



Integrating Soil Morphology, Survey Data, and Classification for Effective Land Use Planning in Tropical Regions

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ABSTRACT

Tropical soils are critical for supporting food production, biodiversity, and ecosystem services, but they face increasing threats from climate change. Rising temperatures, erratic precipitation patterns, and extreme weather events exacerbate existing soil challenges, such as erosion, nutrient depletion, organic matter loss, and disrupted soil biodiversity. These changes significantly affect agricultural productivity, land use planning, and environmental conservation. To address these challenges, climate-smart soil management practices, including agroforestry, conservation tillage, organic amendments, and integrated water management, offer effective solutions to enhance soil resilience and productivity. Future research priorities include localized climate modeling, digital soil mapping, soil carbon monitoring, biodiversity conservation, and community-based solutions to support sustainable land use. Advancements in technology and multidisciplinary approaches are essential for understanding climate-soil interactions and developing adaptive strategies to ensure the long-term sustainability of tropical soils.

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1. INTRODUCTION

Land use planning in tropical regions is a complex and vital process designed to optimize the allocation of land resources for multiple purposes, such as agriculture, forestry, urban development, and environmental protection. These regions, characterized by rich biodiversity, warm climates, and significant rainfall, face unique challenges stemming from the interplay between soil characteristics, climate factors, and human interventions (Fitzpatrick, 2015; Veldkamp et al., 2020). The increasing rates of deforestation, rapid population expansion, and growing agricultural demands have intensified the strain on land resources, highlighting the need for sustainable and effective land management approaches (Roy et al., 2022).

Soil characteristics play a fundamental role in assessing land suitability for various applications in tropical regions. The soils in these areas are highly diverse, ranging from nutrient-rich volcanic soils like Andosols to extensively weathered and nutrient-depleted types such as Oxisols and Ferralsols (Hansen et al., 2020). These soils are often exposed to intense weathering and leaching, resulting in significant differences in fertility, water retention, and nutrient availability (Lal, 2016; Hengl et al., 2017). Therefore, an in-depth understanding of soil morphology, classification, and spatial distribution is essential for making well-informed land use planning decisions.

Historically, land use planning in tropical regions depended on traditional methods such as field-based soil surveys and morphological evaluations. However, technological advancements have transformed this process. Innovations like remote sensing, Geographic Information Systems (GIS), and soil sensing technologies have enabled a shift toward more dynamic, data-driven approaches (Batjes et al., 2020; Siddique, 2024). These modern tools allow for large-scale monitoring and mapping of soil properties, creating opportunities for precision land management to tackle issues such as soil erosion, land degradation, and the impacts of climate change.

Despite these advancements, substantial challenges remain in land use planning across tropical areas. Issues such as soil degradation, deforestation, and climate variability continue to

impede sustainable land productivity. Additionally, the widespread use of advanced technologies is often limited by high costs and the complexities involved in integrating diverse datasets for efficient decision-making (Sanchez et al., 2019). Overcoming these challenges demands a comprehensive approach that integrates scientific progress, technological innovation, and local knowledge to develop sustainable land management practices. Such efforts are essential to preserve soil health, protect biodiversity, and ensure long-term agricultural productivity (Herzberg et al., 2019; Armenteras et al., 2019).

This paper explores the challenges and opportunities associated with land use planning in tropical regions, highlighting the critical role of soil surveys, classification systems, and modern technologies in addressing these issues. By examining these key areas, the study aims to offer practical insights for enhancing land use planning strategies to promote sustainable development. Effective soil resource management, alongside efforts to reduce environmental degradation, is vital for achieving long-term sustainability goals in tropical areas.

2. SOIL MORPHOLOGY AND CLASSIFICATION IN TROPICAL REGIONS

Soil morphology encompasses the visible physical attributes of soils, including color, texture, structure, and horizon development, which are crucial for evaluating soil properties and their suitability for various land uses (Hartati et al., 2023; Olivares et al., 2022). In tropical regions, the wide diversity of soil types and the intricate processes of their formation give rise to a broad spectrum of morphological features, shaped by factors such as parent material, climate, and biological activity (Fitzpatrick, 2015). This section examines the significance of soil morphology and classification in tropical areas, focusing on how these features influence land use planning and environmental management strategies.

