this disruption of the food web and habitat has contributed to the decline of species like White-rumped Vulture in these agricultural landscapes. [22] Desertification is a problem of dryland ecosystems; deforestation, unsustainable farming, overgrazing, and mining can convert fertile land into deserts. Desertification, Land degradation, and Drought (DLDD) have shown a severe effect on our GDP. [23] In India, approximately 81.45 million hectares of land are affected by desertification. Overall, around 32.07% of the country's total land area is undergoing degradation. States such as Rajasthan, Jammu & Kashmir, Gujarat, and Maharashtra account for a significant share of this degraded land. This leads to a drastic loss of biodiversity adapted to those specific ecosystems. [24] Loss of forest cover—primarily due to agricultural expansion, infrastructure development, and urbanization—is a major driver of soil erosion and biodiversity loss in India. The Himalayan region and the Western Ghats, both recognized as global biodiversity hotspots, are particularly vulnerable to these pressures, threatening endemic species and fragile ecosystems. [25]

3.2 Australia

Australia has experienced extensive soil degradation and biodiversity loss stemming from historical and ongoing land management practices. Since the arrival of colonists, significant areas of land have been cleared for agricultural use and infrastructure development, leading to widespread degradation and the loss of native habitats. [26] Extensive clearing of native eucalyptus forests for wheat farming in the Wheatbelt of Western Australia disrupted the water balance, leading to rising groundwater and widespread soil salinization. This increased salt concentration in the topsoil caused the die-off of many salt-intolerant native plant species, resulting in significant habitat loss for diverse endemic marsupials, birds, and insects. The fragmentation of the landscape due to clearing further compounded this biodiversity decline. CSIRO and the Western Australian Department of Primary Industries and Regional Development have extensively documented dryland salinity in the Wheatbelt, with studies showing a direct correlation between land clearing, salinization, and reduced populations of native vegetation and fauna. [27] The Malleefowl, a ground-dwelling bird native to Australia's semi-arid and arid regions, is highly sensitive to changes in soil and vegetation. This species relies on sandy, well-structured soils to build its distinctive nesting mounds, which require loose, aerated soil mixed with organic matter for incubation. Soil degradation caused by livestock overgrazing and land clearing has led to compaction, erosion, and loss of organic matter, disrupting mound construction and reducing native vegetation. This has caused significant declines in Malleefowl populations due to lower breeding success and habitat loss. [28]

3.3 East Asia

East Asia has experienced significant environmental changes, including the loss of substantial areas of its natural forestlands, which in turn has driven deforestation in other ecologically important regions. [29] Deforestation in Southeast Asia, a region with interconnected ecosystems and shared biodiversity, has led to widespread habitat loss, increasing rates of species extinction, and significant soil erosion, impacting the overall biodiversity of the broader East Asian context. [30] Unsustainable levels of livestock grazing on the Mongolian steppes have led to soil compaction, loss of vegetation cover, and increased wind erosion. The degradation of the soil and the reduction in plant diversity directly impact the herbivores that rely on these grasslands, such as gazelles and other ungulates. This, in turn, affects predator populations like wolves and snow leopards. The unique biodiversity of the steppe ecosystem, including specialized plant and insect communities adapted to these conditions, is diminished as the land degrades. [31] Industrial pollution, including the contamination of soil with heavy metals and other pollutants, also poses a threat to soil health and the diversity of life it supports in the region. [32] Overall, land degradation in East Asia, driven by deforestation, agricultural expansion, and industrial activities, is not only affecting food security but also contributing to a significant loss of ecosystem diversity and the services these ecosystems provide.

3.4 Central Asia

Central Asia is facing alarming rates of degradation of its agricultural land, primarily due to a combination of deforestation, soil salinization, and the unsustainable practice of overgrazing. [33] The Central Asian region, including Kazakhstan, Uzbekistan, Turkmenistan, Kyrgyzstan, and Tajikistan, faces significant challenges from soil degradation that directly drive biodiversity loss. Overgrazing in the steppes has led to soil compaction and erosion, reducing native plant diversity critical for supporting local wildlife. [34] In Uzbekistan and Turkmenistan, extensive desertification caused by poor irrigation practices and soil salinization, especially in cotton farming regions like Karakalpakstan, has diminished habitats for endemic species. The Aral Sea crisis exemplifies this interconnection, where river diversion for irrigation caused severe soil salinization and wind erosion, leading to the extinction of 28 native fish species and the collapse of wetland ecosystems. [35] Additionally, dust storms from the exposed seabed spread contaminated soils, degrading vegetation and wildlife habitats over a vast area. Mountain ecosystems in Tajikistan and Kyrgyzstan suffer from soil erosion due to deforestation and overgrazing, threatening species such as the snow leopard and Marco Polo sheep that rely on intact alpine meadows. [36] The UNCCD (2022) emphasizes that soil health decline in dryland Central Asia undermines biodiversity and ecosystem services, creating a feedback loop where degraded soils reduce vegetation cover, further accelerating biodiversity loss and ecosystem instability. [37]

