Sustainable Soil Management: A Challenge for Sustainable Agriculture in Tropical Regions

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Abstract: Sustainable soil management (SSM) is pivotal for advancing sustainable agriculture in tropical regions, where rapid soil degradation threatens food security and ecosystem stability. This review examines the multifaceted challenges posed by tropical environments, including high rainfall-induced erosion, nutrient leaching, acidification, and organic matter loss, exacerbated by practices like monocropping, deforestation, and intensive tillage. Drawing on interdisciplinary literature from soil science, agronomy, and ecology, we synthesize evidence on degradation causes—such as climate variability and anthropogenic pressures—and their socio-economic repercussions, like yield declines of 10-20% in Sub-Saharan Africa and economic losses exceeding USD 6 billion annually in Brazil. Key SSM practices, including conservation agriculture (no-till, crop rotation, cover cropping), biochar amendments, integrated nutrient management, precision technologies, and agroforestry, are evaluated for their efficacy. World data reveal yield boosts of 20-30% in Association of Southeast Asian Nations contexts (ASEAN), enhanced soil organic carbon sequestration (0.28-0.43 Gt C yr^{-1} globally), and reduced erosion by up to 97%. However, barriers like resource constraints, policy gaps, and cultural resistance hinder adoption among smallholders. The review highlights context-specific strategies to overcome these, emphasizing interdisciplinary collaboration and localized research. Ultimately, effective SSM not only mitigates degradation but fosters resilient systems that balance environmental health, economic viability, and social equity. By addressing tropical underrepresentation in studies, this work guides policymakers and practitioners toward innovative pathways for long-term agricultural sustainability, underscoring the urgency of adaptive management in vulnerable ecosystems.
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Introduction

Agriculture plays a pivotal role in supporting human life, providing food, fiber, and fuel for a rapidly growing global population projected to reach nearly 10 billion by 2050 (Hou et al., 2020). In tropical regions, which span vast areas across Africa, Asia, Latin America, and Oceania, agriculture is not just an economic backbone but a lifeline for millions of smallholder farmers. These areas boast rich biodiversity, abundant rainfall, and year-round growing seasons, offering immense potential for high-yield crop production. However, Mason et al. (2023) reported that this potential is increasingly threatened by environmental pressures and unsustainable practices that degrade the very foundation of farming: the soil. As climate change intensifies, with rising temperatures and erratic weather patterns, the need for resilient agricultural systems becomes urgent. This review explores sustainable soil management (SSM) as a critical challenge for achieving long-term agricultural viability in these vulnerable ecosystems.

Soil, often overlooked as mere dirt, is a complex living system essential for plant growth, water filtration, carbon storage, and nutrient cycling (Hou et al., 2020). In tropical regions, soils face unique stressors due to high temperatures, intense rainfall, and rapid weathering processes that accelerate nutrient leaching and organic matter decomposition (Weisse et al. (2023). Common soil types like Alfisols, Oxisols and Ultisols, prevalent in the tropics, are inherently low in fertility, with high acidity and aluminum toxicity that limit root development and crop uptake of essential nutrients (Babajide et al., 2018; Bolan et al., 2023). Degradation manifests through erosion, compaction, salinization, and loss of organic matter, exacerbated by human activities such as slash-and-burn farming, overgrazing, and monoculture cropping. According to Zingore et al. (2023), in Sub-Saharan Africa, acid soils are estimated to reduce crop yields by around 10%, with even steeper declines in certain locales, hindering food security for populations already grappling with poverty and malnutrition. Weisse et al. (2023) also reported that these issues are compounded by deforestation, which exposes soils to erosive rains, leading to sediment runoff that clogs rivers and diminishes arable land.

Sustainable agriculture seeks to meet current food demands without compromising future generations' ability to do the same, integrating economic viability, environmental health, and social equity. At its core lies SSM, which aims to maintain or enhance soil quality while minimizing negative impacts (Hou et al., 2020). As noted by Akinrinola et al. (2022) and Santana et al. (2025), this involves practices that build soil health, such as increasing soil organic carbon (SOC) levels, which improve structure, water retention, and microbial activity. Soil organic carbon acts as a keystone for ecosystem services, including carbon sequestration to mitigate climate change. Sarker et al. (2023) and Santana et al. (2025) demonstrated that this is a vital function given that agricultural soils can store significant amounts of atmospheric carbon if managed properly. Yet, in tropical settings, where decomposition rates are high due to warmth and humidity, maintaining SOC requires deliberate interventions. Conventional farming, reliant on heavy tillage and chemical inputs, often depletes SOC, leading to a vicious cycle of declining productivity and increased fertilizer dependency.