2.1 Soil Morphology in Tropical Regions

Tropical soils are typically marked by significant weathering and leaching, driven by the intense rainfall and elevated temperatures characteristic of tropical climates. These processes often result

in unique morphological features that indicate weathering intensity and nutrient loss. A key characteristic of tropical soils is their deep weathering profiles, which lead to the formation of distinct soil horizons (Soil Survey Staff, 2014). These horizons commonly include an organic-rich surface layer (O-horizon) and a subsoil layer enriched with iron or aluminum, forming an illuvial B-horizon (Lal, 2016).

The color of tropical soils varies widely, but shades of yellow, red, and brown are common due to the accumulation of iron oxides. In poorly drained areas, soils may appear gray or black, influenced by organic matter or reduced iron content (Fitzpatrick, 2015). Many tropical soils, such as Oxisols and Ferralsols, are also characterized by significant clay accumulation, which influences water retention and drainage. These soils often exhibit high bulk density and compact structures, limiting their suitability for certain agricultural activities unless improved through soil management practices (Hengl et al., 2017).

On the other hand, Andosols—volcanic soils found in select tropical regions—tend to display darker colors and more friable textures due to their higher organic matter content and lower degree of weathering. These soils generally possess better fertility compared to other tropical soil types, making them more favorable for intensive agricultural production (Sanchez et al., 2019).

2.2 Soil Classification Systems in Tropical Regions

Soil classification is a structured method of organizing soils based on their morphological, physical, chemical, and mineralogical properties. In tropical regions, soil classification systems are crucial for understanding soil diversity and guiding land use decisions. The World Reference Base for Soil Resources (WRB) and the Soil Taxonomy system are two of the most commonly used classification frameworks worldwide, both of which have been adapted to address the specific characteristics of tropical soils.

The WRB system categorizes soils into broad groups based on diagnostic horizons, properties, and processes. This system is especially relevant for tropical soils, as it highlights the link between soil properties and environmental factors, which is vital in regions with high soil variability (Noviyanto et al., 2020; Mwendwa et

al., 2020). For instance, Ferralsols and Oxisols are frequently found in tropical areas and are classified based on their clay-rich, well-developed horizons and low nutrient content (Soil Survey Staff, 2014).

The Soil Taxonomy system, developed by the U.S. Department of Agriculture (USDA), organizes soils into hierarchical levels, ranging from soil orders to suborders and soil series. In tropical areas, the system acknowledges a variety of soil orders, such as Oxisols, Andosols, and Vertisols, each with distinct features that impact their suitability for various land uses. Oxisols, for example, are categorized by their deeply weathered profiles and low fertility, while Andosols are classified based on their high organic matter content and capacity to retain water and nutrients (Hengl et al., 2017).

A crucial aspect of soil classification in tropical regions is the identification of soil degradation processes like leaching, erosion, and salinization, which substantially affect soil fertility and productivity. Soil classification systems help pinpoint areas more susceptible to degradation, highlighting the need for conservation measures or agricultural practices such as crop rotation, agroforestry, or mulching (Lal, 2016).

2.3 Role of Soil Morphology and Classification in Land Use Planning

Soil morphology and classification are essential in land use planning, providing valuable insights into the suitability of land for different purposes. For example, soils with deep horizons and excellent water retention, such as Andosols, are well-suited for crop cultivation, particularly in areas with sufficient rainfall. In contrast, soils with poor drainage and low fertility, such as Oxisols and Ferralsols, may need soil amendments or alternative land uses, such as forestry or conservation (Sanchez et al., 2019).

Soil classification aids land planners in evaluating agricultural potential, identifying the need for soil conservation measures, and developing sustainable land use strategies in tropical areas. For instance, Oxisols may require consistent fertilization and organic matter additions to maintain crop yields, whereas Ferralsols might be more suitable for agroforestry systems that enhance soil fertility and minimize erosion risks (Batjes et al., 2014). Additionally, the presence of iron- or aluminum-rich soil horizons can affect crop selection and the need

for specialized irrigation systems (Fitzpatrick, 2015).