3.5 Africa

The African continent is experiencing widespread land degradation, affecting a significant portion of its total land area and impacting the lives and livelihoods of millions of people while causing substantial economic losses. [38] Soil erosion is a particularly pervasive problem across Africa, leading to the loss of fertile topsoil, the degradation of agricultural lands, and a decline in overall biodiversity. [39] Across Africa, soil degradation profoundly threatens biodiversity and ecosystem stability, particularly in vulnerable regions like the Sahel, East Africa, and the Congo Basin. In the Sahel, countries such as Niger and Mali face accelerated desertification driven by overgrazing, deforestation, and erratic rainfall patterns, which degrade soils and diminish native plant diversity vital for species like the West African giraffe and the Houbara bustard. [40] In East Africa, particularly Kenya and Ethiopia, intense soil erosion and nutrient depletion from unsustainable farming practices have reduced the regeneration capacity of indigenous forests that serve as habitats for endangered primates such as the Tana River red colobus and the Ethiopian wolf. [41] Meanwhile, in the Congo Basin, illegal logging and slash-and-burn agriculture contribute to soil degradation, fragmenting habitats and threatening flagship species like the lowland gorilla and okapi. [42] Soil compaction and loss of organic matter reduce the land's water retention ability, leading to more frequent droughts and further habitat loss. [43]

3.6 North America

The focus on maximizing productivity in conventional agriculture has often led to the widespread adoption of monocultures and a heavy reliance on synthetic chemical fertilizers and pesticides, which have been shown to harm soil biodiversity and can contribute to habitat loss. [44] Additionally, soil contamination resulting from industrial activities, mining operations, and the use of agricultural chemicals poses significant risks to soil organisms and the broader ecosystems they support. [45] Alarmingly, over one-third of the biodiversity in the United States is currently at risk of disappearing due to a multitude of threats, including the degradation of habitats and various forms of pollution. [46] Conversion of native prairie grasslands to intensive agriculture with practices like heavy tillage and synthetic fertilizers has degraded soil health and eliminated native habitats across the Great Plains. This loss reduces habitat and food for diverse prairie species, including significant declines in grassland bird populations and native plant diversity. The degradation of agricultural soils also impacts crucial soil microbial diversity. [47]

3.7 South America

South America, home to the unparalleled biodiversity of the Amazon rainforest, is facing severe challenges related to soil degradation and biodiversity loss. The Amazon, often referred to as the "lungs of the world," is experiencing significant deforestation driven by agricultural expansion, particularly for cattle ranching and soybean production, as well as logging and mining activities. This deforestation leads to an irreversible loss of biodiversity as habitats are destroyed, and it also degrades soil fertility, impacting the long-term productivity of the land. The extensive loss of forest cover not only threatens the unique and irreplaceable species of the Amazon but also disrupts vital water cycles and contributes to the broader problem of global climate change. [48] The expansion of cattle ranching in the Gran Chaco, spanning Argentina, Paraguay, and Bolivia, has led to overgrazing, deforestation for pasture creation, and soil compaction and alteration of native vegetation structure. This transformation impacts Gran Chaco's unique biodiversity, including species like the South American jaguar and giant anteater, as overgrazing reduces native plant diversity, deforestation destroys habitats, and soil degradation hinders native vegetation regeneration, isolating populations through habitat fragmentation. [49]

3.8 Europe

Unsustainable agriculture is a primary driver of biodiversity loss globally and in Europe, leading to soil depletion and therefore habitat degradation. Conventional farming practices, which are prevalent in Europe where almost 40% of land is used for agriculture, often involve the extensive use of pesticides and fertilizers. [50] These practices diminish soil's capacity to support diverse life forms. When soil biodiversity declines due to factors like intensive agriculture, vital ecosystem services are impaired. This degradation of soil ecosystems contributes directly to the broader loss of biodiversity above and below ground, as many species depend on healthy and living soil environments for their survival. A stark example of the impact of intensive agriculture, which is closely linked to soil health, is the threat to pollinators. In Europe, almost 1 out of every 10 bee species is threatened with extinction, largely due to intensive agricultural practices. [50] Assessments under the EU's Birds and Habitats Directives consistently identify unsustainable agriculture as the most commonly reported pressure on biodiversity. The State of Nature in the EU 2020 report evaluated the status of agricultural species and habitats, including grasslands, farmland birds, pollinators, butterflies, bats, and amphibians. Many of these are directly or indirectly affected by the condition of agricultural soils and the intensity of farming practices. For instance, the report mentions the EU grassland butterfly index as an indicator. [50]