The causes of soil degradation in tropical agriculture are multifaceted, stemming from both natural and anthropogenic factors. Natural challenges include heavy monsoonal rains that cause sheet and gully erosion, particularly on sloped terrains common in regions like the Amazon basin or Southeast Asian highlands (Labrière et al., 2015). Anthropogenic pressures, such as population growth driving land conversion and intensive cash crop cultivation (e.g., oil palm, soybeans, or coffee), further strain soils (Santana et al., 2025). Smallholder farmers, who dominate tropical agriculture, often lack access to resources for better management, resorting to short-term solutions that overlook long-term soil health. Climate change amplifies these problems, with prolonged droughts alternating with floods, disrupting soil moisture balances and promoting salinization in coastal tropics. Moreover, global trade demands encourage monocultures that deplete specific nutrients, while poor infrastructure limits the adoption of restorative techniques.

The consequences of poor soil management ripple beyond farms, affecting broader environmental and socio-economic systems. Degraded soils lead to reduced crop yields, forcing farmers to expand into forests and contributing to biodiversity loss and greenhouse gas emissions from land clearing (Weisse et al., 2023). In tropical regions, this degradation threatens food security, as these areas produce staple crops like rice, maize, and cassava that feed billions. Economically, it perpetuates poverty cycles, with farmers incurring higher costs for inputs to compensate for lost fertility (de Oliveira Ferreira et al., 2023). Environmentally, eroded soils pollute waterways, harming aquatic ecosystems and human health. According to Mason et al. (2023) addressing these requires a shift toward sustainability, but barriers like limited education, policy gaps, and economic constraints persist, especially for resource-poor farmers in developing nations.

Promising SSM practices offer pathways forward, drawing from interdisciplinary research in soil science, agronomy, ecology, and social sciences. Conservation agriculture, encompassing no-till farming, crop rotation, and permanent soil cover with residues or cover crops, minimizes disturbance and erosion while boosting SOC (Cerretelli et al., 2023; Sadiq et al., 2025). Agroforestry integrates trees with crops, providing shade, windbreaks, and organic inputs that enhance soil fertility and biodiversity. Integrated nutrient management combines organic amendments (compost, manure, or green manures) with judicious inorganic fertilizers to optimize nutrient cycles without excess runoff. Research by Liu et al. (2025) indicated that biochar, a stable carbon-rich material from pyrolyzed biomass, shows potential for long-term carbon sequestration and soil amendment, particularly in acidic tropical soils where it can neutralize pH and improve nutrient retention. Precision farming technologies, such as soil sensors and remote sensing, enable site-specific applications, reducing waste and tailoring interventions to variable tropical landscapes (Chan, 2006; Akinrinola and Ozoinyiama, 2024; Mamabolo et al., 2025). Organic farming principles, emphasizing natural processes, further support microbial diversity and resilience against pests and diseases (Akinpelu et al., 2019).

Despite these advancements, implementation varies widely, with adoption rates low in many tropical areas due to knowledge gaps, financial hurdles, and cultural preferences. Research highlights the need for context-specific strategies, as what works in temperate zones may falter in the tropics' humid conditions. In a study by Sadiq et al. (2025), while no-till succeeds in reducing erosion, it can sometimes increase weed pressure without adequate cover crops. Moreover, interdisciplinary approaches are crucial to integrate farmer knowledge with scientific insights, fostering policies that incentivize sustainable practices through subsidies or education programs. Systems-oriented frameworks underscore the interconnectedness of soil degradation with climate adaptation, biodiversity, and governance, calling for holistic research that spans disciplines and regions. Evidence from Mason et al. (2023) indicated that tropical regions are underrepresented in global studies and require more focused investigations to adapt practices effectively.

This review synthesizes existing literature to address these complexities, examining the efficacy of various soil management strategies in tropical contexts. By evaluating successes, limitations, and emerging innovations, it aims to guide policymakers, researchers, and practitioners toward resilient agricultural systems. Therefore, the objective of this study was to explore the most effective SSM practices for mitigating soil degradation and enhancing agricultural productivity in tropical regions, considering environmental, economic, and social dimensions.