Furthermore, integrating soil morphology and classification with modern tools like GIS and remote sensing can improve land use planning. By combining soil maps with environmental data (such as rainfall, temperature, and vegetation), planners can make more precise predictions about soil behavior and tailor land use strategies to specific local conditions (Gregory et al., 2021).

3. SOIL DEGRADATION AND CONSERVATION IN TROPICAL REGIONS

Soil degradation is a significant challenge in tropical regions, where intensive land use, climatic conditions, and high biodiversity make soils highly susceptible to various stressors. This section explores the primary causes of soil degradation in tropical areas, examines the effects of degradation on soil properties and agricultural productivity, and discusses different conservation strategies to alleviate these effects. A thorough understanding of soil degradation processes and the importance of conservation is crucial for fostering sustainable land use in tropical environments.

3.1 Causes of Soil Degradation in Tropical Regions

Soil degradation in tropical regions results from a mix of natural and human-induced factors. The main causes include:

1. **Deforestation and Land Conversion:** In numerous tropical areas, forests are cleared for agriculture, urban expansion, and infrastructure development. The removal of trees decreases organic matter input and degrades soil structure, making it more susceptible to erosion and nutrient depletion. Deforestation also interferes with the water cycle, resulting in higher surface runoff and diminished groundwater replenishment (Lal, 2016; Veldkamp et al., 2017).
2. **Erosion:** Tropical regions are highly vulnerable to erosion because of their heavy rainfall and hilly terrain. When vegetation is cleared for agriculture or urban development, the protective cover that shields the soil from rainfall is removed, resulting in increased soil erosion. This issue is intensified in areas

with steep slopes and heavy rainfall. Soil erosion not only strips away fertile topsoil but also contributes to sedimentation in water bodies, negatively impacting water quality (Fitzpatrick, 2015; Hengl et al., 2017).

3. **Overexploitation of Soil Resources:** Intensive agricultural practices, including monoculture, overgrazing, and continuous cropping without sufficient fallow periods, deplete soil nutrients, causing soil exhaustion. The extraction of nutrients by crops and livestock without replenishing the soil with organic matter or fertilizers accelerates degradation. This leads to nutrient-depleted soils that are less capable of supporting plant growth (Sanchez et al., 2019).
4. **Climate Change:** Climate change is already affecting many tropical regions, leading to higher temperatures, altered rainfall patterns, and more frequent extreme weather events like droughts and floods. These climatic shifts can worsen soil erosion, leaching, and nutrient depletion. Changes in temperature and precipitation can also disrupt soil microbial communities, further reducing soil fertility (Gregory et al., 2021).

3.2 Impacts of Soil Degradation on Tropical Soils

The effects of soil degradation are extensive, impacting both the environment and human communities. The primary consequences include:

1. **Reduced Agricultural Productivity:** Soil degradation significantly affects agricultural output by lowering soil fertility, water retention, and structure. In areas where soil has been severely degraded, crop yields may decrease, making it more challenging for farmers to ensure food security. The erosion of topsoil, which contains vital nutrients for plant growth, further intensifies this issue (Fitzpatrick, 2015).
2. **Loss of Biodiversity:** Degraded soils typically support fewer plant and animal species, leading to a decline in biodiversity. This loss can disrupt ecosystems and hinder the provision of essential ecosystem services, such as pollination, water filtration, and soil formation (Lal, 2016). Soil degradation also

diminishes populations of soil organisms, like earthworms, which are crucial for nutrient cycling and soil aeration.

3. **Water Quality and Availability:** Erosion and soil degradation can cause sediment to accumulate in rivers, lakes, and reservoirs, negatively impacting water quality and availability for both human and agricultural use. In some instances, the degradation of soil and vegetation results in the silting of water bodies, reducing their storage capacity and disrupting water supply systems (Sanchez et al., 2019).
4. **Increased Vulnerability to Climate Change:** Degraded soils are less adaptable to the effects of climate change, such as extreme weather events. For example, soil erosion and compaction hinder the soil's ability to absorb water, increasing the risk of flooding during heavy rainfall. Additionally, degraded soils may become less effective at sequestering carbon, exacerbating climate change (Veldkamp et al., 2017).

