

Soil Color Indicators of Biogeochemical Changes Under Land Use Intensification in Tropical Climosequences

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Abstract

Land use intensification is transforming the structure and function of tropical soils, with significant impacts on biogeochemical cycling, organic matter dynamics, and ecosystem productivity. Among the most visible consequences of such changes is the alteration of soil color—an integrative indicator of soil health that reflects key physical, chemical, and biological processes. This review explores the scientific nexus between land use intensification, soil color variability, and biogeochemical feedbacks across tropical climosequences. Drawing from recent empirical studies and long-term landscape assessments, it synthesizes how shifts from forest to agriculture, agroforestry, and urban systems influence soil color attributes such as hue, value, and chroma. These color changes are further contextualized with respect to alterations in soil organic carbon, iron oxide transformations, redoximorphic features, and nutrient cycling under variable climatic regimes—ranging from humid tropics to sub-humid and dry tropics. We critically compare field-based Munsell assessments, digital imaging, and spectral reflectance techniques used to quantify soil color and relate it to land use gradients. The review also discusses how color signatures can serve as proxy indicators for soil degradation, fertility loss, and hydrological imbalance, especially in low-resource settings. Finally, it outlines research priorities for improving the integration of soil color into land evaluation frameworks, digital soil mapping, and environmental policy across climatically diverse tropical zones. The paper emphasizes the utility of soil color as both a diagnostic and planning tool for sustainable land management under intensifying anthropogenic pressures.

Keywords: Soil color; Land use; Land evaluation; Digital soil mapping; Climosequence

1. Introduction

The rapid intensification of land use in tropical regions over the last few decades has significantly transformed soil systems, with far-reaching implications for ecosystem functions and sustainability. Population growth, expanding markets, and increased demand for food and fiber have driven the conversion of natural vegetation into cultivated lands, pastures, and urban infrastructure. This anthropogenic pressure disrupts native biogeochemical processes, alters soil structure and fertility, and

accelerates degradation, particularly where land use intensification exceeds the natural regenerative capacity of tropical ecosystems (Sanchez, 2019; Obalum et al., 2022).

One of the most visually apparent and diagnostically significant indicators of such changes is soil color. Soil color, though often perceived as merely aesthetic, is a powerful proxy for a suite of biogeochemical processes, including organic matter accumulation, mineral oxidation-reduction dynamics, weathering intensity, and hydrological conditions (Schwertmann and Taylor, 2018). As such, soil color signatures provide a valuable window into the historical and ongoing interactions between land use practices and underlying soil processes.

In tropical environments—characterized by high temperatures, variable rainfall, and intense weathering—soil color changes rapidly in response to land cover alterations. For instance, conversion from forest to cropland often results in lighter soil colors, reflecting a decline in organic carbon and microbial biomass (Obalum et al., 2017). Similarly, prolonged cultivation on sloping terrain enhances erosion and exposes subsoil layers with different chromatic properties, typically redder due to increased iron oxide concentrations (Nuga et al., 2019). These visual shifts correspond with reductions in soil quality, nutrient retention, and crop productivity, thus offering an accessible means to assess and monitor soil degradation across diverse landscapes.

Understanding these transformations requires a landscape-level approach that incorporates climatic gradients—or climosequences—as an essential variable. Climosequences refer to spatial variations in climate (especially rainfall and temperature) that influence soil formation and biogeochemical behavior. In tropical regions, soils along a climosequence—from humid rainforests to sub-humid savannas and semi-arid drylands—exhibit distinct color features reflective of both inherent pedogenic conditions and anthropogenic modifications (Tian et al., 2020; Guo et al., 2020). For instance, red and yellow hues common in Oxisols and Ferralsols of the humid tropics signify advanced weathering and iron accumulation, while darker hues in Vertisols and Alfisols of sub-humid zones indicate higher organic matter and base saturation (Sanchez, 2019).

As land use intensifies across these climatic zones—through mechanized agriculture, deforestation, mining, or urban expansion—soil color patterns provide a valuable record of ecological disturbance and nutrient cycling shifts. Studies have shown that changes in soil hue and chroma closely track declines in organic carbon, increases in soil acidity, and losses in phosphorus and nitrogen, especially in tropical Alfisols and Ultisols (Coulibaly et al., 2021; Kihara et al., 2021). Redoximorphic features, such as mottling or gleying, also emerge in response to altered drainage regimes, compaction, or irrigation practices, particularly in wetland conversion areas (Vepraskas and Lindbo, 2018).

Despite its diagnostic potential, soil color remains underutilized in modern soil monitoring, land evaluation, and policy frameworks. Traditional assessment using the Munsell Soil Color Chart—while inexpensive and widely available—is subjective and limited by lighting and observer variability (Gholizadeh et al., 2019). However, recent advances in digital soil colorimetry, smartphone-based imaging, and visible-near infrared (Vis-NIR) spectroscopy offer more precise and scalable tools for quantifying soil color and linking it to biogeochemical attributes (Ahmad et al., 2023). These technologies, when combined with spatial data and machine learning, can enhance digital soil mapping and support real-time decision-making in land management.

This review aims to provide a comprehensive synthesis of current research on the interaction between land use intensification, soil color variation, and biogeochemical processes across tropical climosequences. Specifically, it:

1. Explores the mechanisms by which land use intensification alters soil color and related biogeochemical properties.

2. Summarizes empirical findings from different tropical zones to illustrate patterns and differences in soil color responses.
3. Critically evaluates traditional and modern methodologies used to assess and interpret soil color.
4. Discusses the implications of soil color changes for land evaluation, agricultural input management, and environmental monitoring.
5. Recommends future research directions for integrating soil color into sustainable land use planning and policy development in the tropics.

By focusing on climosequences, this paper brings attention to the spatial variability and climatic sensitivity of tropical soil systems, recognizing that soil responses to land use intensification are not uniform but modulated by rainfall, temperature, vegetation, and parent material. It emphasizes the need for context-specific approaches that acknowledge this variability while leveraging the diagnostic power of soil color to improve land management outcomes.

2. Conceptual Linkages Between Soil Color, Land Use, and Biogeochemical Cycling

Soil color is a multidimensional attribute that arises from the complex interplay of mineral composition, organic matter content, moisture status, and redox conditions. It is not merely a passive physical characteristic, but rather a visual expression of the dynamic chemical and biological processes occurring within the soil matrix. In tropical agroecosystems—where biogeochemical cycling is both rapid and sensitive to disturbance—soil color can act as a practical and integrative indicator of soil health, fertility, and ecological status. The conceptual linkage between soil color and land use intensification rests on the understanding that anthropogenic land transformations fundamentally alter soil-forming factors, particularly vegetation cover, biological activity, and hydrological regimes, thereby affecting soil color indirectly but significantly. The figure below illustrates how variations in soil color reflect changes in organic matter dynamics, mineralogy (particularly iron oxides), redox conditions, and land-use intensity, and how these processes collectively influence soil fertility, hydrology, and ecosystem degradation.