Sustainable soil management has emerged as a cornerstone of efforts to bolster agricultural resilience, particularly in tropical regions where soils are inherently fragile and subject to rapid degradation (Hou et al., 2020). This literature review synthesizes key findings from recent studies, focusing on the causes and consequences of soil degradation, innovative management practices, their impacts on productivity and environmental health, implementation challenges, and avenues for future research. By drawing on interdisciplinary perspectives, the review addresses the research question: What are the most effective SSM practices for mitigating soil degradation and enhancing agricultural productivity in tropical regions, considering environmental, economic, and social dimensions?

Soil degradation in tropical regions: Causes and consequences

Tropical soils, characterized by high weathering rates, intense rainfall, and rapid nutrient cycling, face unique vulnerabilities that distinguish them from temperate counterparts. Common degradation processes include erosion, loss of organic matter, acidification, compaction, and the accumulation of soilborne pathogens. It is well-documented by Oshunsanya and Akinrinola (2013) and Mesele et al. (2024) that these issues are exacerbated by agricultural intensification, deforestation, and climate variability, leading to diminished soil functions such as nutrient retention and water infiltration. According to Santana et al. (2025), in highly weathered tropical soils like those in Africa, South America and Southeast Asia, the absence of protective cover exposes land to erosive rains, resulting in significant topsoil loss and reduced carbon stocks.

Studies highlight that anthropogenic activities, such as monocropping and excessive tillage, accelerate organic matter decline and biological activity reduction, creating feedback loops that impair crop yields (Akinrinola and Babajide, 2023). In semi-arid tropical areas, salinity buildup from poor irrigation practices further compounds these problems, projecting a 15-25% increase in water erosion by mid-century due to climate change (Zingore et al., 2023). The consequences extend beyond farms: degraded soils contribute to biodiversity loss, increased greenhouse gas emissions, and compromised food security for vulnerable populations. In Sub-Saharan Africa and Southeast Asia, where smallholders predominate, soil acidity and nutrient depletion can slash yields by 10-20%, perpetuating poverty and malnutrition cycles (Mesele et al., 2024). Moreover, global analyses indicate that tropical regions, often underrepresented in soil research, suffer disproportionately from these degradative forces, underscoring the need for targeted interventions.

Interdisciplinary research emphasizes the multifunctional role of soils in ecosystem services, including carbon sequestration and water regulation (Georgiou et al., 2022). For instance, the sensitivity of SOC to temperature variations in Brazilian semi-arid zones illustrates how land use changes can amplify degradation, with implications for climate mitigation (Merten and Minella, 2013; Sarker et al., 2023). Overall, the literature portrays soil degradation not as isolated events but as interconnected challenges requiring holistic management to sustain agricultural viability. To illustrate the extent of degradation, Table 1 summarizes key statistics from various tropical contexts.

Table 1: Extent of Soil Degradation in Selected Tropical Regions

Region/Area	Degradation Type	Extent/Impact	Economic or Additional Notes	Source Citation
Africa	Overall arable land degradation	46% of arable land degraded	Driven by nutrient depletion and erosion	Mesele et al. (2024)
Global Tropics	Primary forest loss	4.1 million hectares in 2022	Equivalent to 11 football fields per minute	Weisse et al. (2023)

Brazil	Annual soil loss	822.6 million Mg/year	Cost of USD 6 billion	Merten and Minella (2013)
Humid Tropics	Soil erosion concentration	Concentrated on bare soil elements	Up to 99% reduction possible with management	Labrière et al. (2015)
Sub-Saharan Africa	Soil acidity and yields	10-20% yield reduction	Hinders food security	Mesele et al., 2024

Sustainable soil management practices

A range of practices has been proposed to counteract degradation, with conservation agriculture (CA) standing out as a foundational approach. The CA practice integrates minimal tillage, permanent soil cover, and crop diversification to enhance soil structure, reduce erosion, and boost SOC levels (Sadiq et al., 2025). In tropical contexts, such as the Association of Southeast Asian Nations (ASEAN) countries, no-till systems combined with cover crops like legumes have demonstrated substantial benefits. For example, no-till reduced weeding labor by one-third and improved maize yields in erosion-prone areas. Similarly, intercropping with *Mucuna bracteata* under oil palm plantations minimized nutrient leaching and cut erosion by up to 97% (Cerretelli et al., 2023). Adeola et al. (2023) demonstrated that the combination of maize and soybean improved soil condition for enhanced crop yields. In their study, Adeola et al. (2024) observed that the cereal and legume mixture positively impact sequential cropping, whereby the cultivated crops benefited from their residual effects.