3.3 Soil Conservation Strategies in Tropical Regions

To reduce the effects of soil degradation and promote the long-term sustainability of land use in tropical regions, various soil conservation strategies are crucial. These strategies encompass both traditional methods and modern techniques, customized to suit local conditions:

1. **Agroforestry:** Agroforestry, which involves integrating trees and shrubs into agricultural systems, is a highly effective method for enhancing soil fertility, preventing erosion, and boosting biodiversity in tropical regions. Trees stabilize the soil, reduce water runoff, and provide organic matter that improves soil structure and nutrient levels. Additionally, agroforestry systems offer economic advantages by generating income from timber, fruits, and other forest products (Sanchez et al., 2019).
2. **Conservation Tillage:** Conservation tillage minimizes soil disturbance during planting and cultivation, helping to maintain soil structure, reduce erosion, and improve water retention. Practices like no-till farming or reduced tillage enhance soil organic matter and protect against wind and water erosion. This approach is particularly beneficial in areas with low soil

moisture and high rainfall intensity (Hengl et al., 2017).

3. **Cover Cropping:** Cover crops, such as legumes or grasses, are planted to protect the soil during off-seasons. These crops help prevent erosion by shielding the soil from rainfall, improve soil structure by contributing organic matter, and boost nutrient cycling. Leguminous cover crops also fix nitrogen, enriching the soil and decreasing the need for chemical fertilizers (Batjes et al., 2014).
4. **Terracing and Contour Plowing:** In hilly and mountainous regions, terracing and contour plowing are effective techniques for reducing soil erosion. Terracing creates a series of level areas along slopes, slowing water runoff and lowering erosion risks. Contour plowing, which involves plowing along the land's contours, helps guide water flow and reduces the impact of rainfall on the soil surface (Fitzpatrick, 2015).
5. **Reforestation and Afforestation:** Reforestation, which involves replanting trees in deforested areas, and afforestation, which is the planting of trees in areas that were previously treeless, can greatly reduce soil erosion, promote biodiversity, and restore ecosystem services. These practices enhance soil structure, improve water retention, mitigate climate change effects, and increase carbon sequestration in the soil (Veldkamp et al., 2017).
6. **Soil Fertility Management:** Soil fertility management practices, such as crop rotation, the use of organic fertilizers, and soil amendments, are essential for maintaining soil health in tropical regions. By rotating crops and incorporating organic materials like compost and manure, farmers can improve soil structure, boost nutrient availability, and prevent nutrient depletion (Lal, 2016).

4. SOIL SURVEY METHODS AND TECHNOLOGIES FOR TROPICAL SOILS

Soil surveys are crucial for understanding the spatial distribution, properties, and potential applications of soils in a specific area. In tropical regions, where soil variability is influenced by diverse environmental conditions, accurate soil surveys are key to effective land management, agricultural planning, and conservation efforts.

This section examines the methods and technologies used in soil surveying, with an emphasis on tropical soils, and highlights how modern advancements improve the precision and efficiency of soil surveys in these complex environments.

4.1 Traditional Soil Survey Methods

Traditional soil survey methods have been foundational in characterizing soils and guiding land use decisions, especially in tropical regions with complex and diverse environments. These methods typically include:

1. **Reconnaissance Survey:** A reconnaissance survey provides an overview of soil types and their distribution in a region. It involves broad regional surveys, often through visual assessments of soil characteristics and landforms, followed by sampling at key locations. In tropical regions, reconnaissance surveys are essential for identifying general patterns of soil distribution, particularly in areas with varied terrain and vegetation (Soil Survey Staff, 2014).
2. **Detailed Soil Mapping:** After the reconnaissance phase, detailed soil mapping is conducted at a more localized scale. This involves the systematic collection of soil samples from different horizons within soil profiles, as well as determining the physical, chemical, and morphological properties of the soil. The data collected are used to create detailed soil maps that help in land use planning and soil management decisions (Fitzpatrick, 2015).
3. **Soil Profiling:** Soil profiling involves examining the vertical sequence of soil horizons, which provides valuable information on soil formation, fertility, and suitability for different uses. In tropical regions, where weathering and leaching are significant, soil profiles offer insights into how these processes influence soil properties, such as organic matter content, nutrient availability, and overall soil health (Sanchez et al., 2019).