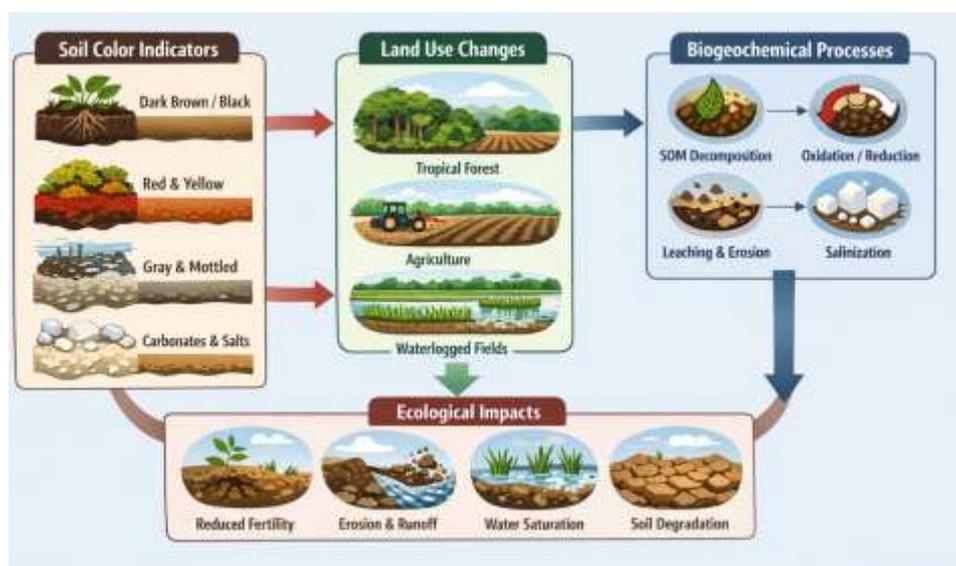


Figure 1: Conceptual linkages between soil color, land use change, and biogeochemical cycling in tropical agroecosystems.

One of the most influential factors affecting soil color is the concentration and quality of soil organic matter (SOM). Organic matter, derived primarily from plant residues and microbial biomass, imparts a dark brown to black coloration to surface horizons (Fudzagbo & Abulraheem, 2020). In undisturbed tropical forests or long-term fallow systems, the accumulation of SOM maintains dark surface colors with low chroma and moderate value, often masking the color of the underlying mineral matrix. However, when such landscapes are converted to arable land or pasture, the input of organic residues is greatly reduced, while microbial decomposition is accelerated due to increased soil aeration and temperature. These processes result in a net loss of SOM, often manifested in the bleaching or lightening of the soil surface color (Abdulraheem et al., 2013). This color shift, from dark to lighter hues, is not merely cosmetic—it typically signals a concurrent reduction in soil fertility, microbial activity, and aggregate stability (Obalum et al., 2017; Nivelles et al., 2021).

Mineralogical transformations also play a key role in soil color dynamics, especially in highly weathered tropical soils rich in iron and aluminum oxides. Iron oxides, such as hematite (Fe_2O_3) and goethite (FeOOH), are responsible for the red, yellow, and orange hues commonly observed in Oxisols, Ultisols, and deeply weathered Alfisols. These minerals form under well-drained, oxidizing conditions, and their color intensity often increases with advanced weathering and leaching. In natural systems, the profile expression of these colors remains relatively stable. However, land use intensification alters water infiltration, erosion, and redox dynamics—leading to either enrichment or depletion of iron oxides in specific horizons. For example, deforestation and continuous tillage increase surface runoff and expose lower horizons through erosion, bringing redder, iron-rich subsoils to the surface. Conversely, waterlogging or poor drainage associated with irrigation or compacted fields can reduce iron oxides to soluble forms, leading to gleying or grayish colors that reflect anaerobic conditions (Vepraskas and Lindbo, 2018; Kihara et al., 2021).

The presence of redoximorphic features—such as mottles, concretions, and gleyed zones—is another biogeochemically significant aspect of soil color. These features form due to the fluctuating presence of oxygen in the soil, often driven by changes in water saturation. In soils where land use changes lead to altered drainage regimes—such as in rice paddies, wetlands converted to agriculture, or floodplain developments—iron and manganese oxides are reduced and mobilized under anaerobic conditions, then re-precipitated upon re-oxidation. The result is a variegated color pattern, typically with gray matrix colors punctuated by reddish or yellowish mottles. These features are not only diagnostic of seasonal waterlogging and hydromorphic processes, but also serve as proxies for soil microbial respiration, denitrification potential, and phosphorus availability (Zhou et al., 2020; Ahmad et al., 2023).

Beyond organic matter and iron oxides, soil color is also influenced by other mineral constituents such as carbonates, sulfates, and clay minerals. In drier tropical climosequences—such as the Sahel or inland savannas—lighter colors often indicate the accumulation of calcium carbonate or gypsum, while darker hues may signal higher clay content and associated cation exchange capacity. Land use practices that affect leaching, salinity, and horizon mixing will thus affect the spatial distribution of these materials and their expression through soil color. This complexity underscores the need for context-specific interpretation of color data, especially when comparing soils across different climatic gradients.

Importantly, land use changes do not operate in isolation but interact with climate to modify the trajectory of biogeochemical cycling. For example, in humid tropical zones with high rainfall and rapid biomass turnover, land clearing may lead to immediate SOM loss and acidification, visible as a transition from dark brown to reddish or yellowish hues. In contrast, in sub-humid or semi-arid zones, the same land use change may lead to crusting, compaction, and salt accumulation, causing grayish or whitish surface colors. These climatically driven differences in soil response reinforce the relevance of climosequence analysis for understanding soil color variation and the associated biogeochemical implications (Sall et al., 2020; Zhang et al., 2021).

The interactions between soil color and biogeochemical processes have implications that go beyond diagnostics. Color is often used, either consciously or unconsciously, by farmers and land users to infer fertility status, moisture retention, or crop suitability. Traditional knowledge systems in many parts of Africa, Asia, and Latin America rely on soil color descriptors to classify soils and guide management decisions. In this way, soil color serves as a bridge between scientific and indigenous knowledge, linking visual perception to functional understanding of land potential and degradation risks (Mbaya et al., 2022). When supported by formal measurements and empirical validation, color-based assessments can inform broader land evaluation systems and serve as inputs to spatial decision-support tools.