Cover cropping emerges as particularly effective for carbon storage in tropical soils. Research on soybean systems shows that incorporating Brachiaria as a cover crop outperforms millet or maize in accumulating total organic carbon, especially in no-till rotations, turning soils into potential carbon sinks (Santana et al., 2025). This is critical in weathered tropical environments where rapid decomposition hampers SOC buildup. Biochar application, derived from pyrolyzed biomass, further supports this by improving pH in acidic soils, enhancing nutrient retention, and sequestering carbon long-term. Biochar has reportedly increased crop yields and soil organic matter, offering a low-cost amendment for smallholders (Abdulsalam and Akinrinola, 2024; Liu et al., 2025).

Organic farming and integrated nutrient management also feature prominently. Organic amendments like compost and manure, combined with judicious inorganic fertilizers (often referred to as organomineral fertilizer), optimize nutrient cycles while minimizing runoff (Oshunsanya and Akinrinola, 2013; Akinrinola, 2018; Akinrinola and Fagbola, 2018; Akinrinola and Fagbola, 2019; Akinrinola and Tijani-Eniola, 2022). Legume rotations, such as red clover, have been shown to elevate SOC stocks by 25% over conventional methods, fostering microbial diversity and resilience (Akinrinola et al., 2022; Sarker et al., 2023; Adeola et al., 2023). In tropical region like Nigeria, mixed amendments enhance microbial interactions, aiding stress resistance in crops (Babajide et al., 2018).

Technological innovations, including precision agriculture (PA), integrate sensors and remote sensing for site-specific management (Akinrinola and Ozoinyiama, 2024). Drones and Global Navigation Satellite System (GNSS) technologies enable real-time monitoring of soil moisture and nutrients, reducing waste and tailoring interventions to variable landscapes (Mamabolo et al., 2025). Nanotechnology, via nanofertilizers, improves uptake efficiency, though risks like ecotoxicity require caution in biodiverse tropical ecosystems. Agroforestry, blending trees with crops, provides additional benefits like shade and organic inputs, enhancing fertility in sloped terrains common in the Amazon and Southeast Asian highlands.

These practices, rooted in interdisciplinary fields like agronomy and ecology, aim to restore soil health while aligning with sustainable development goals.

Table 2: Crop Yield Changes Under Conservation Agriculture in Tropical Contexts

Practice	**Yield Change**	**Soil Health/Other Impacts**	**Region/Context**	**Source Citation**
Conservation Agriculture (overall)	+12% mean increase	Includes agroforestry (+ variable) and cover crops (+ variable)	Global, incl. tropics	Kodzwa et al. (2023)

Conservation Agriculture	Similar to conventional, but +21% soil health	Sustains production after long-term adoption	Global, applicable to tropics	Corbeels et al. (2024)
No-till with cover crops	+20-30% in maize/rice	Reduces erosion by up to 97%	ASEAN (e.g., Indonesia, Cambodia)	Sadiq et al. (2025)
Cover cropping (e.g., Brachiaria)	Variable, outperforms others in SOC	Turns soils into carbon sinks	Soybean systems in tropics	Sarker et al. (2023)

Impacts on agricultural productivity and environmental health

The adoption of SSM practices yields measurable improvements in productivity and environmental outcomes. The CA systems have increased crop yields by optimizing water use and nutrient availability, with studies reporting 20-30% gains in maize and rice in tropical settings (Akinrinola and Fagbola, 2020; Kodzwa et al., 2023; Corbeels et al., 2024). For instance, in the Philippines, pigeon pea cover crops reduced runoff during monsoons, sustaining yields on slopes while cooling soils. Enhanced SOC through cover crops and biochar not only boosts fertility but also sequesters carbon, mitigating climate change by storing up to 10-15% more atmospheric CO_2 in agricultural soils (Georgiou et al., 2022).

Environmentally, these practices reduce erosion, improve water quality, and support biodiversity. Organic farming minimizes chemical pollution, with legume rotations decreasing nitrate leaching and fostering beneficial microbes (Akinrinola and Fagbola, 2021; Sarker et al., 2023; Adeola et al., 2024). In dry tropical woodlands, balanced grazing with tree integration maintains infiltration, preventing compaction. Precision agricultural technologies cut greenhouse gas emissions by 20% through precise inputs, promoting resilience against droughts and floods prevalent in tropics (Chan, 2006; Mamabolo et al., 2025).