4.2 Modern Soil Survey Technologies

Modern soil survey technologies have significantly enhanced the efficiency and precision of soil mapping, especially in complex tropical regions. These technologies include:

1. **Geographic Information System (GIS):** GIS integrates soil data with environmental factors like climate, topography, and land use, enabling spatial analysis and mapping of soil distribution. In tropical regions, GIS helps identify patterns in soil types across varied terrains and climates. When combined with remote sensing data, GIS-based soil maps improve soil classification and land suitability assessments (Batjes et al., 2014).
2. **Remote Sensing:** Satellite imagery and aerial photography are valuable for mapping soils in remote areas of tropical regions. Remote sensing detects surface characteristics such as vegetation cover and moisture content, which are indicative of soil properties. It can also monitor changes in soil properties over time, such as erosion and land degradation. Multispectral and hyperspectral remote sensing are increasingly used to identify soil attributes like texture, organic matter content, and moisture (Hengl et al., 2017).
3. **Soil Sampling and Laboratory Analysis:** Advances in soil sampling, including portable in-situ measurement instruments, enhance the efficiency and accuracy of soil surveys. Samples are collected from various depths to assess properties like texture, pH, and nutrient availability. Laboratory analysis using techniques such as spectrophotometry and X-ray diffraction provides a more detailed understanding of soil characteristics in tropical regions (Lal, 2016).
4. **Soil Sensors and Probes:** Real-time soil sensors and probes enable high-resolution measurement of parameters such as moisture, temperature, pH, and electrical conductivity. In tropical areas, where moisture levels vary widely, these sensors are particularly useful for understanding soil moisture dynamics and guiding irrigation practices (Hengl et al., 2017).
5. **Digital Soil Mapping (DSM):** DSM uses statistical models to predict soil properties across landscapes by integrating soil data with environmental variables like climate and topography. In tropical regions, DSM is valuable for predicting soil properties where traditional surveys are difficult or costly. Techniques such as Kriging generate continuous soil property maps, helping understand soil variability and land suitability (Gregory et al., 2021).

6. **Machine Learning and Artificial Intelligence (AI):** Machine learning and AI analyze large datasets from multiple sources, such as soil sensors and remote sensing, to predict soil properties with high precision. These technologies improve the accuracy of soil mapping in regions with high soil variability, making them particularly useful in tropical areas for predicting soil fertility and texture (Veldkamp et al., 2017).

4.3 Integration of Traditional and Modern Methods

The integration of traditional soil survey methods with modern technologies offers a holistic approach to soil mapping, particularly in tropical regions where access to advanced tools may be limited. Traditional methods, such as field-based observations and soil sampling, remain valuable for gathering localized, ground-truth data. These practices provide essential insights into soil profiles, physical properties, and morphological characteristics. When combined with modern technologies like Geographic Information Systems (GIS), remote sensing, and Digital Soil Mapping (DSM), these traditional methods are enhanced by the ability to analyze larger spatial scales and predict soil properties across diverse terrains.

GIS and remote sensing allow for the integration of environmental data such as climate, topography, and vegetation cover, helping to identify broad soil distribution patterns and assess land suitability. Meanwhile, DSM uses statistical models to predict soil characteristics based on environmental covariates, refining the precision of soil maps in areas where traditional surveys might be difficult to conduct. This synergy between traditional fieldwork and advanced technologies ensures a more comprehensive understanding of soil variability and enables more informed decisions for land management, agriculture, and conservation in tropical environments (Batjes et al., 2014).

4.4 Challenges in Tropical Soil Surveys

Soil surveying in tropical regions faces several challenges due to the inherent complexity and variability of tropical environments. One of the main issues is high soil heterogeneity, as tropical soils exhibit significant variations in properties such as texture, structure, and nutrient content over short distances, influenced by factors like

climate, topography, and parent material. This heterogeneity complicates soil classification and mapping efforts, making it difficult to apply uniform management practices across diverse landscapes (Fitzpatrick, 2015).