Technological advancements are also enhancing the capacity to utilize soil color in biogeochemical assessments. The use of RGB and CIELAB color systems, derived from digital photography and spectroscopic measurements, allows for the quantification of subtle color differences that are often invisible to the naked eye. These digital metrics can be linked statistically to laboratory-measured soil properties—such as organic carbon, pH, total nitrogen, and available phosphorus—providing a scalable and cost-effective method for soil quality assessment. Furthermore, remote sensing platforms and machine learning algorithms are increasingly being employed to map soil color patterns across large landscapes, offering new opportunities for real-time monitoring of land degradation and nutrient dynamics (Gholizadeh et al., 2019; Viscarra Rossel et al., 2021).

In conclusion, the conceptual relationship between soil color, land use change, and biogeochemical cycling is multifaceted and deeply rooted in tropical soil ecology. Soil color is not just a static attribute but a dynamic indicator of the transformations occurring beneath the surface. As land use intensifies across tropical climosequences, shifts in color patterns reveal the underlying shifts in soil organic matter, redox potential, mineralogy, and nutrient flows. Recognizing and interpreting these patterns can enhance our understanding of ecosystem function and inform more sustainable land management strategies tailored to specific climatic contexts.

3. Soil Color Shifts Under Land Use Intensification in Tropical Climosequences: Empirical Evidence

Empirical studies from tropical landscapes provide compelling evidence that land use intensification alters soil color through mechanisms closely tied to soil organic matter decline, mineral transformations, and redox fluctuations. These changes are not uniform but are shaped by regional variations in rainfall, vegetation, parent material, and management practices. Across climosequences, from humid tropical rainforests to semi-arid savannas, land conversion to intensive cropping, grazing, or urban development consistently modifies soil color characteristics in ways that mirror underlying biogeochemical shifts.

In humid tropical zones, such as those found in the Congo Basin, southern Nigeria, and parts of the Amazon, the conversion of natural forest to arable land has been linked to a rapid decline in soil organic carbon (SOC) and a corresponding shift in surface color from dark brown (value 3/2 or 4/2 in Munsell notation) to lighter yellowish-brown hues (5/4 or higher). This transition typically occurs within the first 3–5 years of cultivation, particularly when slash-and-burn or mechanized tillage is used without organic amendments (Obalum et al., 2022; Odedina et al., 2020). Such changes are not only visible to the eye but are also measurable using digital colorimetry, where reductions in CIELAB L* values (lightness) and a* (redness) correspond to declining SOM and increasing oxidation states of iron oxides.

Studies from sub-humid and moist savanna regions in West Africa, such as northern Ghana, central Côte d'Ivoire, and Ekiti State in southwestern Nigeria, have reported similar patterns. For example, Ijah *et al.* (2022) observed that soils under continuous cassava and maize cultivation showed lighter and more reddish hues compared to adjacent fallow and forest plots. These color changes were significantly correlated with decreased total nitrogen, available phosphorus, and microbial biomass carbon. Soils from forested top slopes, typically darker and richer in SOC, were contrasted with eroded mid-slope or

footslope soils, which were brighter and redder due to exposed subsoil material and iron oxide enrichment—a clear manifestation of the toposequential dynamics of land degradation.

In more arid tropical zones, such as the Sahelian belt of West Africa or northeastern Brazil, the patterns differ slightly. The land use intensification often leads to the formation of crusted, bleached, or pale-colored soils, particularly in areas subjected to overgrazing, bare soil exposure, and wind erosion. The loss of surface protection exacerbates evaporation and salt accumulation, leading to whitish surface coatings or speckled appearances (Abdulraheem *et al.*, 2022). In these settings, color change is less driven by organic matter decomposition and more by physical and chemical degradation processes such as salinization, calcification, and compaction (Sall *et al.*, 2020). Notably, Guo *et al.* (2020) found that increased land clearing for irrigation in northern Kenya and Ethiopia led to greyish mottling in topsoils, indicative of poor drainage and reduced iron—a precursor to declining fertility and aeration.

The interplay between land use and soil color is also evident in agroforestry systems and shifting cultivation mosaics. In cocoa- and oil palm-based agroforestry systems of southwestern Nigeria and Ghana, for instance, the presence of leaf litter and minimal tillage practices helps maintain darker surface colors and higher SOM relative to monocropped plots. Akinola *et al.* (2023) demonstrated that even within similar climatic zones, agroforestry plots exhibited significantly lower lightness values (L^*) and higher organic carbon content than intensively cultivated maize fields, despite similar soil texture and parent material (Abulraheem *et al.*, 2018). These findings emphasize that the intensity and type of land use—not merely its presence—determine soil color response.

Wetland agriculture, such as rice cultivation in tropical Asia or swamp farming in central Africa, introduces yet another dimension to the analysis. Repeated flooding and drying cycles influence redox potential and lead to the development of redoximorphic features in the soil profile. Zhou *et al.* (2020) documented that paddy soils often display a grayish or bluish matrix color (chroma < 2) with reddish mottles, due to periodic reduction and oxidation of iron. These features deepen with time under continuous inundation and can be used to infer the history of water management and subsurface drainage efficiency. In landscapes undergoing wetland conversion to upland agriculture, the disappearance of gleyed features and reappearance of oxidized hues offer a chronological indicator of drainage and land use change.

Urbanization also contributes to soil color modifications, although the processes are more complex and driven by multiple, overlapping disturbances. Compaction from construction, sealing of surfaces, artificial fill, and pollution alter both the physical structure and chemical makeup of soils. In urban tropical soils, darker colors may indicate contamination with hydrocarbons or sewage sludge, while pale or mixed hues often reflect soil heterogeneity caused by excavation and infilling. Aide and Rivera (2020) observed that urban sprawl in Latin American cities led to widespread disturbance of soil profiles, creating mosaic-like color patterns that are difficult to classify using standard soil taxonomies.

Several studies have further validated these observations using quantitative tools. Ahmad *et al.* (2023) applied visible-near infrared (Vis-NIR) spectroscopy to tropical soils in Indonesia and found strong correlations between color indices and key fertility indicators, such as total nitrogen, extractable phosphorus, and cation exchange capacity. Digital image analysis, based on smartphone photography and standardized lighting conditions, has also emerged as a promising tool for monitoring soil color shifts over time. Gholizadeh *et al.* (2019) found that RGB-derived color variables could predict organic carbon content with over 80% accuracy in Tanzanian soils, even under diverse land use conditions.