4. Regenerative Agriculture: Restoring Soil's Health, Life, and Biodiversity

Regenerative agriculture represents a paradigm shift in farming practices, moving away from conventional, often extractive methods towards an approach that aims to improve soil health and regenerate entire ecosystems by mimicking natural ecological processes. [51] The concept of regenerative agriculture is rooted in the understanding that farming should work in harmony with nature, rather than against it, to create resilient and productive agricultural systems. [52] The principles guiding regenerative agriculture include minimizing disturbance to the soil, ensuring continuous soil cover, maintaining living roots in the soil for as much of the year as possible, maximizing the diversity of plant species grown, and, where appropriate, integrating livestock into the farming system. By adhering to these principles, regenerative agriculture seeks to not only sustain agricultural productivity but to actively improve the health and vitality of the land and the wider environment.[53] Higher levels of SOM directly enhance the soil biota as SOM is the food source for the soil biota and the activity of the soil ecosystem. [51] In essence, by increasing the amount of organic matter in the soil, regenerative agriculture provides both the food and the habitat necessary for soil microbes and fauna to thrive, leading to a recovery of soil health and the restoration of vital soil functions which nourish the broader biodiversity.

Several key regenerative practices are instrumental in enhancing the levels of organic matter within the soil. No-till and reduced tillage farming significantly minimize the physical disturbance of the soil, which helps to protect the delicate network of soil organisms and allows for the accumulation and retention of SOM. By avoiding or reducing the turning of the soil, these practices prevent the rapid oxidation of organic matter and the disruption of soil structure that can lead to carbon loss. Cover cropping and the use of green manures involve planting non-cash crops, often during periods when the main crops are not growing, to provide a protective cover for the soil. These cover crops add significant amounts of organic matter to the soil as they decompose, improving its structure, fertility, and water-holding capacity. [53] Implementing diverse crop rotations and intercropping strategies, where a variety of crops are grown in sequence or simultaneously in the same field, is another key regenerative practice. This approach not only improves soil health by providing a diversity of root systems and nutrient demands but also helps to reduce the pressure from pests and diseases, enhancing overall soil fertility and organic matter content. The addition of compost and other organic amendments to the soil is a direct way to increase SOM. Compost, rich in decomposed organic materials, improves soil fertility, structure, and stimulates biological activity within the soil. [51] Finally, managed grazing and the integration of livestock into farming systems, when done responsibly, can also enhance SOM.

The grazing of livestock helps to cycle nutrients back into the soil through manure, and when managed appropriately with practices like rotational grazing, it can stimulate plant growth and improve soil health over time. [52] These interconnected practices collectively work to build healthier, living, and more carbon-rich soils that are more resilient and productive in the long term.

Promoting the widespread adoption of regenerative agriculture requires a concerted effort involving various stakeholders and the implementation of supportive policies and practical recommendations. Policy support and the provision of financial incentives are crucial for encouraging farmers to transition to and implement regenerative practices, which may require initial investment and a period of learning. [54] Continued research and the effective sharing of knowledge and best practices among farmers and scientists are essential for advancing the field of regenerative agriculture and ensuring its successful implementation across diverse agricultural systems and environmental contexts. [55] Increasing consumer awareness and generating demand for food produced using sustainable and regenerative methods can also play a significant role in driving the adoption of these practices by farmers and food producers. [56]

6. Conclusion

The complex relationship between soil degradation and the decline of biodiversity on Earth presents a critical challenge to the health of our planet and the well-being of future generations. As detailed in this report, soil degradation, driven by unsustainable human activities and exacerbated by climate change, leads to a significant loss of biodiversity. The regional case studies examined in this paper underscore the pervasive nature of this crisis, demonstrating its manifestations across diverse geographical and ecological contexts, focusing on unsustainable agriculture practices. However, the paper also highlights the transformative potential of regenerative agriculture as a solution to this intertwined crisis. By focusing on the restoration of soil health through practices that increase SOM, it underpins the health and resilience of biodiversity. This approach not only offers a pathway to enhancement of overall biodiversity but also provides significant benefits for sustainable food production, climate change mitigation through carbon sequestration, and addressing water crisis through enhanced water retention and infiltration. Addressing the challenges of soil degradation and biodiversity loss requires a global commitment to prioritizing a healthy and living soil. A collaborative approach involving all stakeholders, including farmers, researchers, policymakers, and consumers, is vital for achieving the widespread adoption of regenerative agriculture and realizing its full potential to create a healthy and living soil to conserve global biodiversity.

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