Another challenge is access to remote areas, as many tropical regions are difficult to reach due to dense forests, rugged terrain, and inadequate infrastructure. Traditional soil surveys can be time-consuming and costly in such areas, and remote sensing technologies have become essential for overcoming these logistical barriers. Remote sensing allows for large-scale monitoring without the need for extensive fieldwork (Sanchez et al., 2019).

The integration of data from various sources—such as field observations, remote sensing, and laboratory analyses—presents another obstacle. The process of synthesizing these diverse datasets can be challenging, particularly in regions with limited data availability. Emerging technologies like machine learning and AI help to manage and analyze large datasets, but they require sophisticated techniques and significant computational resources to produce reliable results (Hengl et al., 2017).

Lastly, environmental and climatic variability in tropical regions poses a significant challenge. The rapid fluctuations in temperature, rainfall, and seasonal changes can lead to quick alterations in soil properties. Soil surveys must account for these dynamic conditions to provide accurate data for land-use planning, which can be difficult due to the temporal variations in soil characteristics (Lal, 2016).

5. THE ROLE OF SOIL CLASSIFICATION IN LAND USE PLANNING

Soil classification plays a critical role in land use planning by providing essential insights for sustainable development, agricultural efficiency, and environmental conservation. By grouping soils according to their properties and potential uses, classification offers valuable information for decision-making processes that influence land management. In tropical regions, where soil variability is particularly pronounced, soil classification is key to ensuring the effective and responsible use of land resources. This section highlights the importance of soil classification in maximizing land productivity, preventing environmental degradation, and promoting sustainable land management practices.

5.1 Soil Classification and Land Suitability

Soil classification is a fundamental tool for land suitability assessments, which aim to identify the most appropriate uses for specific land areas. By categorizing soils based on key characteristics such as texture, structure, drainage, fertility, and chemical composition, classification helps determine their potential for uses like agriculture, forestry, or urban development. This understanding enables land planners and policymakers to reduce the risk of land degradation, enhance agricultural productivity, and efficiently utilize natural resources (FAO, 2015).

In tropical regions, where soils are often affected by challenges like leaching, low fertility, and erosion, soil classification systems such as the FAO World Reference Base (WRB) and USDA Soil Taxonomy are particularly valuable for assessing land suitability. For instance, soils that are highly fertile and well-drained can support intensive crop cultivation, whereas more vulnerable soils may require conservation practices or be more appropriate for extensive grazing or forest preservation (Sanchez, 2019).

5.2 Land Use Planning and Environmental Protection

Effective land use planning, guided by soil classification, ensures the optimal use of land while minimizing adverse effects such as soil erosion, desertification, and biodiversity loss. Soil classification highlights areas prone to degradation based on their inherent properties, such as shallow soils on steep slopes or highly acidic soils with limited nutrient retention capacity. This information is critical for zoning land appropriately and adopting management strategies to protect the environment (Lal, 2016).

In tropical regions, soil classification can identify soils at higher risk of degradation from agricultural activities. For instance, soils with low cation-exchange capacity (CEC) often struggle to retain essential nutrients, requiring precise management of fertilizers and irrigation. By evaluating soil susceptibility to erosion, leaching, or degradation, planners can recommend suitable land-use practices that mitigate environmental risks and promote long-term soil health (Fitzpatrick, 2015).

5.3 Supporting Sustainable Agriculture

Soil classification is essential for sustainable agriculture, as it provides a detailed understanding of soil properties that affect crop growth and productivity. By tailoring farming practices to the specific needs of the soil, farmers can use resources efficiently while avoiding overexploitation. Soil classification, which considers factors like fertility, water-holding capacity, and crop suitability, helps agricultural planners recommend the most appropriate crops, thereby optimizing yields and preserving soil quality (Lal, 2016).

In tropical regions, where soils are prone to rapid nutrient loss due to heavy rainfall and high temperatures, soil classification supports the implementation of conservation practices like agroforestry, contour farming, and cover cropping. These methods improve soil structure, enhance moisture retention, and promote nutrient cycling, thus fostering sustainable farming systems and reducing reliance on external inputs (Sanchez, 2019).