Remote sensing applications are increasingly being used to map soil color and infer land degradation status. While spectral resolution remains a limiting factor in densely vegetated areas, advances in UAV-based imaging and multispectral satellites are improving our ability to detect bare soil patches and map color transitions over large areas. Viscarra Rossel *et al.* (2021) highlighted that combining spectral data

with ground-truth color observations enhanced the accuracy of digital soil maps in the Brazilian Cerrado, offering a model for similar applications across African and Asian climosequences.

Despite this growing body of evidence, some challenges remain. Soil color is influenced by multiple, often overlapping factors, making it difficult to isolate the effects of land use without controlled experimental designs. Observer variability, moisture content, and surface residue can introduce inconsistencies in field-based assessments. Moreover, long-term data are lacking in many tropical regions, limiting our understanding of the temporal evolution of soil color under sustained land use pressure.

Nevertheless, the cumulative findings across tropical regions support the assertion that land use intensification consistently induces changes in soil color that are both diagnostically useful and biogeochemically meaningful. These shifts, when interpreted within a climosequential framework, help distinguish between naturally occurring pedogenic patterns and anthropogenic disturbances. They also underscore the importance of maintaining protective land uses—such as agroforestry, conservation tillage, and fallowing—that preserve the organic and mineral characteristics associated with favorable soil colors and ecosystem functions.

4. Methods and Tools for Assessing Soil Color in Biogeochemical Research

The accurate assessment of soil color is central to understanding and interpreting its role as a proxy indicator of biogeochemical cycling and land use impacts, particularly in the tropics. Soil color serves as a visible cue to multiple subsurface processes such as organic matter turnover, redox reactions, mineral weathering, and hydrological regimes. As interest in soil-based environmental monitoring increases, so does the need for reliable, standardized, and scalable methods to measure soil color effectively. A variety of techniques—ranging from traditional field-based approaches to advanced digital imaging and spectroscopy—are currently in use, each with its own strengths, limitations, and suitability for different biogeochemical applications.

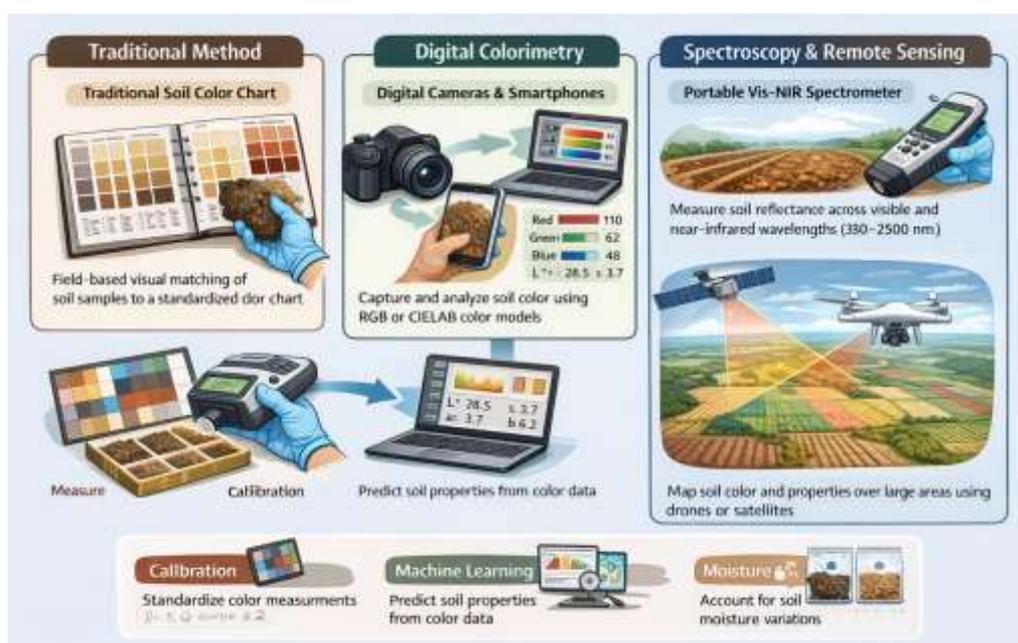


Figure 2: Overview of methods and tools used for assessing soil color in biogeochemical research, illustrating the progression from traditional visual assessment using Munsell Soil Color Charts to quantitative digital colorimetry (RGB and CIELAB systems), visible–near infrared (Vis–NIR)

spectroscopy, and remote sensing approaches, and highlighting their integration with calibration procedures, moisture control, and machine learning for scalable soil monitoring.

The most widely recognized and historically used method for soil color determination is the Munsell Soil Color Chart, developed in the early 20th century and still considered a global standard by many soil scientists. The Munsell system classifies color using three dimensions: hue (the type of color, e.g., red, yellow, brown), value (lightness or darkness), and chroma (color purity or intensity). Field scientists match moist or dry soil samples to the closest chip on the chart, thereby producing standardized, albeit subjective, results. The Munsell system is practical, portable, and inexpensive, making it accessible in remote or resource-limited tropical settings. However, its major drawbacks include observer variability, the influence of ambient light, and inconsistencies in soil moisture or texture that affect perception (Schwertmann and Taylor, 2018; Viscarra Rossel et al., 2021).

To overcome the limitations of subjective visual assessments, researchers have increasingly turned to digital colorimetry. This technique involves capturing soil images using digital cameras or scanners and analyzing color attributes through the RGB (Red, Green, Blue) or *CIELAB* (L^* , a^* , b^*)** color models. The *CIELAB* system, in particular, offers a quantitative and reproducible framework that relates more directly to human visual perception and allows fine discrimination of color differences. In this system, L^* indicates lightness, a^* represents the red-green axis, and b^* reflects the yellow-blue axis. By calibrating digital images with color standards under controlled lighting conditions, soil scientists can obtain accurate and objective measures of soil color suitable for comparison across time, space, and land use types (Gholizadeh et al., 2019; Ahmad et al., 2023).

In the tropical context, digital colorimetry has found applications in mapping soil degradation and monitoring the effects of land use intensification. For instance, Ahmad *et al.* (2023) demonstrated that in tropical Indonesian soils, digital *CIELAB* parameters could predict organic carbon content and pH with high accuracy, especially when integrated with soil texture data. The use of portable smartphone-based color analysis apps is also on the rise, allowing field workers and farmers to collect real-time color data that can be integrated with georeferenced soil databases. These tools, when validated, offer great promise for large-scale citizen science initiatives and participatory land monitoring.

A major advancement in soil color and biogeochemistry research has come from visible and near-infrared reflectance spectroscopy (Vis-NIR). This technique measures the amount of light reflected from a soil sample across a range of wavelengths (typically 350–2500 nm), capturing information related to mineral composition, organic matter, moisture, and pigment concentrations. Spectroscopic data can be used to derive precise color indices while simultaneously predicting a suite of soil properties through chemometric modeling. The advantage of Vis-NIR lies in its non-destructive nature, speed, and the ability to analyze multiple soil properties simultaneously—making it ideal for rapid biogeochemical assessments across heterogeneous tropical landscapes (Gholizadeh et al., 2019; Viscarra Rossel et al., 2021).