Economically, SSM lowers input costs for smallholders, though initial investments can be barriers. Socially, it empowers communities by integrating local knowledge, such as traditional terracing in Bali, which prevents erosion on hillsides. Overall, the literature demonstrates that SSM fosters triple-bottom-line benefits: productive farms, healthy ecosystems, and equitable societies.

Table 3: Soil Organic Carbon Sequestration Potentials in Tropical Regions (Mton C yr^{-1}, Top 20-30 cm Depth)

Practice	Potential Range	Notes/ Limiting Factors
Inorganic Fertilizer application	35 (27-45)	High in low-production areas
Organic Fertilizer application (corrected for manure availability)	8 (8-8)	Limited by manure recycling
No-till/Minimum Tillage	58 (39-77)	Overestimation possible due to data gaps
Cover Crops/Crop Diversification	34 (23-45)	Effective in diverse systems
Crop Residue Incorporation	8 (6-10)	Partial recycling limits potential

Source: Georgiou et al. (2022)

Challenges and barriers to implementation

Despite promising outcomes, barriers hinder widespread adoption in tropical regions. Resource constraints, including limited access to technology and education, pose significant hurdles for smallholders. High upfront costs for PA tools restrict use in developing countries, where food insecurity is acute. Cultural preferences and short-term economic pressures often favor conventional methods over sustainable ones, as seen in the slow uptake of no-till in Africa (Sadiq et al., 2025).

Policy gaps exacerbate these issues; without incentives like subsidies, farmers prioritize immediate returns over long-term soil stewardship. In tropics, humid conditions can amplify weed pressure in no-till systems without adequate covers, requiring context-specific adaptations. Nanotechnology's potential is tempered by regulatory voids and ecotoxic risks, particularly in biodiverse areas (Mamabolo et al., 2025). Interdisciplinary approaches call for better knowledge transfer via workshops and digital platforms to overcome these.

Case studies and regional insights

Case studies illuminate practical applications. In ASEAN, conservation agriculture in Cambodia and the Philippines has curbed erosion on slopes, enhancing resilience to climate extremes (Mamabolo et al., 2025; Sadiq et al., 2025). Brazilian soybean rotations with Brachiaria cover crops have increased carbon stocks, serving as models for Latin America (Sarker et al., 2023). In Sub-Saharan Africa, organic amendments have improved yields in acidic soils, though scaling remains challenging (Babajide et al., 2018; Zingore et al., 2023). These examples highlight the adaptability of SSM but also the need for localized research.

Gaps and future research directions

The literature reveals gaps in tropical-focused studies, with much research skewed toward temperate zones. Future work should prioritize long-term trials on deep soil carbon dynamics and microbial indicators (Mason et al., 2023). Integrating big data and machine learning for predictive modeling could enhance PA accessibility (Mamabolo et al., 2025). Policy research on incentives and farmer engagement is crucial, as is evaluating SSM's role in Sustainable Development Goals (SDGs). Addressing these will guide more effective strategies for tropical agriculture.

Conclusion

Sustainable soil management offers viable solutions to tropical soil challenges, but success hinges on overcoming barriers through innovation and collaboration. This review underscores the urgency of context-specific, interdisciplinary efforts to ensure sustainable agriculture. The sustainable soil management stands as a linchpin for thriving agriculture in tropical zones, where fragile ecosystems battle relentless degradation from climate shifts and human pressures. The examined practices—ranging from conservation agriculture and biochar amendments to precision technologies and agroforestry—demonstrate proven efficacy in curbing erosion, elevating soil organic carbon, and boosting yields by 20-30% in diverse settings like Association of Southeast Asian Nations and Sub-Saharan Africa. Yet, these gains hinge on addressing barriers such as resource scarcity, policy voids, and cultural hurdles that stifle adoption among smallholders. Economically, sustainable soil management promises cost savings and poverty alleviation; environmentally, it fosters carbon sequestration and biodiversity; socially, it empowers communities through inclusive strategies. To realize this potential, stakeholders must prioritize context-tailored research, incentives, and knowledge-sharing. Ultimately, embracing sustainable soil management is not just a choice—it is imperative for securing food sovereignty and planetary health in the tropics, urging immediate collaborative action to transform challenges into enduring opportunities.

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