5.4 Soil Classification and Urban Planning

Soil classification plays a vital role in urban planning, especially in regions undergoing rapid population growth and urbanization. Knowledge of soil properties is essential for designing infrastructure like roads, buildings, and sewage systems, as well as for managing urban agriculture and green spaces. Key soil properties such as drainage, compaction, and load-bearing capacity are critical for evaluating land suitability for construction.

In tropical urban areas, where human activity often alters soil properties, soil classification provides valuable insights into issues like compaction, contamination, and soil stability. Soil maps derived from classification data help planners avoid constructing infrastructure in areas prone to flooding, instability, or poor load-bearing capacity, thus minimizing risks associated with urban development.

5.5 Case Studies in Tropical Regions

Numerous case studies highlight the significance of soil classification in land use planning across tropical regions. For example, in East Africa, soil classification has been instrumental in assessing agricultural potential and identifying risks of soil

degradation. In Kenya, soils classified as rich volcanic soils have been earmarked for agricultural expansion, while areas with highly acidic or infertile soils have been targeted for sustainable land management practices (Gachene and Kimaru, 2003).

Similarly, in Brazil's Amazon region, soil classification has guided land use decisions amid deforestation and the expansion of large-scale agriculture. Soil maps have been used to pinpoint areas where farming could result in significant environmental damage, leading to the development of policies aimed at preserving soil quality and maintaining forest cover (Sanchez et al., 2019).

6. CLIMATE CHANGE AND THE FUTURE OF TROPICAL SOIL USE

Tropical soils, which cover vast portions of the Earth's surface, are vital for food security, biodiversity, and ecosystem services. However, climate change is profoundly altering their physical, chemical, and biological properties, creating challenges for sustainable land management. Rising temperatures, shifting rainfall patterns, and more frequent extreme weather events threaten the stability and productivity of these fragile soils. Developing adaptive strategies is essential to secure the future of tropical soils.

6.1 Climate Change Impacts on Tropical Soil Properties

Tropical soils, such as Oxisols and Ultisols, are inherently low in nutrient reserves, prone to rapid weathering, and susceptible to erosion. Climate change amplifies these challenges, further degrading soil health. Rising temperatures accelerate the decomposition of organic matter, reducing soil organic carbon (SOC) stocks, which are critical for maintaining fertility and structure. The subsequent decline in water retention capacity increases soil vulnerability to degradation (Sanchez et al., 2019).

Variability in precipitation also exacerbates soil erosion and nutrient leaching in tropical regions. Intensified rainfall accelerates the loss of nutrient-rich topsoil, while prolonged droughts result in desiccation, compaction, and reduced microbial activity. These disruptions hinder nutrient cycling and reduce agricultural productivity, particularly in smallholder farming systems that dominate tropical landscapes.

6.2 Tropical Soil Carbon Dynamics and Climate Change

Tropical soils play a critical role in global carbon dynamics, storing approximately 30% of the planet's soil organic carbon (SOC). However, rising temperatures and land use changes threaten this function by accelerating carbon losses through soil respiration, which increases atmospheric CO₂ levels and exacerbates global warming. In tropical regions, deforestation significantly accelerates soil carbon depletion by reducing organic matter inputs and exposing soils to erosion and degradation (Don et al., 2011).

Restoring degraded tropical soils through sustainable practices presents an opportunity for carbon sequestration and climate change mitigation. Techniques such as agroforestry, biochar application, and reduced tillage have proven effective in improving carbon storage, enhancing soil fertility, and reducing greenhouse gas emissions in tropical systems (Lehmann et al., 2019). Moving forward, prioritizing research and investments in tropical soil carbon management will be essential to align soil health with global climate objectives.

6.3 Climate Change and Soil Biodiversity

Soil biodiversity, encompassing microorganisms, invertebrates, and plant roots, plays a critical role in supporting essential ecosystem services such as nutrient cycling, organic matter decomposition, and soil aeration. Tropical soils, which are among the most biodiverse on Earth, face increasing threats from climate change. Elevated temperatures and soil moisture stress disrupt microbial communities, altering the diversity and functionality of beneficial organisms like nitrogen-fixing bacteria and mycorrhizal fungi (Tarnocai et al., 2009). These disruptions can reduce soil nutrient availability, thereby impairing crop productivity in tropical regions.