In many tropical regions, where laboratory infrastructure may be limited, Vis-NIR has emerged as a transformative tool. For example, research in East Africa has shown that handheld spectrometers can effectively estimate soil organic carbon, iron oxide content, and phosphorus availability using minimal sample preparation. When combined with machine learning algorithms such as random forests, support vector machines, or partial least squares regression, these spectral tools provide robust models for interpreting color data and its biogeochemical correlates (Ahmad et al., 2023). Moreover, the integration of Vis-NIR with digital soil mapping platforms facilitates the creation of high-resolution maps that display spatial variations in soil color and fertility, aiding land use planning and intervention targeting.

Another important avenue in color assessment is the use of remote sensing and aerial imagery. Though traditionally limited by vegetation cover and spectral resolution, recent advancements in Unmanned Aerial Vehicles (UAVs) equipped with multispectral and hyperspectral cameras now enable the capture

of high-resolution images of exposed soil surfaces. These images can be processed to extract soil color information, detect bare soil patches, and monitor temporal changes linked to land use practices. Satellite imagery, particularly from platforms such as Sentinel-2 and Landsat 8, also offers the potential to assess large-scale soil color trends, especially in dry-season periods when vegetation cover is reduced (Zhang et al., 2021).

However, remote sensing applications for soil color are not without limitations. In humid tropical zones with dense vegetation and frequent cloud cover, the window for acquiring accurate bare soil imagery is narrow. Moreover, spectral confusion between soil, vegetation, and residues may lead to classification errors. Despite these challenges, when remote sensing is combined with ground-truth color observations, its utility increases substantially. For instance, in the Brazilian Cerrado, Viscarra Rossel *et al.* (2021) demonstrated that the fusion of UAV-derived RGB data with field color measurements improved soil property predictions and spatial mapping accuracy by over 30%.

The recent rise of machine learning and artificial intelligence tools in soil science further enhances the ability to interpret soil color data in meaningful ways. Algorithms trained on large soil databases can learn to associate color parameters with specific land use histories, soil types, and biogeochemical properties. Such models are particularly useful in digital soil mapping, where they can predict unsampled areas with high spatial resolution. Moreover, the increasing availability of open-access soil color databases—such as the World Soil Color Database—provides a valuable resource for model training and validation.

While these modern tools offer substantial improvements in accuracy and efficiency, it is important to recognize that moisture status remains a critical variable affecting soil color readings. Wet soils appear darker than dry ones due to water's effect on light absorption and reflectance. For accurate comparisons, soil samples should be measured in a consistent moisture condition—ideally at field capacity or oven-dry states. Some digital tools include algorithms to correct for moisture, but such corrections require careful calibration and are not always reliable in diverse tropical contexts (Kargar et al., 2019).

Equally important is the need for standardized protocols in sampling, measurement, and data interpretation. Many discrepancies in empirical findings arise not from measurement error but from inconsistent field protocols, including sampling depth, surface preparation, and horizon selection. Training field personnel and local farmers in standardized soil color assessment methods—whether using Munsell charts, smartphone apps, or spectrometers—can greatly enhance the comparability and utility of color data for biogeochemical monitoring and land use planning.

In summary, soil color assessment has evolved from a subjective, qualitative observation to a highly quantitative and technologically advanced discipline. The growing array of tools—from Munsell charts and digital imaging to Vis-NIR spectroscopy and remote sensing—enables researchers to capture, analyze, and interpret soil color with unprecedented precision. In the context of tropical land use intensification, these tools are invaluable for linking visual changes in soil appearance to deeper biogeochemical transformations. When embedded within robust research designs and climosequential frameworks, color assessments can guide sustainable land management, support policy decisions, and foster local knowledge integration in soil stewardship practices.

5. Review of Empirical Studies on Soil Color–Land Use Relationships Across Tropical Climosequences

A growing body of empirical literature provides insight into how soil color varies with land use intensification across diverse tropical climosequences. These studies, often conducted along altitudinal gradients, rainfall zones, or across land use mosaics, help illuminate the extent to which soil color reflects underlying changes in soil chemistry, organic matter dynamics, and environmental conditions.

They also help test the consistency of color-based proxies across biophysical zones, offering evidence for general patterns and local exceptions.

In southwestern Nigeria, Obalum *et al.* (2022) conducted a toposequence-based study assessing how land use affects soil morphological and chemical properties along a slope under humid tropical conditions. The researchers observed significant lightening of soil surface color with increasing cultivation intensity. Forest soils on upper slopes exhibited dark reddish-brown surface horizons (5YR 3/2), rich in organic matter and iron oxides, whereas continuously cultivated plots showed lighter, yellowish-brown colors (7.5YR 5/4) and reduced organic carbon. The color changes correlated with declining total nitrogen, soil aggregate stability, and microbial biomass carbon. Similar trends were observed in mid-slope areas, where erosion exposed subsoil horizons with redder and brighter hues, indicative of iron enrichment and surface layer removal.

In Ghana, Coulibaly *et al.* (2021) evaluated soil phosphorus availability and iron oxide dynamics across different land uses and rainfall regimes. Their results showed that soils in wetter zones had darker colors associated with higher organic matter and more stable iron-phosphate complexes. In contrast, drier zone soils under intensive cultivation showed lighter colors and greater phosphorus fixation, related to increased free iron oxide concentrations. This study affirmed the value of color indicators not only for carbon dynamics but also for inferring nutrient retention and availability across rainfall-driven climosequences.

From East Africa, Musinguzi *et al.* (2021) reported on soil quality in banana-based systems across a rainfall gradient in Uganda. Their findings showed that soil color, particularly surface darkening, was a reliable proxy for organic matter content and cation exchange capacity. Agroforestry systems maintained darker colors (10YR 3/2–3/3), while intensively managed monocultures, especially on steeper slopes, developed yellowish-brown surface horizons (10YR 5/4). In these sites, color lightening was associated with fertility decline, higher bulk density, and reduced infiltration—indicators of cumulative degradation over years of cultivation.

In Latin America, particularly in the Brazilian Cerrado, Viscarra Rossel *et al.* (2021) demonstrated how soil color measurements from Vis-NIR spectroscopy could be used to track changes in carbon content under land use intensification. Their study involved comparing natural savanna areas, no-till fields, and conventional tillage sites. They found that conventional tillage caused rapid declines in organic matter and lightening of soil color within the top 10 cm. Moreover, the a^* (red) and b^* (yellow) parameters from the CIELAB color space increased with disturbance, correlating with iron oxide exposure and SOC loss. Importantly, these trends were consistent across a 500 km climosequence, suggesting soil color is a stable and scalable indicator of soil biogeochemistry.

In the Andean highlands, where steep terrain and altitudinal gradients create complex soil-forming conditions, Davidson *et al.* (2000) examined color changes under potato farming. Their results revealed the formation of grayish hues and mottles in lower slope areas subjected to poor drainage and compacted footpaths—features associated with fluctuating redox conditions. These color patterns were absent in higher-elevation plots under natural grasslands. The study emphasized the role of landscape position and hydrology in driving color variability, even within small climatic zones.

From Southeast Asia, Guo *et al.* (2020) evaluated irrigated paddy soils in Vietnam, comparing rice–rice and rice–vegetable rotations. They reported that rice-only systems exhibited grayish soil matrices with chroma values less than 2, accompanied by yellow to reddish mottles—a result of repeated waterlogging and iron reduction. In contrast, rice–vegetable rotations with intermittent drying reduced the development of gray features, resulting in a shift toward yellow-brown colors and higher iron oxidation states. This contrast highlighted the sensitivity of soil color to land use timing and water management, even within the same agroecological zone.

In the Sahelian tropics, Sall *et al.* (2020) explored land degradation patterns across agro-pastoral systems in Niger and Burkina Faso. Here, intense grazing and deforestation resulted in highly degraded soils with pale colors and surface crusts, reflecting loss of vegetation cover, organic matter, and surface porosity. Soil chroma values were generally low, while value (lightness) increased with degradation severity. These visual features corresponded with declines in available nitrogen, water retention, and infiltration capacity. Importantly, the study developed a soil color degradation index that could be used by farmers and extension agents to assess field-level productivity potential.

In Ekiti State, Nigeria, Ijah *et al.* (2022) assessed color variation across different land uses and slope positions. They observed that upland fallow soils retained darker hues (7.5YR 3/3), indicative of higher organic content and minimal disturbance. Conversely, lowland and mid-slope areas under continuous cultivation had brighter, redder colors (5YR 5/6), corresponding to iron accumulation and SOM depletion. Their study supported the use of soil color as a cost-effective screening tool for land suitability in smallholder farming systems.

Another notable contribution comes from Mbaya *et al.* (2022), who examined soil color and carbon distribution under traditional and modern farming systems in northeastern Nigeria. Their research demonstrated that traditional fallow–crop rotations preserved dark soil colors and high SOC levels, while mechanized farms under continuous tillage had lighter colors and reduced fertility. The authors proposed that incorporating soil color into field surveys and extension programs could enhance farmer awareness and guide sustainable intensification strategies.

Several studies have also explored the influence of redoximorphic features under tropical wetland or floodplain conditions. Vepraskas and Lindbo (2018) found that in areas converted from wetlands to uplands, the fading of gleyed features and emergence of brighter matrix colors corresponded with increased aeration and iron oxidation. They argued that color transitions could serve as a chronological record of hydrological change and nutrient cycling, particularly when linked with laboratory measurements of redox-sensitive elements like iron, manganese, and phosphorus.

Collectively, these empirical studies reinforce the value of soil color as an integrative indicator of land use change and biogeochemical response across tropical climosequences. Whether measured visually or instrumentally, color changes reliably track processes such as SOM depletion, iron oxidation, redox fluctuations, and hydrological shifts. Importantly, these relationships are consistent across continents and climatic zones, supporting the inclusion of soil color metrics in soil quality assessments, land evaluation protocols, and agroecological zoning frameworks.

However, some limitations should be acknowledged. The interpretation of color data can be confounded by parent material, soil texture, and moisture variability. In highly heterogeneous landscapes, color alone may not fully capture all aspects of soil fertility or degradation. Therefore, empirical findings emphasize the importance of coupling color analysis with other indicators—such as pH, bulk density, microbial activity, and erosion status—for a more holistic understanding of soil health. Despite these caveats, the weight of evidence suggests that soil color, when interpreted within biogeochemical and land use contexts, offers a powerful, accessible, and underutilized tool for tropical soil assessment and monitoring.

6. Comparative Analysis of Findings and Methodologies

The review of empirical studies across diverse tropical climosequences highlights not only consistent trends in soil color responses to land use intensification but also notable variations in methodologies, measurement scales, and interpretative frameworks. This section offers a comparative analysis of these approaches, examining how methodological choices influence the interpretation of soil color data and

its correlation with biogeochemical processes. It also evaluates the strengths and limitations of traditional and modern methods used to assess soil color in relation to land use dynamics.

One prominent pattern that emerges across studies is the consistent use of the Munsell Soil Color Chart as a baseline tool for field assessment. Despite its limitations in precision, the Munsell system remains valuable for initial soil classification, especially in low-resource settings. Its widespread adoption ensures comparability across sites and studies. However, the subjectivity inherent in visual matching often leads to inconsistencies in color assignment, particularly when multiple observers are involved or when lighting and soil moisture conditions are uncontrolled. Some studies attempt to mitigate this issue by drying samples before measurement or using photographic documentation to calibrate observer readings, though these practices are not uniformly applied.

In contrast, newer studies adopting digital colorimetry and CIELAB-based analysis provide greater objectivity and granularity in soil color measurement. The CIELAB model, by quantifying color attributes along continuous axes of lightness (L^*), redness (a^*), and yellowness (b^*), facilitates detailed statistical analysis and enhances reproducibility. For example, Ahmad *et al.* (2023) and Gholizadeh *et al.* (2019) utilized image processing software to extract CIELAB values from digital soil images, enabling them to correlate color with soil organic carbon, pH, and nutrient concentrations. These methods outperform Munsell-based approaches in detecting subtle changes across land uses or within climosequential gradients, particularly in areas with minimal visual differences.

Another distinguishing factor among studies is the scale of analysis. Field-based surveys typically assess soil color at the horizon level or across land units within farm plots, offering localized insights. This micro-scale approach allows for direct observation of color shifts under different management practices and slope positions. For instance, Obalum *et al.* (2022) and Ijah *et al.* (2022) employed toposquence sampling to assess how erosion and organic matter redistribution affect color along hillslopes. These studies provided rich contextual detail, showing how color reflects pedogenic processes like eluviation, accumulation, and horizon truncation.