The decline in soil biodiversity also diminishes the soil's resilience to environmental stresses such as drought and flooding. Adaptive strategies, including the use of organic amendments, preservation of native vegetation, and implementation of crop diversification, are vital for maintaining soil biodiversity. Such measures help enhance soil ecosystem services, ensuring that soils remain productive and resilient under changing climatic conditions (Sanchez et al., 2019).

6.4 Climate-Smart Soil Management for Tropical Regions

To mitigate the impacts of climate change, climate-smart soil management practices are essential for promoting the sustainable use of tropical soils. These strategies focus on enhancing soil resilience, adaptation, and mitigation through effective conservation and management. Key approaches include:

- **Agroforestry:** Integrating trees into agricultural systems improves soil structure, increases organic matter content, and enhances carbon sequestration. Deep-rooted trees also reduce soil erosion by stabilizing the soil.
- **Conservation Tillage:** Minimizing soil disturbance helps retain soil moisture, reduce erosion, and build soil organic carbon, offering a buffer against the effects of climate variability.
- **Organic Amendments:** Adding compost, manure, and biochar replenishes soil nutrients, boosts microbial activity, and enhances carbon sequestration, improving overall soil health (Lehmann et al., 2019).
- **Integrated Soil and Water Management:** Practices such as contour farming, terracing, and water harvesting are vital for maintaining soil moisture and minimizing erosion in areas affected by erratic rainfall patterns.

These climate-smart practices not only enhance the resilience of tropical soils to climate change but also improve their long-term productivity and sustainability, providing significant benefits for both ecosystems and local communities.

6.5 Future Directions and Research Priorities

The sustainable management of tropical soils in the face of climate change demands a holistic approach that integrates scientific research, technological innovation, and enabling policy frameworks. Future efforts should prioritize the development of localized climate models to better predict the long-term impacts of temperature and rainfall variability on tropical soils. Advancements in digital soil mapping through GIS and remote sensing can aid in monitoring soil properties, identifying vulnerable zones, and guiding land use planning. Equally important is the continuous monitoring of soil

carbon to enhance sequestration strategies and mitigate greenhouse gas emissions.

In addition, preserving soil biodiversity should be a research priority, as it plays a crucial role in maintaining ecosystem stability and essential soil functions. Finally, fostering community-based solutions by engaging directly with farmers is vital for the adoption of climate-smart practices that are context-specific, cost-effective, and scalable. Together, these strategies will contribute significantly to the resilience and productivity of tropical soils under changing climatic conditions.

7. CONCLUSION AND FUTURE DIRECTIONS

Climate change poses a serious threat to tropical soils, significantly impacting agricultural productivity, environmental conservation, and land use planning. Changes in temperature and precipitation patterns, coupled with extreme weather events, exacerbate existing soil challenges like erosion, nutrient depletion, and organic matter loss. Additionally, disruptions to soil microbial activity threaten soil health and fertility, further complicating the sustainability of tropical agriculture.

To address these challenges, adopting climate-smart soil management strategies is essential. Practices such as soil conservation, improved water management, and organic amendments can enhance soil resilience and productivity. Techniques like agroforestry, conservation tillage, and organic farming also offer sustainable solutions for mitigating climate impacts and restoring degraded soils through increased carbon sequestration.

Moving forward, a multidisciplinary approach that integrates climate science, soil research, and land-use planning is necessary. Long-term studies are critical to understanding the effects of climate change on tropical soils and developing site-specific management strategies. Advances in technologies like digital soil mapping and remote sensing will play a key role in assessing soil conditions and enabling real-time adaptation.

In summary, while climate change presents significant risks to tropical soils, it also opens opportunities for innovation and sustainable solutions. Combining scientific research, technological advancements, and climate-adaptive practices will be vital in protecting soil

resources and ensuring their productivity for future generations. Ongoing efforts must prioritize collaboration, research, and policy support to secure the long-term sustainability of tropical land use systems.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

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COMPETING INTERESTS

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