Conversely, regional-scale studies, such as those by Viscarra Rossel *et al.* (2021) and Guo *et al.* (2020), integrate remote sensing and machine learning techniques to assess soil color across thousands of hectares. These studies employ geostatistical modeling, UAV imagery, and hyperspectral data to link soil reflectance with color and fertility attributes. While these methods allow broader landscape analysis and spatial predictions, they often sacrifice resolution in soil profile detail and may require ground-truthing to ensure accuracy. Nonetheless, their scalability makes them indispensable for national soil inventories and land degradation assessments.

The interpretation of color–biogeochemistry relationships also varies based on study objectives. Some researchers emphasize soil color as a proxy for organic carbon dynamics, focusing on the darkening or lightening of surface horizons under different land uses. This is particularly common in humid or sub-humid regions where SOM plays a major role in soil fertility. Others examine soil color as an indicator of iron oxide transformations, using changes in hue and chroma to infer redox status, leaching intensity, and iron mobility—especially in Ultisols, Oxisols, and floodplain soils.

Still, other studies highlight redoximorphic features—such as mottling, gleying, or concretions—as biogeochemical indicators sensitive to hydrological alteration. These features are best assessed through soil profile description and require close field observation and classification skills. The work of Vepraskas and Lindbo (2018) is exemplary in connecting redoximorphic color patterns to changes in soil aeration, denitrification potential, and phosphorus availability. In comparison, studies relying on remote sensing or topsoil samples may overlook these subsurface indicators unless profile data are integrated.

Another layer of methodological comparison relates to temporal assessment. While most studies are cross-sectional—comparing different land uses or locations at a single time—longitudinal or

chronosequence studies offer insights into how soil color evolves over time under continuous land use. For example, Coulibaly *et al.* (2021) used archived soil data and historical land use records to track changes in color and fertility across a 20-year cultivation timeline. Such designs are more data-intensive but provide strong evidence for causality and allow for modeling of degradation thresholds or recovery trajectories.

Moreover, integration with biogeochemical data is essential for interpreting soil color meaningfully. Some studies report only visual observations of color change without correlating them with soil properties. While these observations are useful, their diagnostic value is limited unless linked to chemical analyses such as soil organic carbon, exchangeable bases, or total nitrogen. In contrast, the best-performing studies—such as those by Sall *et al.* (2020) and Musinguzi *et al.* (2021)—combine color measurements with comprehensive laboratory data, enabling multivariate analysis and stronger inferential power.

The adoption of machine learning techniques for predictive modeling is also gaining traction. Algorithms trained on soil color and laboratory data can predict unsampled properties or classify soils based on land use or fertility status. These approaches require robust training datasets and high-quality metadata but offer substantial benefits in precision agriculture and digital soil mapping. For instance, Ahmad *et al.* (2023) demonstrated that random forest models using CIELAB data outperformed traditional regression models in predicting SOC across diverse land uses in the humid tropics.

Despite the progress, challenges remain. Moisture variability, lighting conditions, and surface residues continue to introduce noise into color measurements. Standardizing sample preparation—such as drying, sieving, and lighting calibration—is critical but often inconsistently applied across studies. Observer bias in Munsell assessments, even when minimized, persists as a limitation. Moreover, some tropical soils exhibit naturally mixed or variable color patterns, making classification and analysis difficult, particularly in transitional zones or disturbed areas.

In terms of applicability, methodological choice must align with research goals, available resources, and spatial scale. For localized studies focused on farmer decision-making or field diagnostics, Munsell charts and smartphone-based digital colorimetry may be sufficient and cost-effective. For national mapping or remote sensing applications, spectroscopic and UAV-based methods offer scalability and integration with GIS platforms. Ultimately, combining multiple methods—visual, digital, spectral, and analytical—yields the most comprehensive understanding of soil color dynamics and their biogeochemical implications.

In conclusion, the diversity of methods employed to assess soil color across tropical climosequences underscores both the richness and complexity of the field. While traditional methods offer accessibility and continuity with past research, modern digital and spectral tools provide precision, scalability, and integration potential. Methodological rigor, including standardization and validation, is essential to ensure reliable interpretation of soil color as a proxy for land use impact and biogeochemical processes. As land pressures increase across the tropics, robust color assessment techniques will be indispensable for monitoring soil health, guiding land management, and supporting sustainable development goals.

7. Implications for Land Use, Soil Management, and Policy

Understanding soil color as a proxy indicator of biogeochemical cycling and land use dynamics holds important implications for land use planning, soil fertility management, and environmental policy—especially in the tropics, where rapid land transformation and limited monitoring infrastructure often constrain sustainable development (Abdulraheem *et al.*, 2025). The visual and measurable shifts in soil color caused by land use intensification are not only scientifically significant but also practically useful,

as they reflect deep-rooted ecological changes that affect soil productivity, environmental quality, and long-term land viability.

At the core of soil color implications lies its diagnostic power for soil fertility assessment. Color transitions from dark brown to lighter hues typically signal a reduction in organic matter content, a key driver of soil nutrient availability, aggregate stability, and water retention. Farmers and land users, particularly in tropical smallholder systems, often recognize these changes intuitively. Darker soils are generally perceived as "more fertile," while lighter or pale soils are treated as "worn out" or "exhausted." Scientific studies, including those by Obalum *et al.* (2022), Ahmad *et al.* (2023), and Mbaya *et al.* (2022), support this perception with empirical evidence, confirming that lighter-colored soils are associated with lower organic carbon, nitrogen, phosphorus, and microbial activity. Embedding color-based indicators into local extension systems and land evaluation protocols can therefore enhance farmer-led diagnostics and improve site-specific nutrient management.

From a land use planning perspective, soil color data can inform zoning decisions, land capability classification, and suitability mapping. In regions with limited access to laboratory analyses, color offers a cost-effective and rapid means of assessing the effects of cultivation, grazing, or infrastructure development. For example, the presence of reddish or yellowish subsoil colors may indicate iron oxide accumulation and good drainage—conditions suitable for certain crops like cassava or yam—while gray or mottled colors may signal waterlogging, necessitating drainage improvement or alternative land uses like rice cultivation. Integrating soil color observations into GIS-based land use plans can help identify priority areas for conservation, rehabilitation, or intensification, particularly when combined with slope, texture, and vegetation data.

On sloping landscapes typical of tropical uplands, soil color provides clues about erosion severity and toposequential degradation. Studies from Nigeria, Uganda, and Colombia have shown that color changes downslope—from dark brown to reddish or pale colors—are often indicative of topsoil loss, horizon truncation, and subsoil exposure (Ijah *et al.*, 2022; Musinguzi *et al.*, 2021). These findings underscore the need for slope-sensitive management strategies, including contour farming, agroforestry, cover cropping, and reduced tillage. Visual indicators such as soil color changes along slopes can be integrated into erosion risk assessments and early warning systems, helping farmers and planners prioritize intervention areas before irreversible degradation sets in.

The redox-dependent nature of certain soil colors, particularly gleyed or mottled hues, also offers insight into hydrological and drainage management. In poorly drained or seasonally saturated areas, grayish soils with chroma values less than 2 often develop, along with reddish or yellowish mottles formed during oxidation events. These features indicate not only anaerobic conditions but also nutrient limitations, particularly in phosphorus and micronutrients like iron and manganese. Recognizing such patterns is vital in tropical wetlands, floodplains, and rice-growing systems, where inappropriate land conversion can lead to nutrient imbalances, greenhouse gas emissions, and biodiversity loss (Vepraskas and Lindbo, 2018; Zhou *et al.*, 2020). Policy interventions should support the mapping and protection of such hydromorphic zones, using soil color data as a screening tool for sustainable wetland use and conservation zoning.

In addition to guiding management, soil color serves a communication role between scientific knowledge and indigenous ecological understanding. Across many tropical cultures, soil color is embedded in traditional land classification systems, often guiding planting calendars, crop selection, and fallow cycles. In parts of West Africa, for instance, farmers differentiate between "black earth" (rich, moist, organic soils) and "red sand" (infertile, erosion-prone soils), making decisions accordingly (Mbaya *et al.*, 2022). By validating and enriching these local classifications with scientific metrics—such as SOM content, cation exchange capacity, or pH—extension services and research programs can foster more participatory, culturally grounded approaches to soil conservation and land rehabilitation.

Policy frameworks and development programs also stand to benefit from the inclusion of soil color metrics in soil health monitoring and land degradation assessments. Initiatives such as the FAO's Global Soil Partnership, the United Nations Convention to Combat Desertification (UNCCD), and the Africa Soil Information Service (AfSIS) have all emphasized the need for accessible, harmonized indicators of land condition. Soil color, due to its low cost, ease of measurement, and ecological relevance, aligns well with the principles of practical monitoring tools for Sustainable Land Management (SLM). When combined with digital mapping platforms and citizen science applications, color-based data can enhance national reporting on land degradation neutrality, support investment targeting, and guide restoration interventions in vulnerable agroecosystems.

Moreover, the increasing adoption of machine learning and remote sensing tools presents an opportunity to scale the use of soil color as a spatially explicit variable in land use and environmental policy. With satellite and drone-based imaging systems now capable of detecting bare soil reflectance patterns, color indicators can be mapped and monitored at landscape and regional levels. Integration with machine learning models—trained on reference datasets with known color-biogeochemistry linkages—can generate predictive maps of soil fertility, erosion hotspots, or organic carbon distribution. These outputs can inform regional agricultural zoning, climate adaptation planning, and soil carbon sequestration programs under frameworks such as REDD+ or Nationally Determined Contributions (NDCs).

Despite its potential, the use of soil color in policy contexts requires standardization and quality assurance. Variability in measurement techniques—such as inconsistent moisture status, lighting conditions, or observer subjectivity—can compromise data comparability and undermine confidence in findings. Therefore, national soil programs and land management agencies must invest in training, calibration tools, and clear protocols for soil color assessment. Digital tools, such as color apps, spectrometers, and image analysis software, offer pathways to improve accuracy and reproducibility, particularly when paired with local capacity-building efforts and open-access data platforms.

In conclusion, soil color offers more than just a descriptive attribute—it is a diagnostic, communicative, and policy-relevant indicator of soil health and biogeochemical functioning. As tropical regions face mounting pressures from agricultural intensification, climate variability, and urban expansion, integrating soil color into land management strategies can enhance both scientific understanding and practical decision-making. Whether guiding field-level interventions, supporting farmer knowledge, or informing national policy, soil color remains a simple yet powerful window into the hidden dynamics of the soil landscape.

8. Future Research Directions

Despite substantial progress in understanding soil color as a proxy for biogeochemical and land use dynamics, several critical research gaps remain. Future studies should focus on developing standardized soil color assessment protocols across diverse tropical regions, considering variables like soil moisture, texture, lighting, and observer effects. Harmonization of methods—whether using Munsell charts, digital colorimetry, or Vis-NIR spectroscopy—will enhance cross-site comparisons and data integration into soil information systems.

Longitudinal studies examining temporal changes in soil color under varying land use trajectories are also needed. While most current research is cross-sectional, chronosequence or monitoring-based designs would provide deeper insight into how rapidly soil color responds to intensification, restoration, or climate-related shifts.

In addition, there is a need for greater mechanistic understanding of how specific biogeochemical processes—such as iron reduction, carbon turnover, and clay mineralogy—translate into measurable color changes. Controlled experiments that isolate these processes under different land management

and moisture regimes would clarify causality and improve the reliability of soil color as a diagnostic tool.

The integration of machine learning and remote sensing with high-resolution soil color data is a promising area for scaling insights to landscape and regional levels. Developing predictive models that link satellite- or drone-derived color indices with key soil health indicators will enhance digital soil mapping and land degradation assessments, particularly in data-scarce regions.

Finally, more transdisciplinary and participatory research is needed to connect scientific findings with indigenous soil knowledge and farmer decision-making. Engaging local communities in soil color monitoring can validate scientific models, foster ownership, and bridge the gap between research and practice in sustainable land management.

9. Conclusion

Soil color is more than a visual characteristic—it is a powerful, integrative indicator of soil biogeochemistry, land use history, and environmental processes. Across tropical climosequences, changes in soil color reliably reflect shifts in organic matter, iron oxides, redox status, and degradation severity driven by land use intensification. Advances in digital imaging, spectroscopy, and geospatial analysis have strengthened the scientific basis for using color as a proxy for soil health, making it a practical tool for both researchers and land users.

Empirical evidence confirms that soil color transitions—especially from dark to lighter hues or from gleyed to oxidized features—are linked to measurable declines in fertility, structure, and biological function. Incorporating soil color into land evaluation frameworks, policy planning, and farmer training programs can help enhance early detection of degradation and guide more sustainable land use decisions.

While methodological challenges and data gaps remain, ongoing innovations in technology and participatory science offer pathways for broader, more reliable application of soil color metrics. As the tropics continue to face complex land use pressures, soil color stands out as a low-cost, scalable, and ecologically meaningful lens for interpreting and managing the health of the soil landscape.

Competing Interest

The authors declare no competing interests. There are no financial, professional, or personal relationships that could be perceived to influence the content or conclusions of this review.

Author's Contribution

The authors jointly conceptualized the review topic, conducted the literature search, critically analyzed relevant publications, organized the manuscript structure, and wrote the entire paper. All aspects of this review were independently completed by the authors

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